Hint: An educational software for heat exchanger network design with the pinch method

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ABSTRACT

A free piece of educational software for heat exchanger network design based on the pinch method is presented. The interface of the program has been designed focusing on getting a clear presentation of the concepts of the pinch design methods and letting students the control of all the stages of the design. The program guides students through all the main steps of the design, including energy and cost targeting, utilities selection, heat exchanger network specification, and optimisation and retrofitting analysis. The program has been tested in a MSc pinch technology course for several years, and the feedback obtained from students during this period has been used to optimise the program functionality and its interface. The use of the program improves the efficiency of the course since it let students practice the concepts of the pinch method while relieving them of tedious repetitive calculations.

1. Introduction

The cost of energy has increased dramatically in the last years, and this trend can be expected to continue. Additionally, there is a growing social concern about the sustainability of current industrial development. In this context, the ability to optimise the use of resources and in particular of energy is becoming an extremely important skill for chemical engineers. Two different methodologies have been successfully applied to minimize the use of energy in chemical processes. With the first one, the Heat Exchanger Network Synthesis (HENS) problem is formulated as a mixed integer non-linear optimisation problem (MINLP) (Biegler et al., 1997). The main advantage of this method is its capacity to find the best possible solution for the HENS problem. However, this method provides very limited information about the factors that determine the minimum energy consumption of a process, and about the possibilities to modify the process to reduce this minimum. The second methodology is the so-called pinch method, which is based on a thermodynamic analysis of the process (Linnhoff and Hindmarsh, 1983; Smith, 2005). The core

elements of this method are the calculation of energy and cost targets for the process, which inform the minimum energy consumption and the minimum cost of the HEN required to reach this minimum, and a systematic methodology for the design of a HEN that actually meets those targets is based on the use of simplified graphical representations of the thermodynamic analysis. The pinch design method offers no guarantee of finding the optimal solution. However, it allows a HEN to be developed that operates with the minimum energy consumption and at the same time is a good approximation of the optimal network. Furthermore, it gives full control of the design to the engineer, and helps to identify the parameters of the process that are limiting the energy savings. For these reasons, the pinch design method is a popular and well-established tool for HEN design.

The calculations required by pinch methodology are conceptually simple and can be done by hand. However, in real-scale problems they can become tedious and time consuming. Thus, the availability of a computer software that performs those repetitive tasks is of interest for the learning and application of the pinch method. Several

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 Abbreviations: GCC, Grand Composite Curves; GUI, Graphical User Interface; HEN, heat exchanger network; HENS, Heat Exchanger Network Synthesis; MINLP, Mixed Integer Non-Linear Programming.

Nomenclature

A	heat exchanger area (m^2)
h	heat transfer coefficient (kW/m^2 °C)
H	enthalpy (kW)
mCp	heat capacity flow rate (kW/°C)
N	number of heat exchangers
T1	supply temperature (°C)
T2	target temperature (°C)
$\Delta T_{\min}$	minimum temperature difference (°C)

commercial flowsheet simulators include pinch analysis tools. The main drawbacks of using these software packages to learn the pinch method are that a previous knowledge of the use of the simulator is required, and that sometimes the implementation of pinch design concepts in these packages is not clear and it makes learning difficult.

This work presents non-commercial software for the design of heat exchanger networks with the pinch method called *Hint* (*H*eat *int*egration). Special care has been taken in the design of the program interface so as to allow students to concentrate their efforts in learning the concepts of the pinch method and not in learning how to use the program. Additionally, when possible the input forms and the results of the program are presented in a very similar way as in the reference books (Linnhoff et al., 1994; Smith, 2005), which is the most familiar format for students. A second criterion considered for the design of the program is to avoid unnecessary automatic design tools that could give students the wrong impression that the program is doing something that they would not be able to do by themselves, or could make them consider the program as a black box that can be used to get some results without knowing how they are obtained. The program also shows some key intermediate results, which allow students to check their hand calculations.

The development of the program started in year 2000, and since then the program has been tested in the MSc-level course on pinch technology of our University for several years. During most of this time the program has also been available through the Internet and it has been used by several Universities as well as by a few companies with different backgrounds and from different countries, which have contributed their experiences and suggestions. The information gathered from this experience has been used to optimise the capabilities and interface of the program, and since the first version in 2000, six revisions of the program have been developed. *Hint* is distributed without charges on the web page www.iq.uva.es/integ/Hint.zip and it can be installed by the students on their personal computers.

2. Heat Integration course at the University of Valladolid

In the Chemical Engineering Department of the University of Valladolid we have taught a course on heat integration of chemical processes based on pinch methodology since 1996, in the first years as a part of a course about Integrated Design of Chemical Processes, and since 2001 as an independent course. This is a one-semester course with four teaching hours per week for a total of 60 teaching hours. It is offered as an elective subject to MSc students of Chemical Engineering, and is

I. Analysis of the use of energy

Topics: Energy requirements of chemical processes.
Traditional analysis tools.
Cost and energy targets.
The energy pinch and its significance.

Skills: Understanding of the economic and social repercussions of energy use
Calculation of energy and cost targets by the Problem Table Algorithm.
Identification of the pinch and elaboration of simplified diagrams (composite curves, grid diagram...).
Identification of parameters that influence energy integration.

II. Design of heat exchanger networks

Topics: Representation of heat exchanger networks (HENs).
Design of HENs. Feasibility criteria and Remaining Problem Analysis.
Simplification and Optimization of HENs.

