Gas Processing Journal

Vol. 4, No.1 , 2016
http://gpj.ui.ac.ir

Area Energy and Throughput Targeting in Debottlenecking of Heat Exchanger Networks with Decomposition Approach

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Article History

Received: 8 August 2014 *Accepted: 5 September 2016* *Published Online: 20 November 2016*

Abstract

For energy saving retrofit projects, its economics are usually evaluated in terms of capital investment and payback time. The capital investment is in direct relation to the total heat recovery area of the network and the payback time factor is base on both the area and the energy savings. The debottlenecking is an increased throughput, which can be profitable in economic sense. The combination of these two different objectives leads to a new definition of payback time, which differs, from the simple payback of savings to investment ratio. The correlation among area, energy savings and throughput increase is assessed based on pinch technology. The variation in energy savings and network area with throughput increase considering both economic factors of investment and payback time is reflected in the results. The decomposition approach is implemented as well, and its contribution in rapid detection of the most economical opportunity of network debottlenecking is discussed and the findings are diagramed separately. A visual software code is developed and validated in this study.

Keywords

Debottlenecking, Throughput Increase, Pinch Technology, Heat Exchanger Network

1. Introduction

Pinch technology is one of the best conceptual heat exchanger network synthesis techniques applied in designing new heat exchanger networks (grassroot design) and energy saving retrofits as well as debottlenecking of the existing networks. This method of heat integration provides promising alternatives while other methods like inspection and computer search lack the potential of providing the optimum network (Shenoy, 1995). The most straightforward heat exchanger network design situations are those of grassroot design with the most freedom in choosing the design options and heat exchangers size (Smith, 2005), but this is a relatively rare situation. What is common in most researchers is facing the task of analyzing an existing heat exchangers' network and see whether it can be improved, to reduce energy and increase profitability. This may be a retrofit or debottleneck situation. The design strategy for retrofit or debottleneck is completely different from that of a new (grassroot) design (Kemp, 2007). One of the most common motivations to modify an existing plant is to increase capacity or to debottleneck the plant. During such debottlenecking projects, investment in new equipment should be kept to a minimum by applying the existing equipment to the fullest extent. Further, since these plants were designed and built when energy was considerably cheaper, it is imperative to carry out energy conservation measures (MUKHERJEE, 1988)???.

Retrofit projects are commonly designed to maximize the application of the existing equipment and reduce investment on the new unit operation, with respect to changes in

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ISSN (Online): 2345-4172, ISSN (Print): 2322-3251

production objectives change. Some examples of this change consist of increasing the throughput, incorporating new feedstocks, improving the value of products' and reducing operating costs and energy consumption. These changes may have some consequences like limited heat recovery, hydraulics of heat exchanger network, overflow and fouling in distillation column and pressure drop alteration, all of which cause some bottlenecks in the process Tahouniet al (2014). Retrofit for debottlenecking after increasing the petroleumplants throughput has been and is widely studied in various studies with a focus on heat exchanger network and distillation systems. The retrofit for debottlenecking should be aimed to have a more efficient heat recovery network. Panjeshahi & Tahouni, (2008) developed a method for targeting based on optimum pressure drops, which was effectively applied in the retrofit of a crude oil pre-heat train after increasing the throughput. They considered the stream pressure drop as a key variable, which optimizes the unit specifications in targeting stage. (Smith et al (2010) proposed a retrofit design method in processing streams with temperature-dependent thermal properties. Soltani & Shafiei, (2011) developed a new procedure to retrofit HEN sincluding pressure drop where numerical methods are applied (Wang et al, , (2012) presented a new design approach for HEN retrofit study based on heat transfer enhancement, which analyzed the physical insight of enhanced exchangers. Bao et al, (2010) worked on process integration and cogeneration analysis of GTL processes. Park et al (2012) proposed the concept of a retrofit design for a boil-off gas handling process in liquefied natural gas through fundamental analysis. (Jiang et al (2014) presented an approach to a cost-effective HEN retrofit with a fixed network structure.

During debottlenecking of plants, existing heat exchanger networks often become limiting endeavors, as they are unable to handle increased throughputs and heat duties. Instead of replacing these heat exchangers with and bigger ones at considerable expense, an optimum strategy should be evolved which would provide a combination of extra utility, throughput increase and additional area.

Evaluating the engineering project economics is subject to capital cost (investment) or payback time terms. For energy saving retrofit projects, any of the these two terms may be applied, while the grass root and debottlenecking projects are based on an investment ceiling (payback time is usually not an economic criterion here) (Polley & Amidpour, 2000).

