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Process Integration in the Danish Food Industry. A Case Study[*]

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Abstract

This paper describes the results from a case study in the Danish medium-size industry. A heat-recovery system, producing 120 m^3 of hot water per working day, has been constructed and has been in operation since the beginning of the year 2000.

In this study, simplified procedures and networks for heat recovery were combined with economic evaluations based on suppliers' offers and the marginal values of the investments. By logical procedures described in an earlier paper, the problem was reduced to the design and optimisation of a network for production of hot water. A short description of the basic ideas is given in the Appendix.

Key words: thermal heat storage, heat exchangers, energy saving, food industry, simplified procedure, marginal payback period, standard solutions, process integration.

1. Introduction

It is a well-established fact that medium-size companies are reluctant to engage in process integration studies and projects. This may be due to the high consultant cost or the limited potential for savings compared to the risk that the integrated systems often seem to involve. The persons in the companies who are responsible for the operation often demand low complexity and high flexibility. The best argument for investing in process integration is the demonstrated performance of the system in question. That is why standard "off-the-shelf" solutions are suggested as a way of making process integration more attractive to the suppliers, by establishing a market, and to the investors, by making the solutions more reliable and less expensive.

Process integration studies usually start by establishing an overview of the relevant process streams. This is followed up by quick assessment of the possibilities that may be supported by an overall pinch analysis. Subsequently, it has to be decided whether to look for custom-made solutions based on network optimisation techniques, or to concentrate on simplified methods and off-the-shelf solutions as shown in *Figure 1*.

In medium-size industries, simplified methods and off-the-shelf networks are often necessary or may be preferred. When the decision has been made to go for a simple optimisation strategy, it is important to determine what can be achieved within the budget and the time frame available. The method of Limiting Match, described in a previous paper (Dalsgård et al.,

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1999), removes economically unattractive streams from the analysis and an index, labelled worth factor, is appended to the remaining streams. The previous paper also described a method in which direct heat exchanges (black boxes) were combined locally with production of hot water (*Figure 2*). Supplying a central heating system could be an alternative or supplemental solution to the hot-water production addressed in the present paper.

In the present project, the above steps were carried out and a system configuration was selected. It was a system with which the company felt comfortable and safe. Consequently, this structure was chosen and subsequently the number and sizes of heat-exchangers were determined and optimised.

Also, at that time, the length of the acceptable marginal payback period (MPBP), as defined below, was chosen as basis for the economic optimisation.

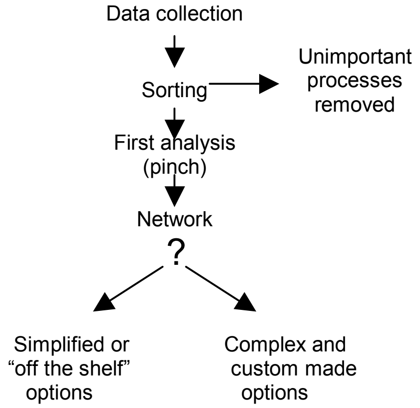

Figure 1. Initial stages of the traditional design process

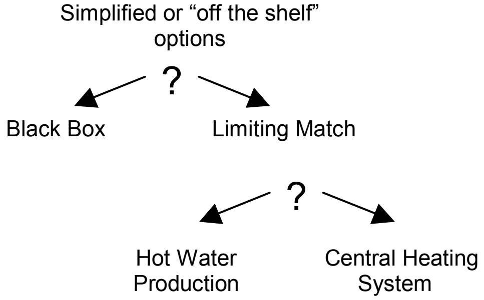

Figure 2. The simplified design option

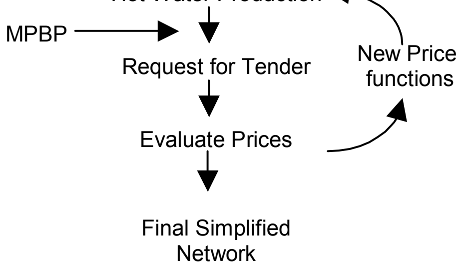

Figure 3. Price optimisation of simplified network

2. Marginal Pay Pack Period (MPBP)

In order to evaluate the economics of a heat-exchanger unit or a network, the Net Present Value (NPV) and/or the Payback Period (PBP) have commonly been used as criteria for the best solution. In some cases solutions have included marginal investments with a much higher PBP or lower NPV than is typically acceptable for the decision-maker. Using the payback period for the last invested € can be one way of ensuring that the last investment also is economically attractive.

