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A decomposition approach for retrofit design of energy systems in the sugar industry

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Abstract

Sugar factory retrofit often includes improvements in the factory's energy system comprising power plant, multiple-effect evaporator and process heating equipment. To reduce the energy consumption, the evaporator subsystem and the process heating subsystem should be retrofitted to make improved heat recovery possible. The retrofit design procedure includes two stages: targeting for various options of the evaporator structure and selecting the most promising one, and designing both subsystems for targets so determined. At the targeting stage, one is confronted with the problem of designing the evaporation process and simultaneously considering the energy consumption. This constitutes an extension of the established targeting approach that assumes process conditions to be fixed. The problem can be transformed by decomposing the energy system, that is, conceptually separating the evaporator (in which vapours and condensates are generated) from the process heating subsystem (in which these heat carriers can be regarded as utilities). The transformed problem is one of targeting under constraints and can be solved iteratively by combining pinch analysis algorithm with evaporator simulator. The second stage of the retrofit design procedure requires defining the details of process heating subsystem that includes a heat exchanger network. This problem is conveniently solved using the network pinch approach. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Sugar industry; Energy system; Process integration; Multiple-effect evaporator; Heat exchanger network; Retrofit; Targeting; Design; Decomposition

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1. Introduction

For economic and environmental reasons, there is a constant need of reconstruction of sugar factories. The dominating trend is to increase the production rate and take advantage of advances in sugar technology and environment protection technologies. Energy efficiency is also an important issue in factory reconstruction as the fuel cost is of the order of 10% of the overall cost of sugar production and fuel burning in the power house is responsible for a major part of atmospheric emissions. Consequently, sugar factory retrofit typically includes improvements in the factory's energy system to reduce energy consumption. Several alternative designs with varying capital and operating costs are usually produced, and the final retrofit design is selected from these alternatives. A beet sugar factory is typically operated during three months per year, and therefore, the cost of the retrofit investment has to be carefully balanced against the value of the attainable reduction of the operating cost.

Until now, no systematic methods for energy system retrofit in sugar factories have been widely accepted. Research carried out in the 1970s on the application of mathematical modelling and non-linear programming methods [1] turned out to be premature because with the computer technology available at that time, these methods were too difficult to implement in practical design. Early applications of pinch based techniques to energy improvements in British and other European sugar factories could only confirm that conventional design methods were sufficiently effective [2–4]. Methodological problems limiting the efficiency of pinch based techniques in their applications to sugar factories were also identified [5,6]. As a consequence, engineering companies specialised in sugar factory retrofit still rely mainly on their own design methods employing inspection techniques based on previous experience [7,8].

Advances in process integration methods made during the 1990s facilitated the extension of their applications to various branches of the industry. Taking advantage of the accumulated experience, these methods are now being implemented in retrofit design of energy systems in sugar factories. In a recent study, a pinch based approach served the purpose of describing and comparing the energy efficiency of various design options rather then directly augmenting the decision making [9].

In the present paper, process integration methods are considered as decision making tools. It is proposed that an initial evaluation of the optimal level of heat recovery in the sugar manufacturing process should be based on the well-known targeting approach. Owing to special features of thermal systems currently used in the sugar industry, this approach should be modified as outlined in Section 3.2 below.

On the basis of results obtained by targeting, a detailed retrofit design can be worked out. Special importance is attributed to a new method, the so-called network pinch method, that was developed for the purpose of automated and interactive retrofit design of heat recovery systems [10]. This method is reviewed in detail in Section 3.3 below.

2. Problem formulation

2.1. Background

The most energy intensive steps of the sugar manufacturing process are:

- extraction of juice from sliced beet sugar,
- juice purification to reduce its content of non-sugars,
- evaporation to remove excess water and concentrate the juice,
- evaporating crystallisation of sugar from concentrated juice.

In each of these steps, heating is required as either temperatures of process streams must be increased, or water must be evaporated.

The usual arrangement of energy flows in a sugar factory is shown in Fig. 1. The energy system can be divided into three subsystems: power plant, multiple-effect evaporator and process heating subsystem.

The operating principle of the power plant is that of combined generation of heat and power in a steam cycle employing a boiler and a back-pressure turbine. Steam from the turbine exhaust is the hot utility supplied to the evaporator and, if necessary, to other units of process equipment.