The capital investment in heat exchanger network could often estimated by the heat exchanger network total area calculation alone while there are more than one parameter present in the payback formulation. The simple payback is estimated by dividing the investment into the savings.

It should be mentioned that pinch technology applies algorithms to determine energy saving and network area as a function of the minimum temperature approach ($\Delta T_{\min}$) allowed for the network. Retrofit and debottlenecking procedures are similar in being implemented in an existing network with dissimilar objectives. Most often, the objective of heat exchanger network retrofits is to reduce the costs of energy by increasing the energy saving while the debottlenecking objective is to increase throughput.

The existing retrofit or debottlenecking procedures apply the savings-investment plot to find the optimum target for energy saving (retrofit) or throughput increase (debottlenecking). This plot, in Fig. (1) shows the variation in energy saving with investment (corresponded to the total heat recovery area added to the network) in a range of $\Delta T_{\min}$.

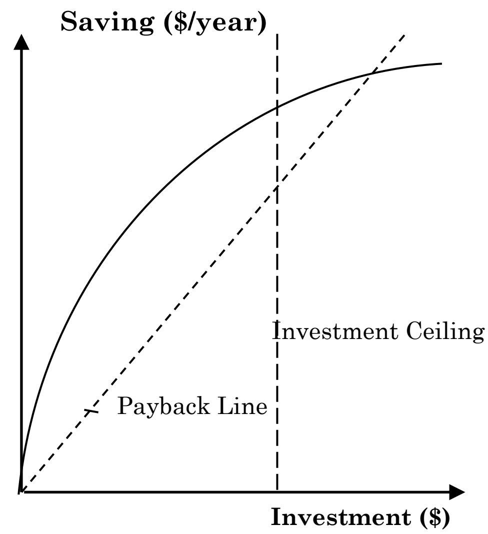

Figure 1. Saving-Investment Plot

After defining the target through the specified economic criterion (payback or investment), a number of targeting curves are drawn for redesigning the new network. These curves and their target are displayed in an area-energy plot, Fig. (2). For plotting the ideal area-energy curve, area targets are generated for different energy levels.

The existing process (positioned at point X in Fig. (2)) does not apply the installed heat recovery areain an ideal manner. With the amount of area actually installed, the process could be operated with the quantity of energy associated with point A. That is, for the quantity of actually consumed heat, the ideal representation of the area at point B is required.

Many different target curves are suggested since the actual correlation between additional area and resultant energy saving is a function of cost, area efficiency, network structure and how modifications to the network are best introduced. The general assumption of adding new area to the network in an ideal manner prevails and the results as target curves are in parallel with ideal area-energy curve.

The ideal target curve for the increased throughput lies above the corresponding curve for the existing throughput. This is because the heat recovery area is inadequate to operate at the higher throughput, therefore it must be compensated through additional utility. Said otherwise, every point on the area-energy plot (including the existing design) due to the extra utility required for a given area moves horizontally to the right when the flow rates are increased, Fig. (3).