The Marginal Pay Back Period (MPBP) for a given heat-exchanger unit is defined as the PBP for the last increment / amount of money invested. The MPBP and the NPV are closely related. The simplest case without any kind of interest (inflation, return of investment or bank interest) is used to illustrate the connection between the MPBP and the NPV.

Simple PBP: $$\mathrm{PBP}(x) \equiv \frac{I(x)}{S(x)} \tag{1}$$

Marginal PBP: $$\mathrm{MPBP}(x) \equiv \frac{\Delta I(x)}{\Delta S(x)} \tag{2}$$

Simple Net Present Value:
$$\mathrm{NPV}(x) \equiv -I(x) + S(x) \cdot n \tag{3}$$

The maximum value of NPV at a given time (n=const.) is given by:

$$\frac{d\mathrm{NPV}(x)}{dx} = -\frac{dI(x)}{dx} + \frac{dS(x)}{dx} \cdot n = 0 \tag{4}$$

Maximum NPV can very well be one of the objectives during optimisation of energy systems. By manipulation of equation 4 it is possible to see the link between maximum NPV and MPBP.

$$\begin{aligned} &\frac{d\mathrm{NPV}(x)}{dx} = -\frac{dI(x)}{dx} + \frac{dS(x)}{dx} \cdot n = 0 \Leftrightarrow \\ &\frac{dI(x)}{dx} = \frac{dS(x)}{dx} \cdot n \Rightarrow \\ &\frac{dI(x)}{dx} \cdot \frac{dx}{dS(x)} = n \Rightarrow \\ &\frac{dI(x)}{dS(x)} = \mathrm{MPBP}(x) = n \end{aligned} \tag{5}$$

This derivation shows that, by maximising the NPV for a given value "n", e.g. 10 years, the network designer implicitly accepts a payback period of 10 years on the last invested €.

The use of MPBP as an economic criterion together with the total PBP will give an improved insight into and understanding of the dependence of equipment size and economical benefits.

Figure 4 and TABLE I below illustrate the differences between optimization of NPV over a 10 year period, accepting an investment with a total payback period of 3 years, or accepting a marginal payback period of 3 years as the basis for choosing the size of a given heat-exchanger.

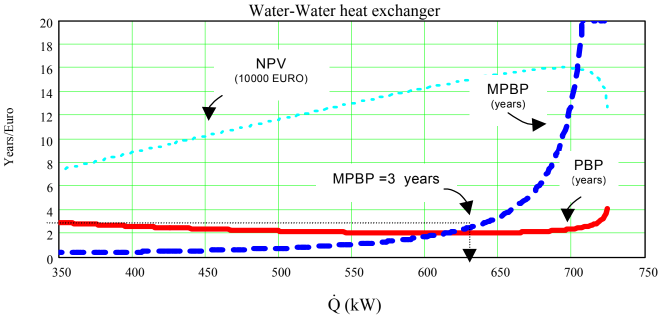

Figure 4. Result of economic calculations for one of the heat exchanger in the present project (the water-water heat exchanger).

TABLE I. RESULT OF OPTIMISATION OF A HEAT EXCHANGER WITH THREE ALTERNATIVE OBJECTIVE FUNCTIONS

Objective function	PBP (years)	MPBP (years)	NPV (EURO)	Investment (EURO)	Savings (EURO)
NPV	2.3	10	160,000	48,000	20,800
PBP	3	60	150,000	65,000	21,500
MPBP	2.1	3	153,000	40,000	19,200

By investing in a heat exchanger with a total payback period of 3 years, the last 2300 € savings will cost 25,000 € in additional investment. By optimising NPV the last 1600 € costs 8000 €. This example illustrates the difficulties associated with the use of the NPV and of the total PBP.

3. The Case - Danpo, a Food Processing Factory

During the exploration of energy savings in the new chicken-processing factory in Jutland, Denmark the company Danpo approved and adopted a proposal to establish a heat-recovery system for hot water production.

By using the simplified approach described in the introduction of the present paper, a network was established with the purpose of utilising the surplus heat from the central cooling system for water heating and an economic optimisation was performed on the basis of a survey of heat-exchanger prices (Munkøe et al., 1998).