Skills: Design of energetically optimum HENs.
Improve the design by relaxing the constraints of Pinch Methodology.
Retrofitting analysis of HENs using thermal loops and paths.

III. Utilities

Topics: Utilities in Chemical and Process Engineering
Design of Utilities based on the Grand Composite Curves

Skills: Elaboration of Grand Composite Curves
Optimum selection and design of utilities

IV. Integration of other unit operations

Topics: Cogeneration. Refrigeration. Integration of reactors, distillation towers etc.
Skills: Design of HENs including the main process unit operations
Identification of the possible energy gains by modification of the design of reaction, separation etc. taking into account the energy integration

Fig. 1 – Structure of the Heat Integration course of the University of Valladolid, based on the books by Smith (2005) and Linnhoff et al. (1994).

usually taken by 20–30 students per year. The contents of the course are based on the books by Smith (2005) and B. Linnhoff and collaborators (1994). An overview of the course is presented in Fig. 1. As presented in this figure, the course is divided into four main sections. In the first one the importance of reducing the energy consumption of chemical processes is presented to the students, and then several tools based on targeting are explained, which can be used to study and quantify the efficiency of the use of energy in a process. The second section presents the methodology for the design of energetically integrated HENs, and also tools for the simplification and retrofitting analysis of existing networks. The third section deals with the selection and design of the optimum utilities to provide the energy requirements of the process. The fourth section presents advanced topics such as the implementation of cogeneration, or the heat integration of different unit operations including reaction and separation systems.

Several years we have used different commercial simulators with pinch technology capabilities in the course. The main problems that we have found with the application of these commercial packages are: (a) a previous knowledge of the use of the simulators is required to use their pinch technology tools. Frequently we had students that had not used these simulators before, and we had to spend a considerable time teaching them the use of the simulator, which is not the specific objective of this course. (b) Sometimes the implementation of the pinch concepts in these programs is not clear, or is simply different to the one presented in the textbooks, which is confusing for students. (c) In some cases the application of pinch concepts in commercial programs is reduced to semi-automatic design tools, which have reduced possibilities for interaction and learning. (d) A few of the concepts and design tools taught in our course were not

implemented in the programs. These considerations lead us to the design of our own software.

Hint has been design to guide students through the design of the HEN following the same methodology and order presented in the theoretical lectures (Fig. 1). The following sections of this article present the main features of Hint as well as the resolution of a sample problem with this package. This problem is normally used in our Heat Integration course. The different activities and exercises related to the resolution of this problem that are normally proposed to the students in our course are also described as well as the application of Hint for these activities.

3. Problem description

Table 1 presents the stream table of the HENS problem considered. This problem includes two hot and two cold streams, as well as heating and cooling utilities and information on utilities and equipment costs, and was originally proposed by Zamora and Grossmann (1997).

Fig. 2 shows a screen capture of the Graphical User Interface (GUI) of Hint. The interface is divided into three sections. The bottom section is a table that can be used to introduce the thermal properties of the streams. The central section is used to display different diagrams, such as the Composite Curves or the Grid Diagram, during the design of the HEN. The Grid Diagram is fully interactive and allows to select or move streams and heat exchangers by clicking and dragging them, to open property forms with a double click on a stream or a heat exchanger, or to display a contextual menu with shortcuts to different actions by right-clicking. The left panel displays auxiliary diagrams on a smaller scale as well as a property sheet of the selected element of the Grid Diagram.

Table 1 – Problem data

Stream	T1 (°C)	T2 (°C)	mCp (kW/°C)	h (kW/m^2 °C)
H1	180	75	30	0.15
H2	240	60	40	0.10
C1	40	230	35	0.20
C2	120	300	20	0.10
Heating utility	325	325		0.50
Cooling utility	25	40		2.00

Cost of heat exchangers and coolers ($/year) = 15000 + 30A (m^2)$^{0.8}$.
Cost of heaters ($/year) = 15000 + 60A (m^2)$^{0.8}$.
Cost of cooling utility = 10 $/kW year.
Cost of heating utility = 110 $/kW year.

4. Energy and cost targeting

A convenient methodology for the design of chemical processes is the so-called "onion method" (Smith, 2005). With this method, the first stage of the design is the calculation of the reaction and separation sections of the process. The result of this stage is a basic flowsheet of the process, which is used as input data for the HENS problem. The first step in the design of the HEN with the pinch method usually is the calculation of energy and cost targets, which give a good estimation of the potential performance of the process. Target calculations are also a good tool for evaluating different flowsheet design alternatives as well as for proposing modifications in the flowsheet that may result in improvements for the energy efficiency of the process. Energy target calculations are one of the first heat integration tools taught in our course (Fig. 1).