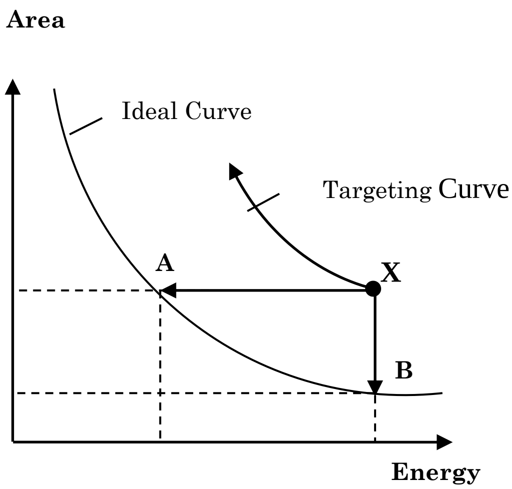

Figure 2. Area-Energy Plot

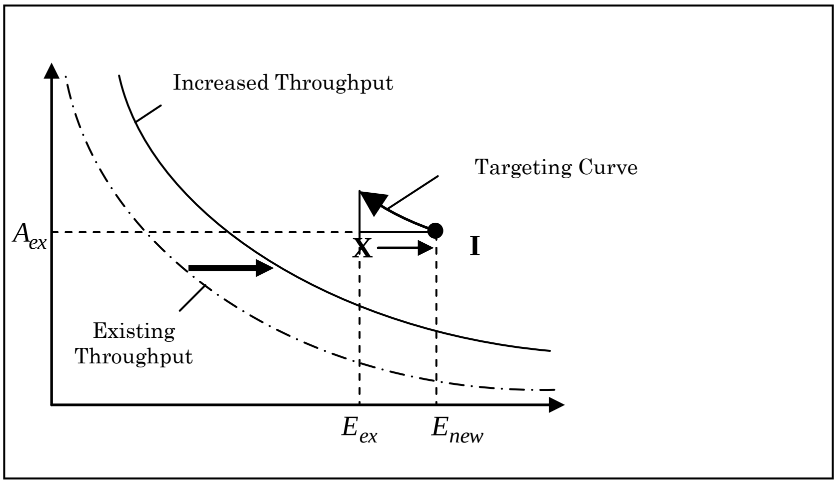

Figure 3. The Area-Energy Plot for Increased Throughput

As observed in Fig. (3), for the increased throughput, the existing design point X moves towards point I . If the operation for increased throughput is to be conducted at the existing utility level, energy saving and the corresponding heat recovery area are required. After obtaining one percent increase in plant capacity, it is necessary to avoid purchasing additional expensive equipment like furnace and refrigeration systems, increased utility consumption due to reduced capacity. Targeting curve in this level is in parallel with the Ideal Area-Energy targeted curve. The optimal energy level increaseis considered as the ideal curve and the end point (point H). At this stage utility regains its initial value (before increase) creating an extra area of HX in Fig. (3), the representative will be required to overcome the limitations utility.

2. Analysis

2.1. User-Software Interface

In this study, a visual software applied to implement the procedure of area, energy and throughput targeting. Choosing this software is advantages in writing the code: its "Visual" property refers to the method adopted in creating what the user sees or the graphical user infers and it provides access to databases stored in different data sources such as Microsoft office; therefore, it is not necessary to input the extensive data at every program runs. Furthermore, the possibility of inter operation between the software and Microsoft excel can be applied for automated charting and graphing.

On the first run of the program, the data related to the streams and heat exchangers (e.g. temperatures, flow rates, heat transfer coefficients and specific heats of the streams and areas or duties and the inlet and outlet temperatures of the heat exchangers) are accepted from the user or retrieved through databases.

The second run increases the throughput percentage for every stream and some economic parameters like: annual value of the product sales price, annual cost of the unit duty for hot and cold utilities and the investment or the payback time.

The third run is designed to display the results.

2.2. Area, Energy and Throughput Targeting in a Simultaneous Manner

For simultaneous targeting of area, energy and throughput, a new targeting curve is considered in area-energy plot, Fig. (4).

The heat recovery area associated with point D is required if the operation for increased throughput is to be conducted at the existing utility level. An amount of A_{Deb} heat recovery area is required for debottlenecking. It is possible to perform an energy saving retrofit targeting from point D to get to the point R which can be determined according to the economic criterions. This requires an additional heat recovery area with the amount of A_{Ret} .

The targeting procedure in both targeting curves is based on energy and area targets established for ΔT_{min} target and the targeting curve is considered to be parallel with ideal area-energy curve of the increased throughput.

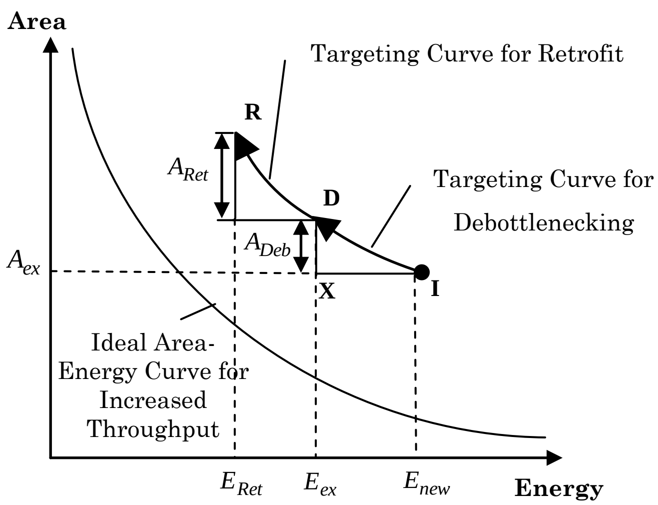

Figure 4. Simultaneous Area, Energy and Throughput Targeting

The first stage of the targeting procedure for network debottleneck, is almost similar to the first stage of plant debottleneck procedure suggested byAhmad & Polley, (1990). This procedure includes a process simulation at the desired increased throughput with additional utility consumption obtain the required temperatures, an improvement in the energy recovery by applying the area-energy plot considering the additional utility requirement as the scope of an energy saving retrofit. The target ΔT_{min} for this stage is determined according to the area and energy consumption associated with the existing network (point X). The second stage is the targeting procedure for network retrofit, the project scope is expanded for greater energy saving according to the target $\Delta T_{\min}$ which meets the economic criterions.