The evaporator can be regarded as a subsystem generating vapours and condensates at various temperature levels corresponding to the individual evaporation stages. Vapours and condensates are the carriers of medium temperature heat to be used for process heating.

The process heating subsystem includes an extractor, a set of evaporating crystallisers and a heat exchanger network. Crystallisation vapours are the carriers of low temperature heat that can partly be recovered (by precondensation) while the remaining part is discharged (after

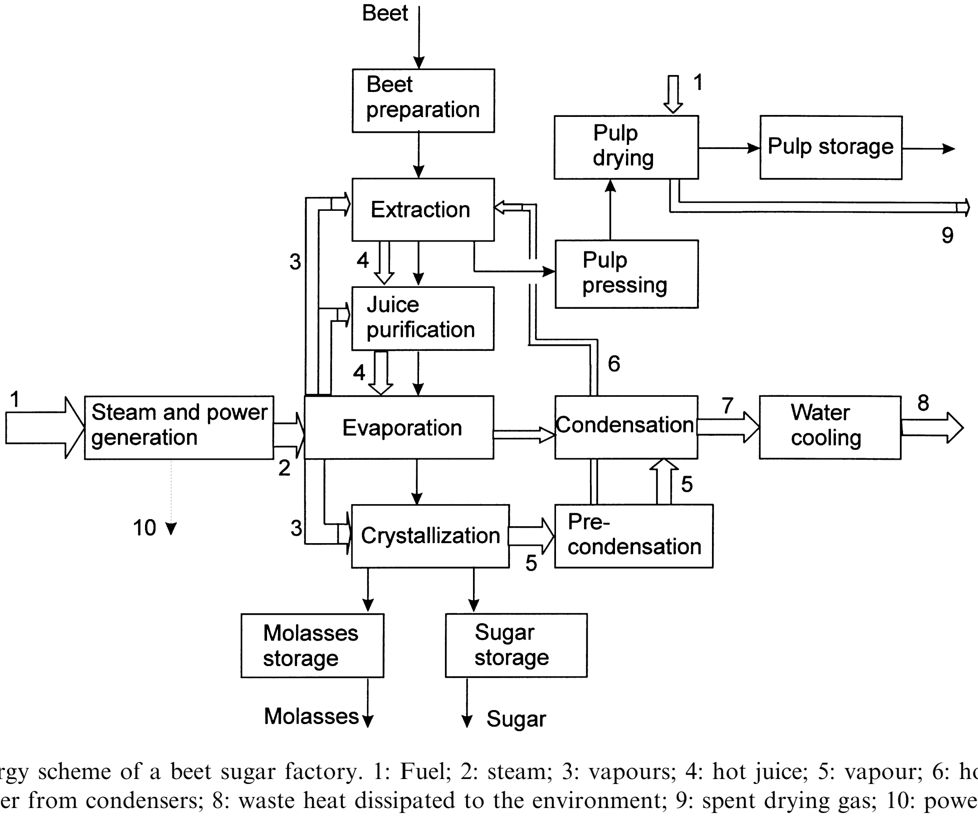

Fig. 1. Energy scheme of a beet sugar factory. 1: Fuel; 2: steam; 3: vapours; 4: hot juice; 5: vapour; 6: hot water; 7: cooling water from condensers; 8: waste heat dissipated to the environment; 9: spent drying gas; 10: power.

condensation) to cooling towers. Atmospheric air flowing through the cooling towers is the cold utility.

A retrofit strategy, that is of particular interest to sugar factory operators, assumes reducing energy consumption by retrofitting the subsystems of evaporation and process heating so as to make improved heat recovery possible. This may create an opportunity to increase the sugar output while avoiding costly investments in the utility systems.

2.2. Problem statement

The problem of energy system retrofit can be stated as follows. The parameters of the extraction, juice purification and crystallisation processes are given. These parameters define a set of hot cold streams with their supply and target temperatures, heat capacity flow rates and heat transfer coefficients. Data on:

- inlet and outlet conditions of the multi-stage evaporation process;
- existing process equipment units including evaporators and heat exchangers as well as their connections;
- costs for additional heat transfer area in the evaporator and in the heat exchanger network;
- current use of utilities and availability of utilities (for heating and cooling)

are also given.

