Kirk-Othmer Encyclopedia of Chemical Technology.

PROCESS INTEGRATION TECHNOLOGY

In the past, most of the work in the field of chemical process design has been focused on the design of individual unit operations such as reactors, separators, furnaces, heat exchangers, etc. Procedures for the design of these items of equipment are well established and are familiar to most chemical engineers. However, the combination of these operations to create an overall process flowsheet, or *process integration*, has, to date, received far less attention. Process integration addresses the questions of which unit operations should be selected and how they should be interconnected in order to give the best solution to a given design problem. The designer must determine the structure of the process as well as the more quantitative variables such as temperatures, flowrates, compositions, etc. Because the number of process alternatives is enormous—often too large to enumerate—this problem is far more complicated than that of designing a unit operation.

The multitude of possibilities means that an exhaustive or trial-and-error approach is extremely unlikely to yield the best possible solution, which is true, even with the availability of large and powerful computers today. Without a systematic approach, one can only consider a few alternatives, which is in fact what happens in most cases. However, considering a limited number of options means that the true optimum—which can be far better—may be missed or even that the design becomes trapped in a structure that is significantly different to the optimal one. Depending exclusively on previous experience also means that the potential for innovation is reduced. It is necessary to recognize that even the best and most advanced equipment, if improperly integrated, will give a poor overall process. Over the past two decades, systematic procedures for process integration have evolved and continue finding their way into industrial application. Much of the work originated at the University of Manchester Institute of Science and Technology (UMIST) in the early 1980s and was rooted in energy conservation. Today the activity has broadened to take account of the drive toward greater efficiency in the use of raw materials in general and of increasing pressures to design processes that are environmentally friendly, while making effective use of capital. Significant contributions have been made by other organizations as well. This article will discuss the state of the art in process integration and how it has matured. It will show how the boundaries have been extended to embrace a whole new set of innovative methodologies and applications.

Many engineers are already familiar with the original energy-focused work, which centered around the well-known pinch analysis methodology. However, the recent developments described in this article will probably be new to most readers. The major aim of this article is not to provide technical details, but rather to expose readers—both academic and industrial—to the broad scope of technology that exists today. Before proceeding, it is worth spending a few words discussing the background to process integration. As mentioned above, this is concerned with the design of chemical and other manufacturing processes. The Onion Diagram (Fig. 1) is a very useful representation of the hierarchy of process design as described by Smith (1). It shows the process design as comprising a number of layers. A new or "grassroots" design will start by choosing the reactor design—the center of the onion—and then moving outward through the various layers. The reactor design dictates the separation and recycle problem and so the separation and recycle system is designed after the reactor. The reactor and separation and recycle system designs together define the process heating and cooling requirements, and so the heat exchanger network is designed next. This design then fixes the requirements for

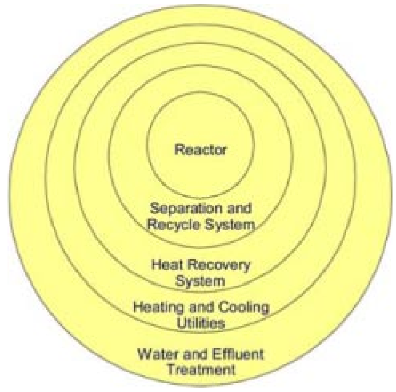


Fig. 1. The Onion Diagram shows the hierarchy of process design.

external heating and cooling utilities such as steam, cooling water, refrigeration, etc. Thus, the utility system is designed after the heat exchanger network. As water use is an essential feature of virtually all process industries, a water distribution and effluent treatment system also needs to be designed. The overall process design is thus a complex problem with many facets. Also, the different layers all interact with each other. Decisions or changes made in any layer will impact all the layers outside of it. Note that retrofitting an existing process will not necessarily follow this hierarchy, which is mainly for new designs. Later in this article, we will look at a very common case, where the heat exchanger network retrofits are done while being constrained by an existing utility system.

Over the years, two main "schools" developed for process integration. One was based up thermodynamic methods (2), while the other made use of mathematical optimization technology. The thermodynamic approach found great success in the area of heat integration and will be discussed in the section on heat integration. A recent review of the advances that have taken place in the mathematical programming approach to process design and synthesis is provided by Grossman and co-workers (3).

1. Heat Integration

The roots of process integration are in heat integration (see Heat exchange technology network synthesis). A breakthrough in this area was the development of pinch analysis, which emerged against the background of the energy crisis of the late 1970s and started out as a method of designing heat exchanger networks for minimum energy consumption. The main distinguishing feature of pinch analysis is that it is a thermodynamic approach as opposed to a mathematical one. In pinch analysis, the designer uses physical and thermodynamic fundamentals to gain valuable insights into the system performance and characteristics, which allows performance targets to be set without any design and with no commitment to a particular structure. The next step is to design a system to meet these targets, using special design techniques.