2.3. The Economic Criterions

As mentioned previously, in order to reduce the energy consumption in the second stage of the project modifications it is necessary to first determine the target $\Delta T_{\min}$. For this purpose an economic criterion should be chosen first. One of these criterion is the investment ceiling. This investment is mostly related to the additional heat recovery area capital cost. After assigning the required investment to A_{Deb}, the remained investment defines the amount of A_{Ret} and its corresponding $\Delta T_{\min}$. Capital cost of a heat exchanger represented by:

$$C = a + b.A^{c} \qquad (1)$$

where, *a, b* and *c* are the cost law coefficients which depend on the material of construction, the pressure rating and the type of heat exchanger(Mascia et al (2007).

By applying the above equation, the correlation between total heat recovery area added for both debottleneck and retrofit targets $A_{tot} = A_{Deb} + A_{Ret}$) and its capital cost (investment) can be represented as follows:

$$Investment = a.N_m + b.N_s (A_{tot}/N_s)^{c} \qquad (2)$$

where, N_m is the number of matches and N_s is the number of shells after rounding off:

$$N_m = \left[\frac{A_{tot}}{A_{Ave,\,m}}\right] \qquad N_s = \left[\frac{A_{tot}}{A_{Ave,\,s}}\right] \qquad (3)$$

where, $A_{Ave,m}$ is the average area per match and $A_{Ave,s}$ is the average area per shell for the existing network:

$$A_{Ave,\,m} = \frac{A_{existing}}{NM} \qquad A_{Ave,\,s} = \frac{A_{existing}}{NS} \qquad (4)$$

where, NM is the number of heat exchangers and NS is the total number of shells for the existing network.

The other economic criterion is the payback time, chosen instead of investment to control the project target by defining the amount of energy saving in the second stage of modifications. In this study a new definition of payback time is presented for simultaneous targeting of area, energy and throughput increase:

$$Payback = \frac{Investment}{U_{Cost}.(E_{ex} \quad E_{Ret}) + PR_{Price}.\dot{M}_{PR}} \qquad (5)$$

where, $(E_{ex} \quad E_{Ret})$ represents the amount of energy saving in the retrofit targeting phase of the project, U_{Cost} and PR_{cost} are the annual cost of unit duty for all utility and annual value of product sales price, respectively and $\dot{M}_{PR}$ is the in the product flow rate.

2.4. The Decomposition Approach

Amidpour & Polley (1999) introduced problem decomposition into process integration analysis. By decomposing the overall integration problem into self-contained regions, the engineer is handling a small number of sub problems. The design of these smaller individual networks is likely to be a simpler and faster task. The combination of these regions or zones can be analyzed in economical sense. Despite the advantages of problem decomposition, solving the difficult problems through inspection (analyzing all the zones and the combination of them) is very time consuming, therefore, Amidpour has developed a stream cascade table for a faster identification of required changes.

The problem decomposition approach with throughput increase targeting by applying of computer programming is combined in this study. In this procedure economic analysis is applied for individual streams and the combination of streams which their flow rates are increased. This throughput increase can also be different from one stream to another. This throughput targeting procedure for heat exchanger networks' debottleneck making has three important advantages:

1. Making the omission of the infeasible throughput increase easy and make the problem less complex (e.g. the flow rates of some streams are not allowed to be higher and for some streams some limitations should be devised to increase their flow rates)
2. In real throughput increase projects, the flow rate increase may not be the same for all of the streams. By considering a specific flow rate increase for each stream, a more real network can be pursued in the next stage
3. It reveals that' flow rate increase, offers the best opportunity for energy saving in the network.

The software introduced in this article is able to quickly implement the procedure of area, energy and throughput targeting with and without using decomposition approach.

2.5. Validation of the Code

The accuracy of the developed computer code is validated by simulating a solved example from reference source of, establishing debottlenecking targets (Shenoy, 1995), hence: Example: it is sought to increase the throughput for the following network Fig. (5). The heat transfer coefficients, dirt factors and physical properties of the streams, the specifications of the existing exchangers and the cost data are available and applied to the program. It is assumed that only flow rates of the streams are increased and temperatures remain unaffected.