Hint performs energy target calculations using the Problem Table Algorithm (Linnhoff and Flower, 1978). The information required for this calculation are the thermal properties of the
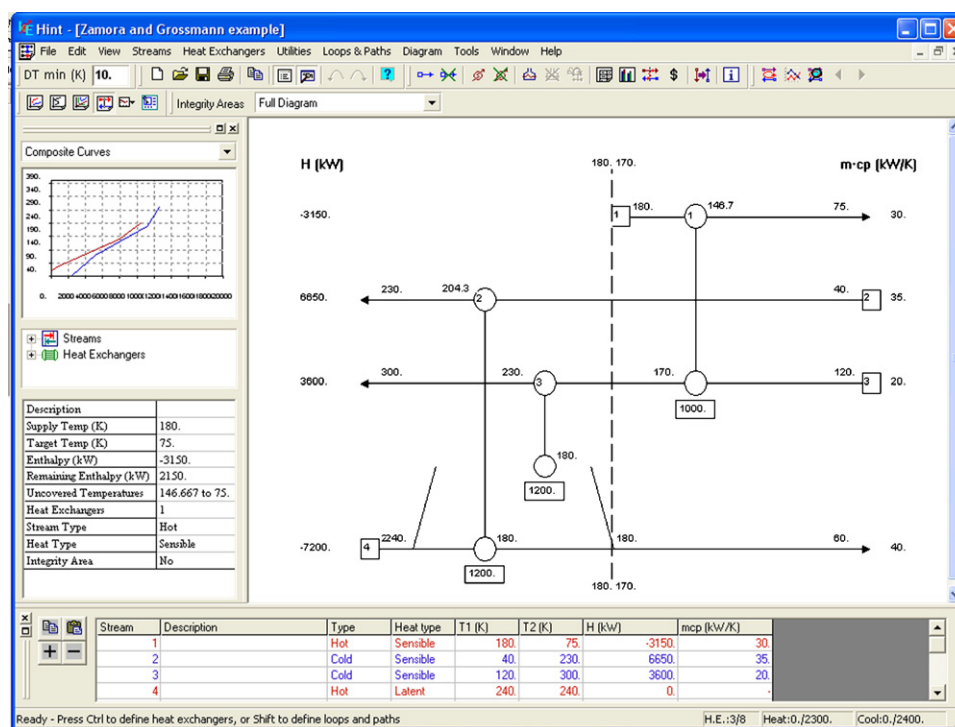

Fig. 2 – Graphical User Interface of Hint. The central section can display several diagrams and shows the Grid Diagram in this case, which is fully interactive. The bottom section is a stream table used to introduce streams thermal properties. The panel on the left displays auxiliary diagrams (Composite Curves in this case), and the properties of the selected element of the Grid Diagram.

Fig. 3 – Energy target calculations with the Problem Table Algorithm for the problem of Table 1 with a minimum temperature difference of 10 °C.

streams (supply/target temperature T1/T2 and enthalpy H or heat capacity flow rate mCp), which are obtained form the basic flowsheet, and the minimum temperature difference ΔT_{min} which is a design parameter. In many cases the streams can be considered linear, that is with constant mCp over the temperature interval $T1 - T2$. In these cases the thermal properties of streams can be easily supplied to *Hint* through the stream table located in the bottom of the main GUI. *Hint* is also able to handle non-linear streams, which are defined by a temperature–enthalpy table of arbitrary size introduced in the *Streams/Add/Enthalpy* form. *Hint* displays the results of the energy target calculations in the *Streams/Cascade* form. Fig. 3 shows the results as presented by *Hint* for a typical minimum temperature difference of 10 °C. It can be seen that the minimum heating requirements are 2300 kW and the minimum cooling requirements are 2400 kW, with a pinch temperature of 175 °C. This form also displays some intermediate results, such as the stream population graph or the enthalpy balance in each temperature interval, which can be used by students to check their hand calculations. A graph closely related to energy targeting is the Composite Curves (Fig. 4), generated by *Hint* with the *Diagram/Composite Curve* command. These figures give a visual indication of the energy recovery possibilities. In this example, these possibilities are good, as shown by the large extent of overlap between the Hot
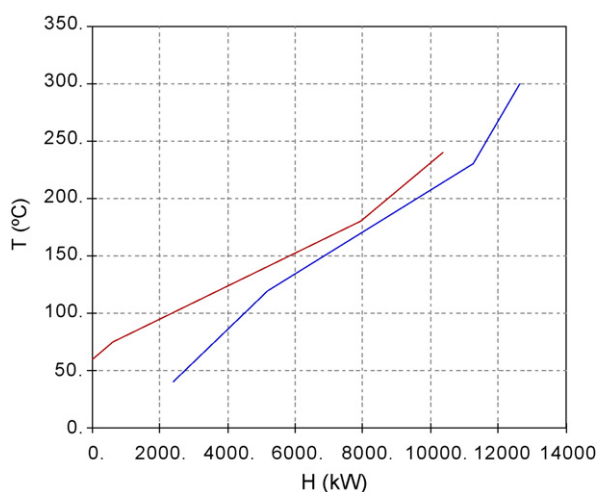

Fig. 4 – Composite Curves for the problem of Table 1 with a minimum temperature difference of 10 °C.

and Cold Composite Curves. If the Composite Curves are displayed as an auxiliary diagram (top-left section of the GUI), they are integrated with the Grid Diagram and when a stream is selected in this diagram its contribution to the Composite Curves is highlighted in green. This makes the identification of the streams that are limiting the heat recovery easier.