The retrofit objective is to increase the energy system throughput to a predetermined value while minimising the total cost comprising investment and operating costs. No investments in the utility systems are allowed.

2.3. Comments

In the evaporation subsystem, changes in the evaporator structure including addition of new evaporator units and changes in the evaporation load of existing units can be considered. In the process heating subsystem, structural changes in the heat exchanger network and changes in the allocation of heating duties to individual exchangers are allowed. It should, however, be noted that changed heating duties in the HEN necessitate adjustments of the evaporation process because flows of heating vapours extracted from the individual evaporation stages are changed. It is interesting to note that in the context of application of process integration methods to sugar factories, this problem was identified in the early 1990s by Bruhns [5]. However, he was not able to handle process changes and energy minimisation simultaneously.

As can be seen, the retrofit design problem is a complex one involving interactions between the process and the energy system. Additional complexity stems from the fact that the required process changes are subject to various constraints relating to the process or to the existing equipment. For example, changes in vapour flows extracted to process heating must not increase juice concentration at evaporator outlet above the predetermined value, and it may also be necessary to account for constraints reflecting the need for relying on heat transfer surfaces of the existing evaporator units.

3. Proposed method

3.1. General idea

From the user point of view, there are two important requirements for the retrofit design method. Firstly, it should be able to consider modification costs but without estimating the costs for all potential options prior to design. Secondly, the method should allow for a reasonable degree of automation of the design work without loosing the advantages of user interaction.

In general, the evaporation process may be difficult to design as the design decision is characterised by many degrees of freedom [11]. The case of sugar factory reconstruction is different because compared to HEN modifications, evaporator retrofit is more costly and is subject to more stringent local constraints. For this reason, the acceptable structural options of the evaporator are usually few and rather easy to identify. The optimum option can be selected by exhaustive search employing targeting and evaluation of targeting results. By exhausting the acceptable options for evaporator structure, this procedure generates a set of cost-effective retrofit designs and identifies the best one.

Once the retrofit design has been selected, it becomes possible to re-design the evaporator and the process heating subsystem including HEN. The entire retrofit design procedure is schematically shown in Fig. 2.

3.2. Targeting

As the established targeting approach is based on the assumption of fixed process conditions, it cannot properly reflect the energy improvement potential associated with interactions between evaporation and process heating. In order to improve heat recovery in a sugar factory, it is necessary to modify vapour generation in the individual evaporation stages while adjusting

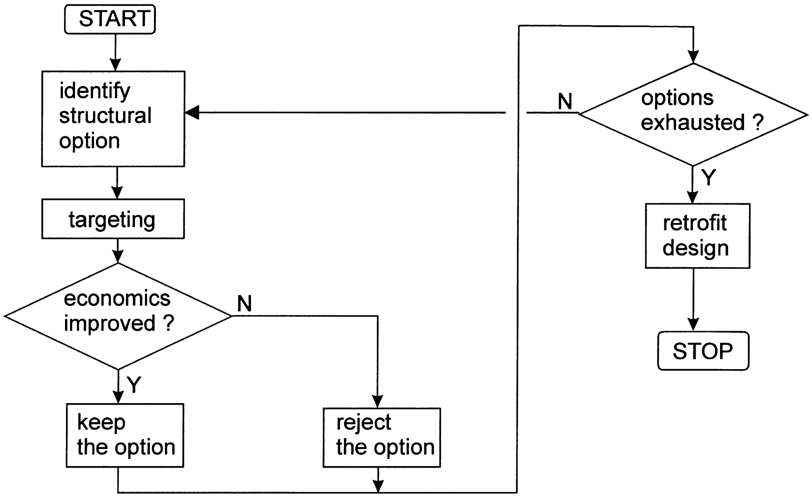

Fig. 2. Block diagram of the retrofit design procedure.