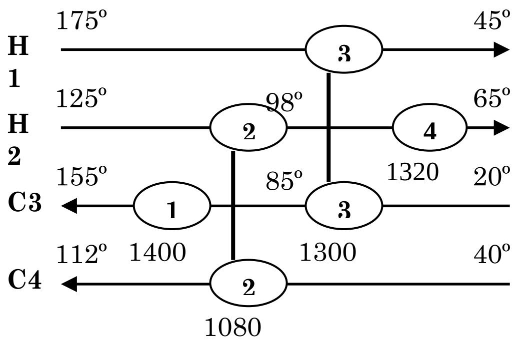

Figure 5. The Existing Heat Exchanger Network

3. Results and Discussion

3.1. Energy Saving-area-Throughput Increase Plot with an Investment Ceiling

The amounts of energy savings computed in different heat recovery areas of network (investment) and in different throughput increase within 1% to 10% range are tabulated in Table 1.

Table 1. Energy Savings Versus Heat Recovery Area and Throughput Increase (fixed investments)

		Throughput Increase (%)									
Investment ($)	Area Added (m²)	1	2	3	4	5	6	7	8	9	10
50000	136.6	264	251	237	224	211	197	184	171	157	144
70000	191.2	355	342	330	317	305	292	280	267	255	242
90000	245.8	436	424	413	401	390	377	366	354	342	330
110000	300.5	747	717	709	701	693	685	677	669	660	652
130000	355.1	783	774	767	759	752	744	737	729	721	714
150000	409.7	851	826	819	812	804	798	790	783	776	769
170000	464.4	970	950	944	938	932	927	921	915	910	904
190000	519.0	922	915	908	902	896	890	884	877	871	865
210000	573.6	1036	1033	1029	1026	1022	1018	1015	1011	1008	1004
230000	628.2	995	989	983	978	972	967	961	956	950	945
250000	682.9	1198	1033	1029	1026	1022	1018	1015	1011	1008	1004

The qualitative trends of these values are of high importantance in this study, a 3-D chart of these values is plotted Fig. (6).

As observed in Fig. (6), the amount of energy savings decreases with an increase in the throughput. This is because the utility requirements increase with an increase in throughput, therefore we have to add more heat recovery area at the first stage of targeting procedure (debottlenecking) and since a fixed investment (area) is already fixed, the area for second stage of targeting (energy saving retrofit) is reduced and this finally leads to less energy savings depending on the heat recovery area added (the more heat recovery area the more energy savings).

3.2. Energy Saving-Area-Throughput Increase Plots Considering Different Payback Times

When investment is applied as an economic criterion, the economic effects of energy saving and throughput increase are not considered. By applying the payback time, Eq. (5) as the economic criterion, both capital and operating costs will be targeted at their optimum values. The correlation between area-throughput increase and energy saving-throughput increase with payback time criterion are shown in Figs. (7 and 8), respectively.

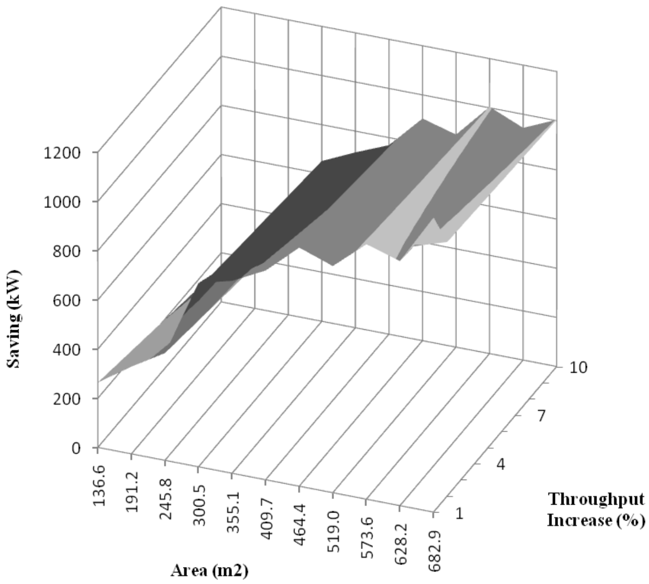

Figure 6. Qualitative Illustration of Correlation between Energy Savings and Area with Throughput Increase in Fixed Investments