In our course, after explaining the Problem Table Algorithm and showing the resolution of a very simple problem (normally with 2–3 streams) on the board, we propose the students a problem like the one presented in Table 1, and we ask them to work in groups to calculate the energy targets and draw the Composite Curves, using the Problem Table Algorithm, and doing all the calculations by hand. This is done in a seminar with the aid of the teachers. This allows students to learn the mechanical aspects of the calculations. Normally the resolution of the problem takes students about 1 h. In the next lesson, we ask students to again work in groups to solve the same problem with *Hint*. This first contact of the students with the program is very easy because they just have to type the data on the stream table of Fig. 2. In comparison, when commercial simulators are used, generally a long time has to be invested to prepare the simulation before the first energy target-related calculation can be done. After this, students are asked to display the *Cascade* form (Fig. 3) and compare the results of the program with the results of their own hand calculations, and if necessary, to correct their calculations. The format used to display the Energy Cascade and the Composite Curves is very similar to the format used in Smith (2005), and it is the same format students have been taught to use in the seminar about hand calculation of energy targets. Therefore this format is familiar for students. Next we propose students to change different parameters as stream temperatures, enthalpy, minimum temperature difference, etc., and see the influence of these parameters on the Composite Curves and energy targets. As doing any of these changes involves re-calculating completely the energy cascade by the Problem Table Algorithm, students normally feel little interest to do it if they have to do all the calculations by hand. However, using *Hint* these calculations require very little effort (just change the data in the stream table), and students have freedom to test different parameters, see the influence of these parameters on the Composite Curves and understand the meaning of the Composite Curves themselves.

Cost and area target calculations are complementary to energy target calculations because together those two contributions add to the total cost of the process. *Hint* calculates heat exchanger area targets, taking into account the possible differences in the heat transfer coefficients of the streams (Hall et al., 1990). It also calculates capital cost targets using cost correlations of the form $cost = a + bA^c$, with A being the heat exchange area (m^2), and a, b and c are correlation parameters. Each stream can have a different cost correlation. Operating cost targets are calculated from the energy targets and an estimation of the cost of the utilities. All the information required for area and cost target calculations is introduced in the forms *Streams/Area Target* and *Streams/Cost Target*, respectively. *Hint* also includes assistants for the estimation of heat-transfer coefficients and cost correlations. These assistants are also useful for showing students the information required for a good estimation of these parameters (i.e. type of heat exchanger, construction material, pressure rating and cost index for cost correlations). With the parameters presented in Table 1 and a minimum temperature difference of 10 °C, Hint reports a minimum area of 7185 m^2 and a minimum cost of

$436 000 year^{-1} which is close to the value of $420 000 year^{-1} obtained by Zamora and Grossman by mathematical optimisation (Zamora and Grossmann, 1997). *Hint* can also calculate diagrams of energy, area and cost targets as a function of the minimum temperature difference (*Diagram/DTmin analysis* commands), which are useful for optimising ΔT_{min}.

Teaching area and cost target calculations without the support of a computer package can be problematic because these calculations are time-consuming. In our course we dedicate a 1 h seminar to solve an area and cost target problem by hand, again working in groups and with the assistance of the teachers. Some simplifying assumptions, such as constant heat transfer coefficients and identical cost correlations for all the streams, are imposed to make calculations less burdensome. The next class with the computers is started asking students to repeat the calculations with *Hint* and to check their hand calculations. After that, students are asked to improve the estimations by assigning specific heat transfer and cost correlations for each stream, based on the description of the properties of the streams given in the flowsheet and their knowledge of heat transfer. For the calculations of heat transfer coefficients and cost correlations, they use the assistants provided by *Hint*. This lets students learn the parameters they need to know to calculate these properties. When they finish, different groups are invited to present the correlations they have chosen and the correspondent cost target results. Considering the information available to students at this point, and the accuracy of the cost correlations, normally several solutions are possible, with significantly different results. This demonstrates students that the key point for the calculation of cost targets is not the mechanical procedure of the algorithm, which can be easily solved by any computer package such as *Hint*, but a careful selection of the data and correlations used to estimate the cost. Additionally, students can study the influence of the minimum temperature difference on the cost and energy targets, and optimise the ΔT_{min} with the *Diagram/ DTmin analysis* commands, a type of calculation that is excessively time consuming to be done by hand. The lesson is finished presenting students literature where they can find updated information about heat exchanger costs.

5.   Utilities selection

Once the basic flowsheet and the energy requirements of the process have been established, the next step in the design is the selection of the utilities that will supply these energy requirements. The Grand Composite Curve (GCC) is a very convenient tool for this selection. This curve represents the heating and cooling demands of the process at each temperature. Utilities must be chosen so as to supply these demands. A good approach for utilities selection is to design them so as to have a small separation between utilities and process GCCs, since this selection optimises the use of the available temperature difference.

The design of utilities with *Hint* follows this methodology. First, the process GCC is calculated, and this curve is used to identify the temperatures at which utilities are required. Based on this information, the utilities that could be used in the process are defined (*Utilities/Add* form). Then, these utilities are combined so as to obtain a utility GCC that covers all the energy requirements of the process (*Utilities/Combine* form). The cost of each utility can be introduced to study the total cost of different combinations (*Utilities/Cost* form).

Fig. 5a shows the GCC with the utilities proposed by Zamora and Grossmann (1997) and presented in Table 1. It can be seen that actually this utility selection is poor since there is a big separation between utilities and process GCCs. A more convenient selection would comprise the use of a sensible heat transmitting fluid as a thermal oil. It would be also interesting to study the possibility of using excess thermal energy to produce low pressure steam at 100–110 °C. Fig. 5b shows the obtained GCCs with this selection. It can be seen that the separation between process and utilities GCCs is much smaller in this case. The introduction of steam generation causes a utility pinch at 115 °C. *Hint* displays this information on the Grid Diagram (Fig. 6), and it is able to solve problems with several utility pinches. In the rest of this work, the utilities presented in Table 1 will be considered.