4. System Design for Heat Recovery From Cooling Plant

The system was designed to utilise as much energy from the cooling plant as possible within a marginal payback period of 3 years. The maximum amount of hot water needed was estimated to be 120 m^3/day.

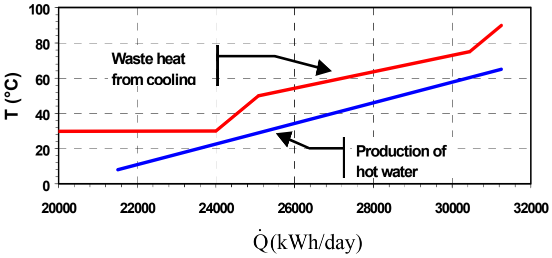

Figure 5. Composite curves (hot water demand and waste heat) resulting from the pinch calculations for the Danpo food processing factory.

Only counter-flow plate heat exchangers were considered for the network solution. The pinch temperature was 26.3°C, and the result of the pinch analysis was that only 2500 kWh/day of the heat in the condensation of ammonia in the cooling plant was to be utilised. Because of the limited amount of hot water needed, and the temperatures of the waste-heat sources, it was reasonable to assume that the pinch target for the hot-water production could be reached (need for external heat utility = 0 kWh/day). Thus the temperature of the hot water produced by waste heat would reach 65°C (the temperature required for cleaning).

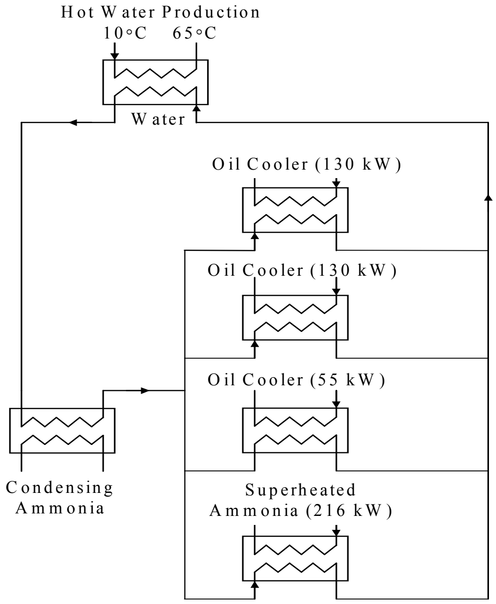

Figure 6. Heat recovery network

Hot water was primarily needed for night-time cleaning, while the production of hot water was carried out during the day. A simple variable-mass and fixed-temperature storage was expected to be easy to operate under these conditions.

The possible structure for a network capable of achieving the objectives is shown in *Figure 6*. The heat exchange media and capacities are summarised in TABLE II.

The oil coolers must be designed for a maximum load of 130 kW and 55 kW, but only an average of 85% of this load will be available for waste-heat recovery.

TABLE II. HEAT EXCHANGERS IN THE HEAT-RECOVERY NETWORK (DESIGNATED BY NUMBERS)

Heat-Exchanger 1	Heat-Exchanger 2	Heat-Exchanger 3	Heat-Exchanger 4	Heat-Exchanger 5
Water & Condensation of Ammonia (? kW)	Water & Oil (130kW)	Water & Oil (55 kW)	Water & Ammonia (216 kW)	Water & Water (? kW)

4. Optimisation Results

TABLE III shows the results of the initial optimisation of the system. The maximum marginal payback period was 3 years and the initial costs were accounted for by multiplying the cost of the stand alone heat-exchanger by a factor 3.2.

The price of the stand-alone heat exchangers are listed in the last row of TABLE III. The costs exclude tanks, other accessories and installation. The total estimated price for all heat exchangers, based on original cost functions, is 35,770 €.

5. Tenders From Suppliers

Two suppliers were asked for bids on delivery of the plate heat exchangers. The number of sizes and shapes of heat exchangers available from suppliers was high but not unlimited. This, together with a suboptimisation performed by the suppliers, resulted in temperatures and mass flow that deviated from those described in the call for tenders.

In order to be able to evaluate the original cost functions that were used during the initial optimisation it was therefore necessary to recalculate the prices using the heat-exchanger data given by the suppliers.