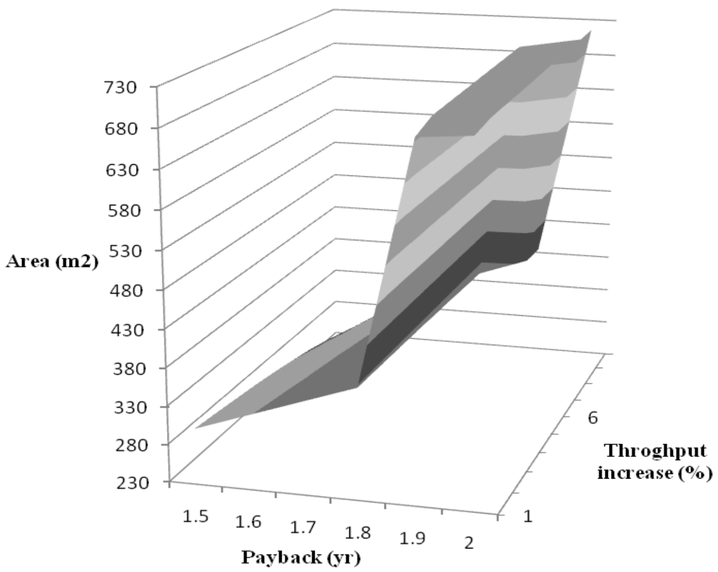

Figure 7. Correlation among Area, Payback and Throughput Increase

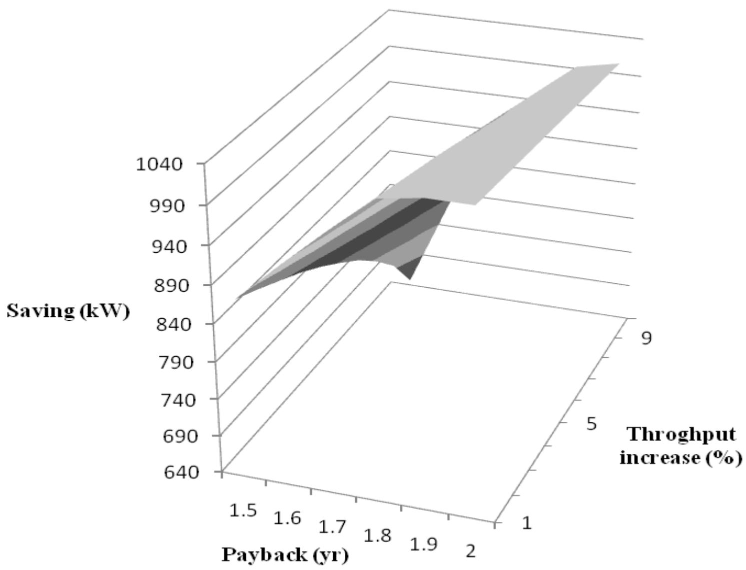

Figure 8. Correlation among Energy Saving, Payback and Throughput Increase

The results indicate that, both the heat recovery area and the energy saving decrease when the throughput increases while, the rate of decrease of energy saving is much more than that of the area. This rate decreases with payback time as increase until the saving becomes insensitive to the throughput increase at a constant payback time. This is because in low payback times the amounts of investment and energy savings are low, as observed in theFigs.). As the payback time increases, both the heat recovery area and the energy saving amount increase in a constant throughput increase. More investment means more area required for energy saving retrofit. In contrast, more throughput increase at a constant payback means more debottlenecking area requirements are as a consequence, the energy saving decreases.

The variations discussed above reveal opposite and competing effects on a constant value of energy saving. Asthe payback time and throughput increase approach this value of energy saving the optimum targeting is obtained. This result is observable through the 2-D view of Fig. (8) where the payback time increases as the throughput increase. That is, the throughput itself can become a bottleneck in increasing the payback time allowing the investment to yield higher energy savings.

There exist two possible important limitations: existence of an investment ceiling criteria, indicating a limitation for the total area that can be added and also the payback time will be limited. and the fact that, the maximum network potential for economical energy saving is limited by ΔT min, as the payback time increases the least value of ΔT min becomes closer to (here 5 °C).

The saving-investment plot for the problem is shown in Fig. (9). Where, that the savings increases with an investment increase until it reaches a relatively constant value.