As in previous cases, the main advantage of the use of *Hint* to study utilities design is that it gives student freedom to try different solutions without feeling constrained by the time required to complete the calculations by hand. In our course we include a seminar in which we propose several problems with different GCCs. For instance, some problems with very steep GCCs which are indicated for using sensible-heat transmitting utilities, others with flat GCCs for which latent heat utilities are more adequate, and others with different sections which make convenient the selection of multiple heating and/or cooling utilities. Students can then use *Hint* to test different parameters of the utilities and see how they affect the shape of the GCCs. This allows them to learn the
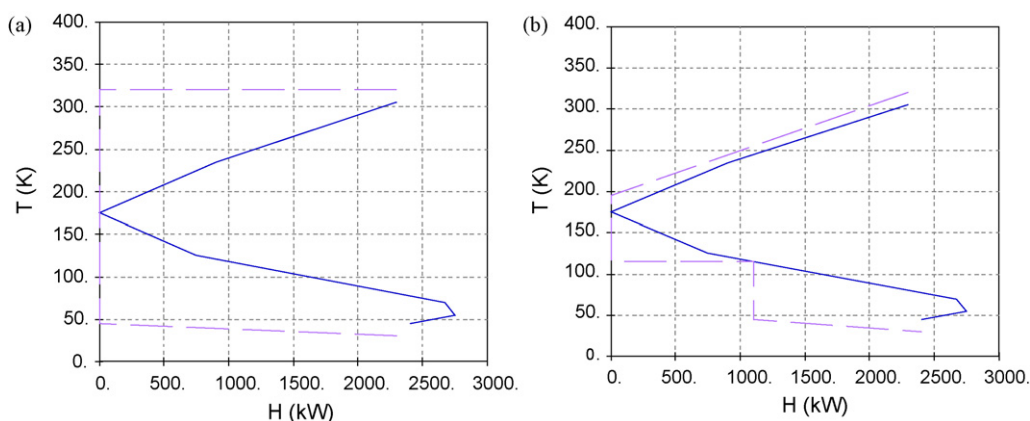

Fig. 5 – Process (continuous line) and utilities (dashed line) Grand Composite Curves (a) with the utilities presented in Table 1 and (b) using a thermal oil and generation of steam at 110 °C.
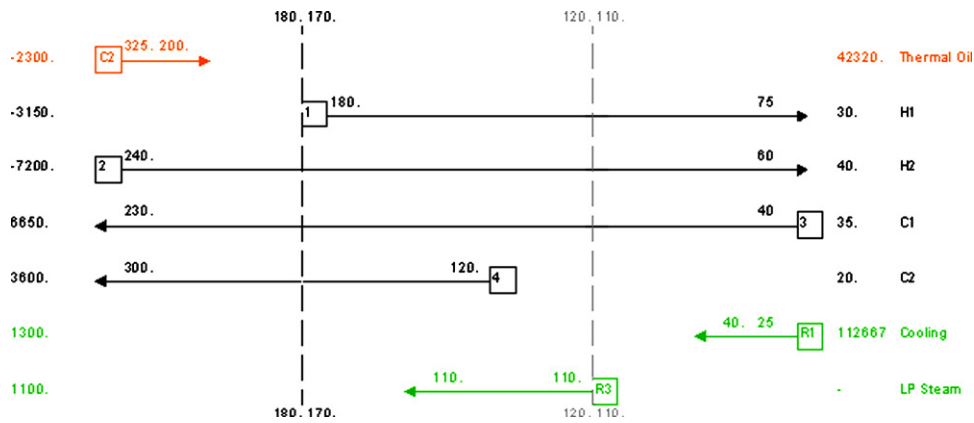
Fig. 6 – Grid Diagram with the utilities of Fig. 5b, showing utilities pinch at 115 °C.

meaning of this diagram and the significance of the different shapes of the CGGs.

6. Heat exchanger network design

Once that the flowsheet and the utilities have been established, the design of the HEN can be started. The key rule to achieve the previously calculated energy targets is to avoid heat transfer across the pinch. The design of the HEN usually starts at the pinch, since this is the most constrained region. The heat exchangers that have the minimum temperature difference in one end are usually called pinch heat exchangers. Aids to design the pinch heat exchangers are the following feasibility criteria (Smith, 2005):

- Stream population: At the hot side of the pinch, the number of cold streams must be bigger or equal to the number of hot streams, $N_{cold} \geq N_{hot}$. In the cold side of the pinch $N_{hot} \geq N_{cold}$.
- Heat capacity flow rate difference: In a pinch heat exchanger, at the hot side of the pinch, the heat capacity flow rate of the cold stream must be higher than that of the hot stream, $mCp_{cold} \geq mCp_{hot}$. At the cold side of the pinch, $mCp_{hot} \geq mCp_{cold}$.

If necessary, process streams can be split to adjust their population and mCp so these criteria are fulfilled.

A convenient presentation of these feasibility criteria is placed together with an mCp table of the stream population on each side of the pinch that can be used to find the feasible matches. *Hint* displays these tables in the *Streams/Feasibility* forms (Fig. 7). Pinch heat exchangers can be defined in these forms simply by clicking on the mCp of the hot and cold streams. If necessary, a stream can be split by double-clicking on its mCp. This opens the *Split Stream* form that allows the parameters initial/final temperatures and mCp of each branch to be specified. A branch of the stream can be split again to produce any desired topology. In the proposed example, stream H2 must be split above the pinch to meet the mCp difference feasibility criteria. Below the pinch, H2 can be matched with C3 and H1 with C4. The mCp of the streams that are matched in pinch heat exchangers are written in the same colour in the mCp tables, as shown in Fig. 7.