The estimated prices calculated using the original cost functions are shown in TABLE IV and TABLE V. The "Calculated Price" is shown in the first row, and the "Calculated Price (U)" where the heat-transfer coefficient specified by the suppliers was used instead of the initially assumed coefficient, is shown in the second row.

It is clearly seen that there were large differences between the estimated cost and the bids, even if the same heat-transfer coefficient was used. The differences range between 10% and 100%. On the basis of the initial bids it was decided to purchase the heat-exchangers from supplier no. 1.

TABLE III. RESULT OF OPTIMISATION WITH ORIGINAL COST FUNCTIONS (MPBP=3 YEARS)

	Primary side		Secondary side		Primary side	Second. side	Heat transfer coef.	Heat duty	Heat exchanger	Heat exchanger
HE	T_{1in}	T_{1out}	T_{2in}	T_{2out}	$\dot{m}_1$	$\dot{m}_2$	U	$\dot{Q}$	Area	Price
number	°C	°C	°C	°C	kg/s	kg/s	kW/m²°C	kW	m²	EURO
1	12.1	28	30	30	2.6	0.15	2	171	11.8	4040
2	28	70	75	55	0.8	3.2	2	130	4.6	2420
2	28	70	75	55	0.8	3.2	2	130	4.6	2420
3	28	70	75	55	0.3	1.4	2	55	1.9	1330
4	28	71.6	90	30	1.2	1.4	0.5	216	36.7	15820
5	8	65	70.8	12.1	2.65	2.58	2	632	64.5	12870

TABLE IV. BIDS AND CALCULATED PRICES FOR HEAT EXCHANGERS SUGGESTED BY SUPPLIER 1

Heat Exchangers	Condensation of ammonia (€)	Oil cooler 1 (€)	Oil cooler 2 (€)	Desuper-heating of ammonia (€)	Water/ Water (€)	Total all HE (€)
Calculated price	3110	2*2560	1890	12930	10430	33480
Calculated price(U)	2200	2*5790	3990	13440	8470	39670
Bids	2490	2*7600	4280	8350	6430	36740

TABLE V. BIDS AND CALCULATED PRICES FOR HEAT EXCHANGERS SUGGESTED BY SUPPLIER 2

Heat Exchangers	Condensation of ammonia (EURO)	Oil cooler (130 kW) (EURO)	Oil cooler (55 kW) (EURO)	Desuper-heating of ammonia (EURO)	Water/ Wate (EURO)	Total all HE (EURO)
Calculated price	4120	2*2330	1790	18800	9120	38490
Calculated price(U)	2680	2*5120	2970	22950	7510	46350
Bids	5250	2*8130	5520	16110	11000	54150

TABLE VI. RESULT OF THE OPTIMISATION WITH ORIGINAL (Munkøe et al., 1998) AND NEW COST FUNCTIONS (IF=3.2)

Heat-exchangers	Condensation of ammonia (m^2)	Oil cooler (130 kW) (m^2)	Oil cooler (55 kW) (m^2)	Desuper-heating of ammonia (m^2)	Water/ Wate (m^2)
Original functions	11.8	2*4.6	1.9	36.7	64.5
New functions	5.8	2*16.5	7.0	47.1	54.9

TABLE VII. RESULT OF THE FINAL OPTIMISATION WITH ORIGINAL (Munkøe et al., 1998) AND NEW COST FUNCTIONS AND HEAT TRANSFER COEFFICIENTS (FIXED COST = 110 000 EURO).

Heat-exchangers	Condensation of ammonia (m^2)	Oil cooler (130 kW) (m^2)	Oil cooler (55 kW) (m^2)	Desuper-heating of ammonia (m^2)	Water/ Water (m^2)
Original functions	28.8	2*5.4	2.3	34.5	135.4
New functions	14.3	2*21.1	21.1	46.8	76.6

6. Second Optimisation

In order to carry out a refined optimisation of the network, supplier no.1 was asked to provide supplemental prices for each of the heat exchangers (area ±10%). From these prices it was possible to recalculate the cost functions for heat-exchangers used by the supplier.

These new cost functions were used for the final optimisation of the system using the original optimisation strategy (installation factor (IF) = 3.2). The sizes of the different heat exchangers are presented in TABLE VI above.

7. Last Optimisation

The costs of the heat exchangers represented only a part of the total investment. In addition to the heat-exchanger costs were the costs of supplementary equipment (hot-water tank, pumps, valves, automation, etc.) and of installation. These fixed costs amounted to175,000 €.