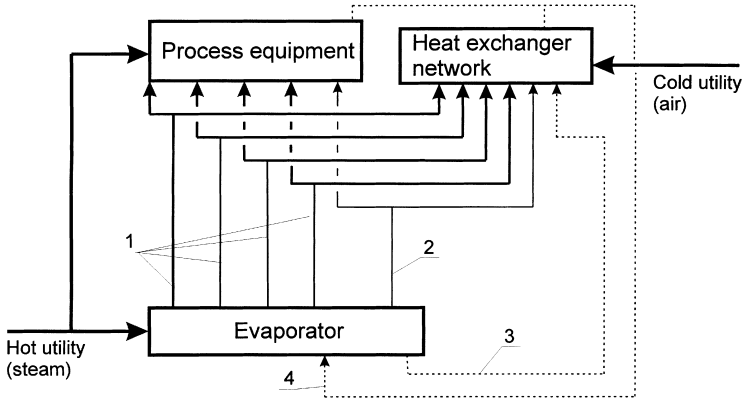

Fig. 3. Decomposition of the thermal system in a sugar factory. 1: Evaporator vapours (artificial utilities); 2: last effect vapour (process stream); 3: hot condensate (process stream); 4: returned condensate (process stream).

allocation of vapours to various heating operations. Energy consumption and process changes thus need to be considered simultaneously, necessitating an extension of the established approach.

The extended targeting problem can be transformed by decomposing the thermal system, that is, regarding the evaporator and the process heating equipment as two interacting subsystems [12]. The decomposition principle is illustrated in Fig. 3. If targeting is restricted to the process excluding evaporation, then vapours generated in the evaporator — except last effect vapour — can be regarded as utilities (last effect vapour is regarded as a process stream). As a consequence, the results of restricted targeting will include utility consumption, that is, flows of vapours extracted from the individual evaporator effects. These vapour flows must not violate the constraints of the evaporation process and, in particular, the total evaporation must not be greater than the available water amount determined by inlet and outlet values of juice concentration. Other possible constraints may reflect the need for relying on the heat transfer surfaces of the existing evaporator units. One can establish whether or not constraints are satisfied by simulating the evaporation process with the flows of extracted vapours set equal to the values obtained by targeting. In case the process turns out to be not realisable, corrections should be introduced in the process streams.

The decomposition approach thus makes it possible to transform the extended targeting problem to a problem of targeting under constraints. It can be solved iteratively by combining a conventional targeting algorithm with evaporator simulator built into a procedure schematically shown in Fig. 4. Corrections of process stream data are usually limited to the flows of last effect vapour and condensate. Starting from initial flow values that are later changed depending on the results of evaporator simulation, correct targets are typically obtained in a few steps.

3.3. Re-design of the evaporator and the process heating subsystem

Once the extended targeting problem has been solved, re-designing the evaporator is straightforward. As the targeting results apply to a definite evaporator structure, evaporation loads in the individual effects are known and thus new evaporator units can be sized. Simulation results also make it possible to size condensate tanks, piping, etc.

The solution of the extended targeting problem also provides a starting point for the retrofit of the process heating subsystem. As the decisions on extractor and crystalliser heating have already been taken at the targeting stage, the attention can now be restricted to the heat exchanger network. HEN retrofit can be conveniently solved using the network pinch approach [10]. In this new approach, the design task is decomposed into a search for topology changes, which is called the diagnosis stage, followed by an evaluation stage and a cost optimisation stage. Promising modifications are selected from the diagnosis stage, and they are assessed in terms of the impacts towards implementation cost (piping, foundation, etc), operability and safety. The options, which are found impractical, are removed and the remaining options are optimised, together with the existing heat exchanger network to give the final HEN retrofit design. Owing to this, energy saving target can be achieved with minimal modifications required. The new approach combines mathematical optimisation techniques with a better understanding of the retrofit problem, based on thermodynamic analysis and practical engineering, to produce a systematic procedure capable of efficiently solving industrial size retrofit problems.

The improved understanding is achieved by introduction of the network pinch concept that provides new insights to the HEN retrofit problem and plays an important role in selecting promising modifications, which forms the foundation of the new method. This concept has been applied to mathematical formulation resulting in a significant simplification of the mathematical models while maintaining good quality of solutions. The major characteristic of the approach is that the design tasks are automated while user interactions are allowed.

4. Application example

4.1. Retrofit problem

The application example given here was preliminarily discussed in two recent conference papers [12,13]. In the latter paper, another application example was also summarised.