After the pinch heat exchangers have been specified, the remaining process heat exchangers must be designed, ensuring that cooling utilities are not used above the pinch, and heating utilities are not used below the pinch. At this stage, there can be several feasible solutions. A useful tool for comparing these alternatives is the remaining problem analysis. This analysis consists on calculating the cost and
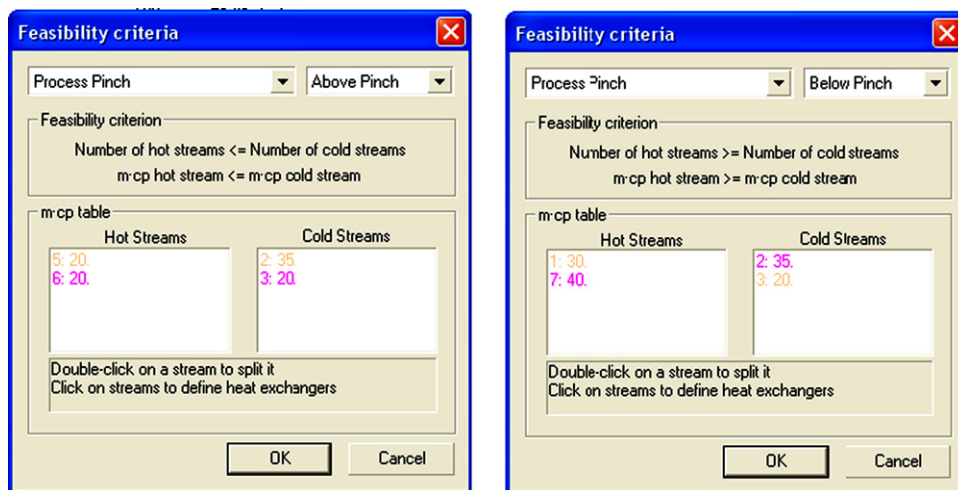

Fig. 7 – Feasibility criteria forms for the streams above the pinch temperature (right) and bellow the pinch temperature (left). The upper section displays the feasibility criteria on each side. The lower section displays the mCp tables. Streams that are connected with a pinch heat exchanger are marked in the same colour in the mCp tables.

Fig. 8 – Heat exchanger specifications form. The upper section displays the number of the heat exchanger and the streams connected by it. The middle section allows to select the type of specifications. The lower section is used to select which variables are specified and their value.

energy targets for the fractions of the streams that are not already covered by heat exchangers, and adding them to the cost of the already installed exchangers. In this way an estimate of the final cost of a partially completed design is obtained and several alternatives can be compared without completing the corresponding designs. *Hint* presents a remaining problem analysis in the *Heat Exchangers/Remaining Problem* form. This form compares graphically the initial energy and cost estimations with the sum of the cost of the already installed exchangers and the energy and cost targets of the rest of the problem.

Heat exchangers are defined with the *Heat Exchangers/Add* form (Fig. 8). This dialog can also be opened by Ctrl + clicking on the streams that are to be matched in the exchanger. Usually three parameters of the heat exchanger must be specified by the user: either the heat load and two temperatures (specification type: "User supplied enthalpy"), or three temperatures (specification type: "User supplied tempera-

tures"). Temperatures and enthalpies can be specified in different ways. The simplest one is just to introduce their numerical value. However, it is also possible to specify that a temperature is equal to the stream target/supply temperature, to the pinch temperature or to the outlet/inlet temperature of a previous/subsequent heat exchanger, or to specify that the enthalpy of the heat exchanger must be the value required for exhausting one of the streams. These types of specifications cover most of the situations when a HEN is being designed with the pinch method, and usually it is possible to specify the whole network without typing any numbers. Additionally, if these specifications are used and then one of these parameters is varied (for instance, the supply temperature of a stream), *Hint* will automatically correct the calculations of the heat exchangers to take into account the variation.

In the example presented in Table 1, there is no need for more heat exchangers between process streams apart from pinch exchangers, and the HEN design can be completed just by taking all process streams to their target temperatures with utilities. The corresponding heat exchangers can be most conveniently defined using the "Enthalpy to complete …" specification. The obtained HEN is presented in Fig. 9. After completing the design, the estimation of the costs of the network can be improved by assigning specific heat transfer coefficients and cost correlations to each heat exchanger instead of to each stream. In this case, the obtained network operates with the minimum energy consumption and a total annual cost of \$458 000 year^{-1}, close to the value obtained by targeting.

In our course we first dedicate a seminar to solve a design problem such as the one presented in this section by hand, and then the next day students repeat the design with *Hint* so they get familiarized with the way of specifying heat exchangers in the program. Specifically, the *Feasibility criteria* forms are very similar to the *m*Cp population tables presented in Smith (2005). The interactive presentation of the tables in these forms encourages students to actually use them and to learn the usefulness of feasibility criteria. To our knowledge this type of interface for specifying pinch heat exchangers is not available in other computer programs.