This fixed cost was 110,000 € more expensive than a standard hot water system (65,000 €).

In the final optimisation, the excess of fixed cost (110,000 €) together with the variable cost of heat exchangers should be paid by the savings from installing the hot-water storage system.

The approach of using a fixed cost gave results closer to the real cost estimates than with proportional cost using the installation factor. The optimisation resulted in the heat-exchanger sizes shown in TABLE VII.

The changes of heat exchanger areas shown in TABLE VII confirmed the observation that the structure of the heat-exchanger network in medium-size industries should not be established on the basis of estimated cost functions – the inaccuracy would result in an almost arbitrary network structure.

The total investment in the heat exchangers using the supplier's cost functions, listed in the last row of TABLE VII, was estimated to be 37,000 €. The cost of heat exchangers was only one-fifth of the total investment. The annual savings were estimated to 65,000 €, and the total payback period for the system was estimated to be 2.2 years.

8. Conclusion

This first practical application of the simplified method and the introduction of one of the standard (off-the-shelf) solutions resulted in at system that is presently in operation. Thus the simplified methods and standard concepts seemingly have broken down some of the real and imaginary barriers that impeded the practical implementation of Process Integration in this particular plant.

In the view of the difficulties experienced in estimating cost functions and the uncertainty in determining the values of the heat-transfer coefficients the selection of a network configuration that offers flexibility and simplicity ahead of a detailed economic evaluation is strongly recommended.

Acknowledgement

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Nomenclature

n	Number of Years
S(x)	Annual Saving
PBP(x)	Payback Period
MPBP(x)	Marginal Payback Period
I(x)	Investment
x	Arbitrary Variable
NPV(x)	Net-Present Value

Appendix

A Short Summary of the Basic Ideas of a Procedure for Simplification of Process Integration in Medium Size Industries.

It can be argued that the largest potential for energy savings based on process integration is in intermediate size industries, but this is also the industrial scale in which it is most difficult to make the introduction of energy saving measures economically interesting.

The reasons are that the required engineering effort is too great and therefore too expensive, and that the resulting systems designs often become inordinately complex and therefore not attractive in operation.

The present appendix describes steps that aim at reducing the magnitude of the theoretical work and engineering effort associated with a given process integration study in an intermediate size industry. This is based on the observation that the systems that eventually result from a process integration project and that are economically and operationally most interesting are also quite simple.

Four steps that may be used separately or in series ahead of or simultaneously with the conventional process integration procedures (for example, the Pinch Point Method) are described. The method is demonstrated and applied to an industrial case study in an earlier paper (Dalsgård et al., 1999) of the same title as the appendix.

It is often the case that most of the time is spent on possibilities that are not exploited in the final solution. By eliminating the time used on fruitless investigations a significant reduction of the needed time and work will be achievable.

The data collection and the hours spend on "getting to know" the process often takes up most of the time available. Obtaining a total data foundation for the process integration analysis often results in investigation of streams that end up being useless or economic uninteresting. This is especially a risk in medium size industry, where the saving potential is limited.

Being able to focus on the streams that are valuable, and rejecting all other streams will make the process integration study simpler and cheaper to perform.

The "Steps"

The above observations constitute the basis for developing four different steps to be carried out instead, of initiating procedures that are normally regarded as constituting the core of a process integration project. These four steps are:

Step No. 1	**Black Box Division.** The problem is divided into possible subproblems on the basis of location, temperature and/or time. Each subproblem (black box) is optimised separately with respect to economic and other objectives.
Step No. 2	In view of the often great needs for **hot water** as raw material, for heating and for cleaning, the effort of recovering heat is firstly focused on production of hot water.
Step No. 3	**Limiting Match.** This step consists of an evaluation of the various streams after the unimportant ones are discarded. An extra parameter (the limiting log-mean temperature) for each stream is calculated, taken

the economic criterion in consideration (e.g. PBP). The parameter is based on the stream capacity and the stream conditions.

Step No. 4 Establishment of the **basic network** configuration and an initial economic optimisation.

It might be feared that geographical grouping and preselection of stream matches would limit the "freedom of movement" and therefore lead to non-optimal economic solutions, which may be right. But the objective of the optimisation is not to reach the best economic solution, but to relatively quickly design a simple and operationally friendly network without losing too much energy saving potential.

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