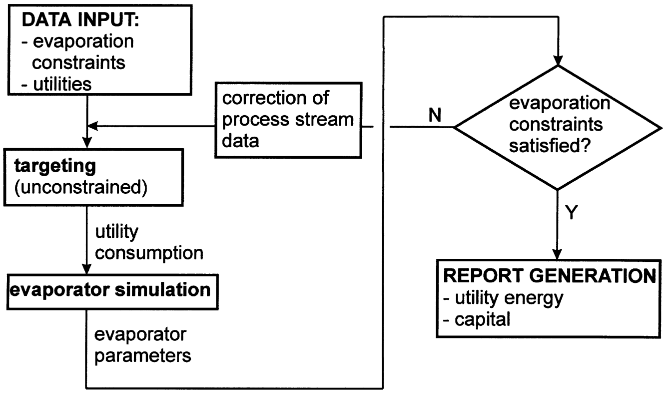

Fig. 4. Block diagram of the extended targeting procedure.

The sugar factory to be retrofitted has a processing capacity of 2400 ton beet/day, and the specific fuel consumption is about 5 kg coal equivalent (29.3 MJ/kg) per 100 kg beet. Extraction of sugar from sliced beet takes place in a trough-type extractor that requires heating with vapour at a temperature not lower than 110°C. Juice evaporation is carried out in six Robert-type (natural circulation) evaporator units arranged in five effects as schematically shown in Fig. 5a, and final juice concentration is 66 kg/100 kg. Sugar is crystallised in three strikes using batch-type, natural circulation evaporating crystallisers that require heating with vapour at a temperature not lower than 120°C. Juice and syrup heating is carried out in a heat exchanger network that includes seven shell-and-tube type and seven plate-type units.

The retrofit is primarily aimed at increasing the processing capacity to 3500 ton beet/day, and secondary aim is to increase sugar yield, improve sugar quality and reduce specific energy consumption. In the sugar manufacturing plant, de-bottlenecking, selective process changes and improved heat recovery are needed. By taking advantage of the capacity margin of the existing power plant and improved energy efficiency of the sugar manufacturing plant, it should be possible to avoid power plant extension.

Process changes should be introduced in the evaporation and crystallisation sections as the concentration of thick juice (supplied from evaporation to crystallisation) will be increased to 70 kg/100 kg. The crystallisers should be reconstructed to make heating with vapour at 105–106°C possible. In order to satisfy changed needs of the crystallisation section and eliminate a critical bottleneck, the evaporator should be extended. By properly combining evaporator extension with HEN retrofit, heat recovery should be improved.

4.2. Evaporator options and targeting

Four options of evaporator structure listed below in the order of increasing energy efficiency

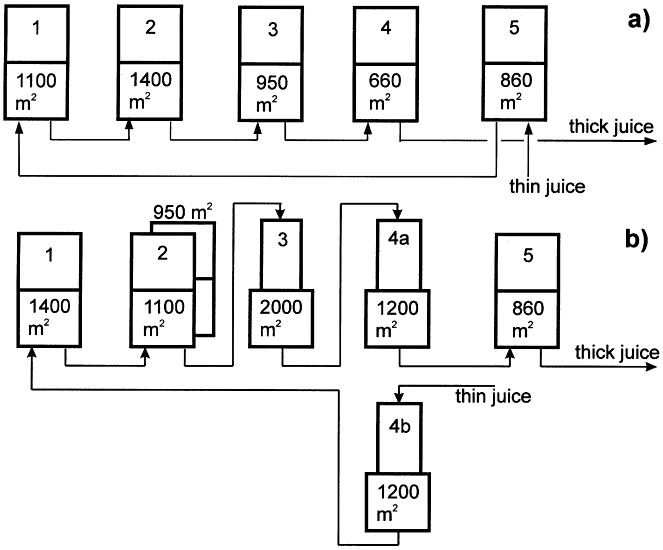

Fig. 5. Juice flow schemes of the evaporator station (vapour connections not shown): (a) existing, (b) after retrofit.

are considered as acceptable with respect to the required space and the estimated investment cost. The least expensive option having a rather low energy efficiency is considered as a reference solution and placed at the top of the list:

a. forward-feed, four-effect arrangement and crystalliser heating with second vapour;
b. forward-feed, five-effect and crystalliser heating with second vapour;
c. forward-feed, five-effect and crystalliser heating with third vapour;
d. five-effect with backward-feed pre-evaporator in the fourth effect supplying vapour to crystalliser heating, and forward-feed arrangement of the remaining effects.