At this point, a common mistake of students is to think of pinch method as a kind of mechanical design methodology that upon following certain rules automatically leads to an optimum HEN design. This wrong perception is corrected proposing students a more complex problem (with 10–15 streams) with several possible solutions. We teach students to go through the different steps of the design, applying the Remaining Problem Analysis technique and their Chemical
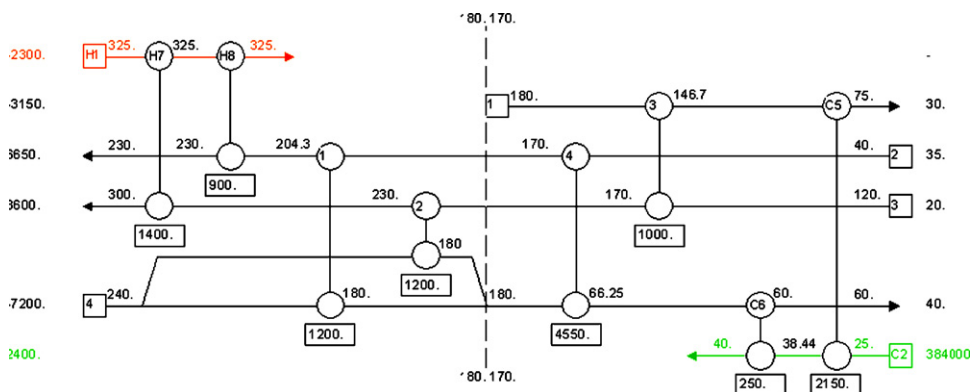

Fig. 9 – HEN design for the problem presented in Table 1.

Engineering knowledge to select amongst various different solutions when possible. We think that this is the best methodology for handling this kind of complex problems, and the only way of teaching it is in connection to the resolution of large problems, because normally Remaining Problem Analysis calculations are unnecessary in small problems. Again, this is only possible with the aid of a computer package because otherwise excessive calculation effort is required to apply Remaining Problem Analysis calculations to large problems. The resolution of large problems with different possible solutions also encourages the discussion between students of the different alternatives, which is very positive.

7. Simplification, optimisation and retrofitting analysis of HENs

One of the main drawbacks of the design of HENs with the pinch method is that usually complex network configurations are obtained, and this can cause controllability problems. Additionally, the pinch design methods aims to achieve a network that operates with the minimum energy requirements and in which all the heat exchangers operate at least with the minimum temperature difference, and sometimes it is possible to obtain a lower total cost (operational + capital) if these constraints are relaxed. Another frequent situation is the retrofitting analysis of existing HENs. In this situation, the objective is to modify the network so as to achieve the maximum improvements in the energy efficiency of the

network compatible with limited modifications of the existing HEN.

Since the direct modification of an energetically integrated HEN can be a complex task, a systematic method to handle the modifications is necessary. This can be done by operating with heat exchanger paths and utility loops (Linnhoff and Hindmarsh, 1983; Smith, 2005). Loops and paths can be easily defined in *Hint* just by Shift + clicking on the heat exchangers of the Grid Diagram that constitute them. Then the amount of heat transferred through the loop or path is specified in the *Loops&Paths/Add* form. The variation of different parameters such as the area, temperatures or heat load of a heat exchanger or the total cost of the network with the heat transferred can be tracked with the *Loops&Paths/Analysis* form. Additionally, *Hint* includes an exclusive search algorithm capable of finding all the loops and paths of the network even in problems with several utilities or with split streams.

Let us consider the example presented in the Grid Diagram of Fig. 10a. Let us suppose that for the operation of the process, it is essential to have a good control of the target temperature of stream 3, while important perturbations are expected in the supply temperature of stream 1. With the proposed diagram, it is obvious that the perturbations in stream 1 will be directly transmitted to stream 3 through heat exchanger 4. Therefore the simplification of the network should aim to eliminate this exchanger. Moreover it would be useful to install a heater at the end of stream 3 since it would be much easier to achieve a good control of the target temperature of this stream with a utility heat exchanger than with a process exchanger. Fig. 10b
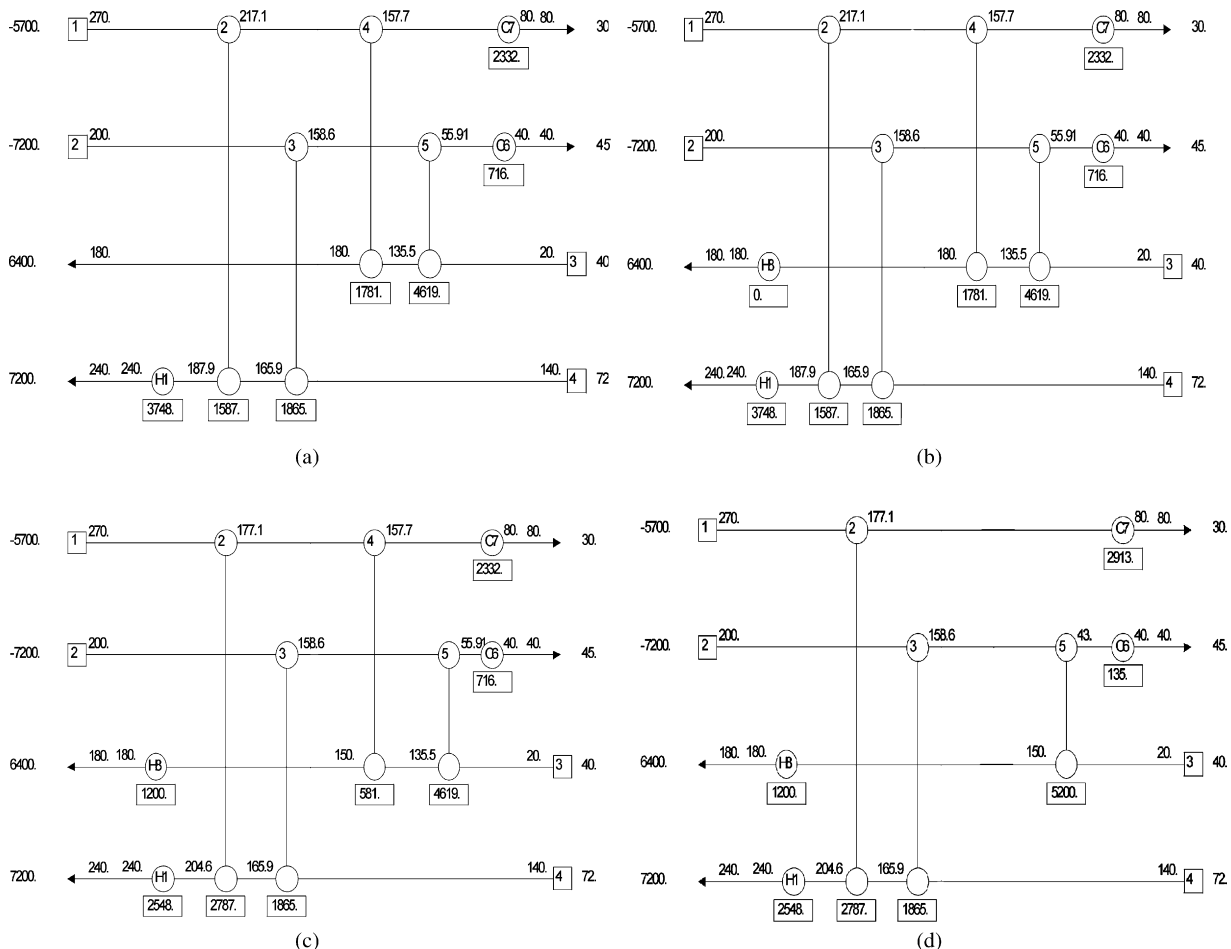