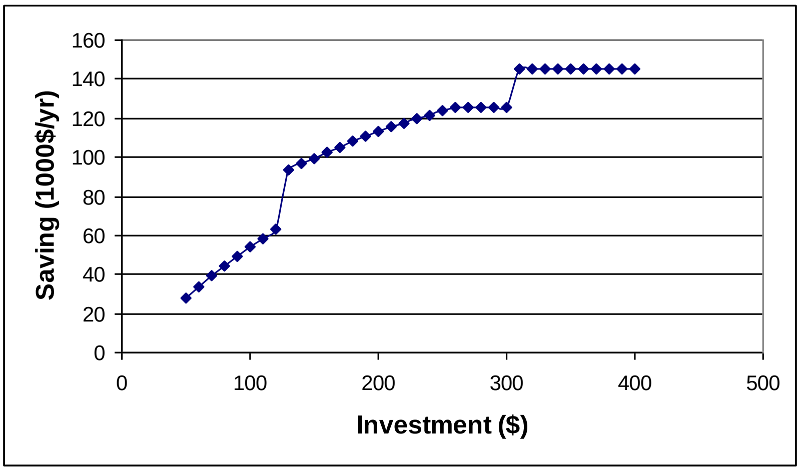

Figure 9. The Saving-Investment Plot of the Problem

The correlation between the payback time and the area is shown in Fig. (10), where, three separate regions are distinguished for this curve: The low, medium and high additional areas. The payback time is relatively high in low investments at (additional areas). This is because of low energy saving and depends on the fixed cost coefficient (parameter a”) in Eq. (1). High fixed cost coefficient results in high payback in this region.

In the second region, the payback increases with the area and there is a normal train between energy saving and area Fig. (1).

In the third region, although the payback increases with the area, the energy saving remains constant as the area increases. As mentioned before, this is because we have got to the maximum potential of network for energy saving is reached.

The low payback times (less than 2 years) is due to the contribution of additional area (investment) in both energy saving, throughput increase and the fact that the throughput increase is usually much more profitable than energy saving alone.

3.3. Energy Saving-Area-Components Plot in an increased Throughput (Decomposition Approach)

The amounts of energy saving and area for each combination of streams (components) are tabulated in the table 2 based on a fixed investment of $ 200,000 which is a direct output of the software.

The first column displayed all the different combination of the streams whose flow rates are increased. We call them “components”. For example, S234 means that the flow rates of the streams 2, 3 and 4 are increased to the desired value.

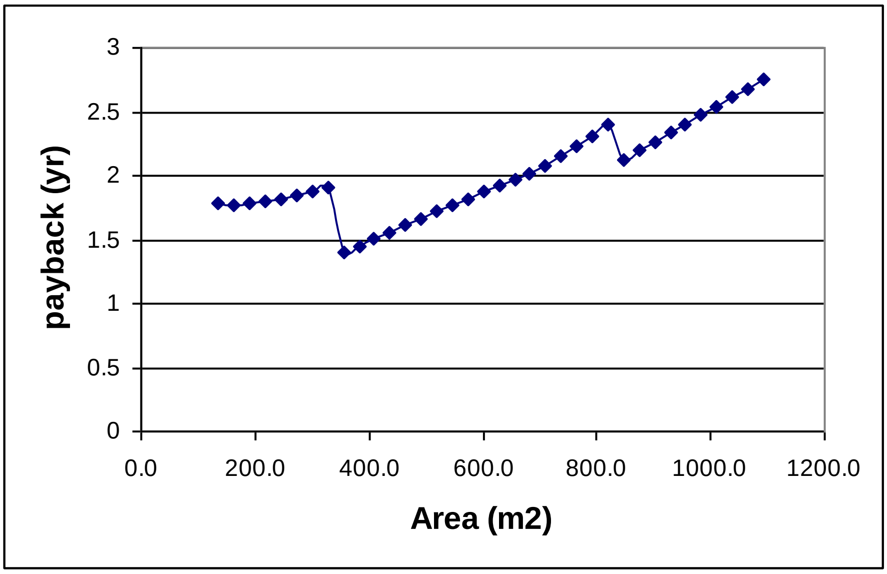

Figure 10. The Correlation between the Payback and the Total Heat Recovery Area

Table 2. Area and Energy Saving amounts for Components (in a fixed investment)

	Atot (m2)	Esaving (kW)	ΔTmin (ºC)		Atot (m2)	Esaving (kW)	ΔTmin (ºC)		Atot (m2)	Esaving (kW)	ΔTmin (ºC)		Atot (m2)	Esaving (kW)	ΔTmin (ºC)
S1	546.3...	833.2...	43.43	S12	546.3...	986.9...	43.43	S123	546.3...	919.7...	41.3...	S1234	546.3...	914.3...	40.8...
S2	546.3...	970.3...	42.7...	S13	546.3...	903.5...	41.3...	S124	546.3...	987.4...	42.8...				
S3	546.3...	875.6...	40.7...	S14	546.3...	968.4...	42.8...	S134	546.3...	893.0...	40.8...				
S4	546.3...	945.9...	42.1...	S23	546.3...	892.2...	40.7...	S234	546.3...	886.7...	40.1...				
				S24	546.3...	966.3...	42.1...								
				S34	546.3...	864.7...	40.1...								