Even more advanced options, for example, sixth effect with pre-evaporator in the fourth effect, would require too much space and are too costly, and therefore, cannot be considered.

Regarding HEN retrofit, it is assumed that all the existing plate heat exchangers should remain in use. Shell-and-tube units should be replaced by new plate units, except one or two units in which the value of the temperature approach is less important.

For each of the four evaporator options, energy and capital targets that describe retrofit concepts for the entire energy system were determined using the procedure outlined in Section 3.2. The procedure was implemented using UMIST targeting program STAR and Polish evaporator simulator STACJA. After investigating $\Delta T_{\min}$ values in the range 1–9 K, the optimum value of $\Delta T_{\min}$ corresponding to the minimum total cost was found to be 2 K. The Composite Curves and the Grand Composite Curve for optimised evaporator option d are shown in Figs. 6 and 7, respectively. A summary of targeting results is given in Table 1. As can be seen, the most advanced evaporator arrangement (option d) ensures the lowest total cost.

4.3. Final design

The reconstructed evaporator station includes four existing Robert-type units (heat transfer areas 1400, 1100, 950 and 860 m^2) and three new falling-film units (heat transfer areas 2000 m^2 and twice 1200 m^2). The proposed evaporator arrangement is schematically shown in Fig. 5b.

Using evaporator simulation results that are a part of the solution of the extended targeting problem, process stream and utility data were extracted for the HEN retrofit problem. The optimum HEN design was found using UMIST program SPRINT. The retrofitted network

Table 1
Solutions of the extended targeting problem, four options of evaporator structure

Structural option	a	b	c	d
Number of effects	4	5	5	5[a]
Crystalliser heating from effect no.	2	2	3	4
Estimated investment cost (10^3 USD/year)[b]	180	219	222	236
Estimated energy cost (10^3 USD/year)	995	890	820	750
Estimated total cost (10^3 USD/year)	1175	1109	1042	986

[a] With pre-evaporation in the fourth effect.
[b] Depreciation period 6 years.

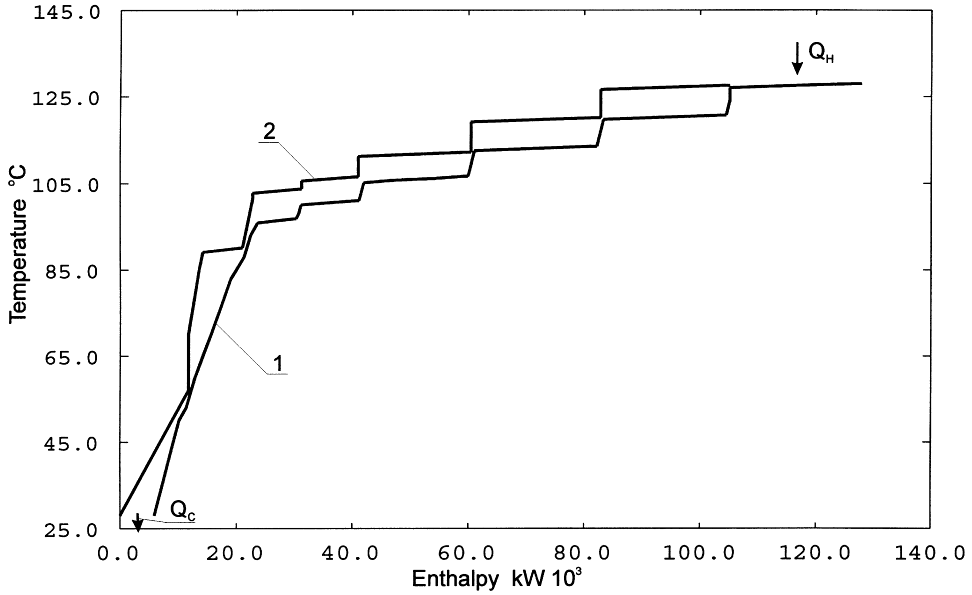

Fig. 6. Composite curves for evaporator option d (minimum temperature difference in the heat exchanger network is 2 K). 1: cold composite; 2: hot composite; Q_H: hot utility; Q_C: cold utility.