Fig. 10 – Example proposed for simplification analysis (a) initial diagram, (b) diagram after definition of the additional heater in stream 3, (c) diagram after transferring heat load from exchanger 4 to heater H8, (d) final diagram.

shows the diagram after the definition of this exchanger. Next, part of the heat load of heat exchanger 4 must be transferred to the heater H8 This can be done with the loop formed by the heat exchangers H1-2-4-H8. With the Loops&Paths/Analysis tool, Hint reports that the maximum heat flow that can be transmitted through this loop is approximately 1500 kW, because larger flows would cause a temperature crossover in heat exchanger 2. In order to avoid an excessive reduction in the temperature difference in this exchanger, the heat transmitted has been reduced to 1200 kW. The resulting diagram is presented in Fig. 10c. Finally, the remaining heat load of exchanger 4 can be eliminated with the loop formed by exchangers C7-4-5-C6. This leads to the diagram presented in Fig. 10d. In this diagram the transmission of perturbations from stream 1 to 3 has been eliminated, and a utility heat exchanger that allows a better control of the target temperature of stream 3 has been installed. Additionally, since only heat exchanger loops have been used, the total energy consumption of the process has not been altered.

Further optimisation of this HEN could focus on improving the energy consumption of the network. Using the installed minimum temperature difference of 8 °C, Hint reports that the network consumption of heating and cooling utilities of this network is 948 kW above the minimum. In the *Heat Exchangers/ Matches across the pinch* form *Hint* shows that the reason for this is the transmission of heat across the pinch in heat exchangers 5 (75 kW) and 7 (873 kW). Therefore in order to reduce the use of utilities these transmissions should be eliminated.

The optimisation and retrofitting analysis techniques presented in this section are indeed the most difficult part of the pinch method for students, because due to their limited experience, they feel more comfortable following the rules of the pinch design method strictly (i.e., no violation minimum temperature difference, no heat transmission across the pinch), and they are reluctant to be flexible with them. The only solution for this problem is practice, and for this in our course we propose student several examples as the one presented in this section, and we encourage discussion of the possible solutions amongst themselves and with the teachers. For this, the application of *Hint* is also useful because it reduces the time spent with repetitive calculations and lets students practice with a larger variety of problems. As presented in this section, heat loops and paths are particularly useful tools for handling this type of simplification and optimisation problems, yet they are not implemented in some commercial packages. Additionally, the loops and paths search algorithm implemented in *Hint* is an exclusive algorithm developed in our group that is not available in any other computer program.

8. Conclusions

Educational software for the design of heat exchanger networks has been presented and its capabilities have been described with the resolution of an example. The program is able to assist students through all the main steps of the design, including energy and cost targeting, utilities design, heat exchanger network design, and optimisation and retrofitting analysis based on the use of heat exchanger loops and utility paths. Special care has been taken in the design of the user interface to ensure that the program helps students to do the calculations required by the application of the pinch method but without hiding how or why are these calculations done. The program has also being designed to be consistent with the methodology and design strategies taught in our Heat Integration course. The program has been tested in the pinch technology course of our University for several years. The use of the program improves the efficiency of the course since it lets students practice the concepts of pinch technology with a larger number of examples without spending too much time with repetitive calculations and without requiring previous knowledge of commercial flowsheet simulators. The program is available for download both in Spanish and English languages in the following web page:

www.iq.uva.es/integ/Integracion.zip (Spanish)
www.iq.uva.es/integ/Hint.zip (English)

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