By applying this software which implements the decomposition approach of area, energy and throughput targeting, the streams which offer the best opportunity for energy saving are identified in a rapid manner. By applying the output bar charts through which an example is represented in Fig. (11) it is much easier to determine the desired optimum conditions in a rapid manner(e.g. the most energy saving rate after considering the streams constraints in a fixed investment). The values of energy savings in this bar chart depends on the selected economic criterion (investment or payback time), the capital cost, energy cost definitions and the flow rate increase for each stream.

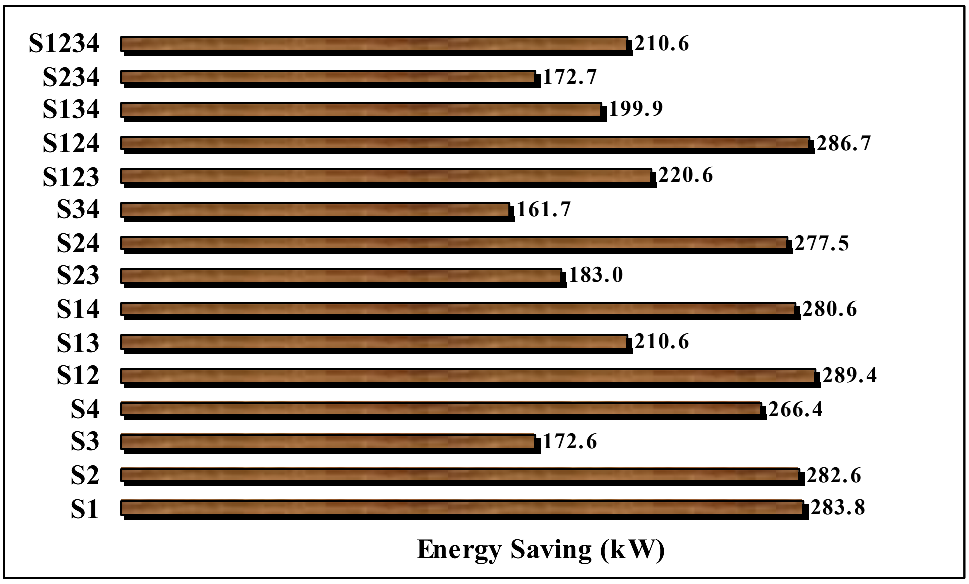

Figure 11. A Bar Chart Representation of the Energy Saving for Different Components in a Fixed Investment

4. Concluding Remarks

Analyzing the qualitative manner of different targets by the means of the pinch methods is a quit time consuming work and needs extensive calculations. A computer program assists the quick implementation of the procedures in a rapid manner. Another practical approach is the decomposition approach, which makes the procedure more real by considering the real constraints of process streams and the calculations to be made much faster.

A simultaneous targeting of throughput increase (debottleneck) is decreased and energy saving (retrofit) was described and new definitions of payback time is presented. The correlation among the area, energy savings and throughput increase is assessed base on two different economic criterions (investment and payback time). All applicable equations are identified and different limitations and scopes of simultaneous targeting were considered. An optimum condition for payback time and throughput increase is introduced base on both the debottlenecking and maximum energy saving retrofit targeting. Decomposition is implemented as an applicable approach for simultaneous targeting and the results are presented and assessed.

Nomenclature

$A_{Ave,m}$ Average area per match for the existing network (m^2)

$A_{Ave,s}$ Average area per shell for the existing network (m^2)

A_{Deb} Heat recovery area added for debottlenecking (m^2)

$A_{existing}$ Total heat recovery area (m^2)

A_{Ret} Heat recovery area added for retrofitting (m^2)

A_{tot} Total heat recovery area added (m^2)

C Capital cost of heat exchanger ($)

E_{ex} Utility consumption of the existing network (kW)

E_{Ret} Utility consumption of the retrofitted network (kW)

HU_{Cost} Annual cost of unit duty for hot utility ($/kW.yr)

$\dot{M}_{PR}$ Product flow rate (kg/s)

N_m Number of matches

N_s Number of shells

NM Total number of matches for the existing network

NS Total number of shells for the existing network

PR_{cost} Annual value of product sales price ($/kg/s.yr)

a, b, c Constants related to material of construction, pressure rating and heat exchanger type

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