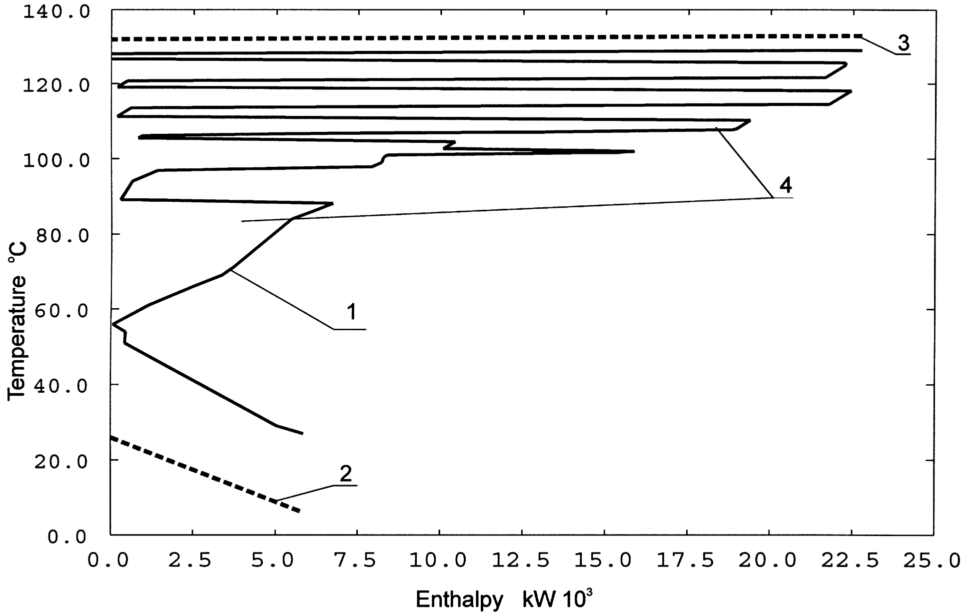

Fig. 7. Grand composite curve for evaporator option d (minimum temperature difference in the heat exchanger network is 2 K). 1–3. Lines representing process, cold utility and hot utility, respectively; 4: "pockets" indicating heat recovery potential.

Table 2
Expected results of sugar factory retrofit (ce: coal equivalent 29.3 MJ/kg)

Parameter	Attained	Proposed
Processing capacity (ton beet/day)	2,412	3,500
Beet worked during 85 days (ton)	205,020	297,500
Sugar produced during 85 days (ton)	25,320	40,200
Fuel consumed during 85 days (ton ce)	9,759	10,100
Specific fuel consumption (kg ce per 100 kg beet)	4.76	3.40
Simple pay-back period (years)	–	4

should include seven existing and seven new plate heat exchangers, and an existing shell-and-tube unit. Of the existing plate units, one should have its heat transfer surface reduced, another one should be re-piped and three units should have their heat transfer surfaces extended. The combined heat transfer area of existing plate units, after adjustments, was estimated at 550 m^2, and that of new units at 324 m^2. The duty of the existing shell-and-tube unit (160 m^2) should be changed.

The expected results of sugar factory retrofit are summarised in Table 2. The energy saving (understood as the reduction of specific fuel consumption) is estimated at 29%. The pay-back period of 4 years reflects the combined effect of increased sugar output and reduced specific energy consumption.

5. Conclusions

This paper introduces a new approach for the retrofit design of energy systems in sugar factories. This approach is based on system decomposition and employs a search of the best option for evaporator retrofit on the basis of extended targeting that includes simultaneous consideration of changes in the evaporation process and in the heat recovery.

The extended targeting problem is transformed to a problem of targeting under constraints and solved using a procedure that combines pinch analysis algorithm with evaporator simulator. The solution includes a complete set of process stream data making it possible to design the evaporator. The process stream data are subsequently used as input to HEN retrofit procedure based on the network pinch concept.

The effectiveness of the new design approach has been demonstrated on the example of its application to an industrial retrofit problem.

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