Perhaps the best known tools of pinch analysis are the composite curves for energy targeting (2). The first step is to identify all the heating and cooling requirements of the process streams in terms of temperatures and enthalpies (Fig. 2**a**). Next, the hot streams are plotted on temperature–enthalpy axes and the individual stream profiles are combined to give a hot composite curve (Fig. 2**b**), which is repeated for the cold streams (Fig. 2**c**). Finally, these are plotted together so that they are separated by a predetermined minimum approach temperature, $\Delta T_{\min}$ (Fig. 2**d**). This representation shows the targets for the minimum heating and cooling

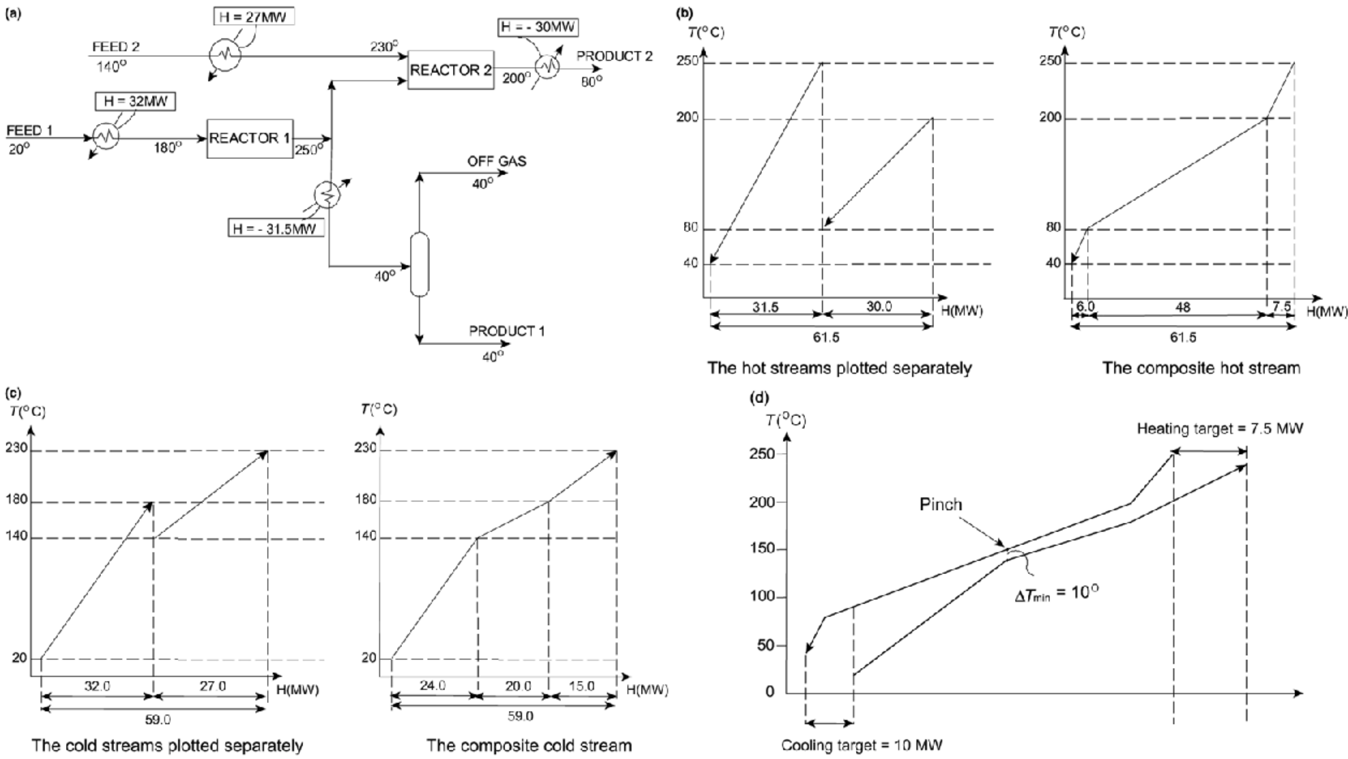


Fig. 2. (**a**) Individual heating and cooling requirements are extracted from a process flowsheet. (**b**) Plotting hot stream profiles and the hot composite curve. (**c**) Plotting cold stream profiles and the cold composite curve. (**d**) Plotting the composite curves together gives targets for energy recovery and heating and cooling utilities.

requirements of a process. It also locates the heat recovery pinch, which is a bottleneck on heat exchange. It is important to note that these targets are set ahead of any design effort and are based only on stream data.

The pinch design method was also developed in order to allow these targets to be achieved in design (2). This method is based on avoiding cross-pinch heat transfer as this is wasteful of both hot and cold utility. A useful network representation, the grid diagram, was developed and is shown in Figure 3. This diagram is used for network design and is much more convenient to use and understand than a conventional flowsheet. In this representation, hot streams run from left to right and cold streams run the opposite way. Heat exchangers are shown as a pair of circles joined by a line, with the heat duty transferred shown below. Heaters and coolers are represented as circles.

Later, the grand composite curve (Fig. 4) was developed to give a clear picture of the process–utility interface and to allow the best mix of utilities to be selected before design. It shows clearly where cheaper utilities such as medium pressure steam heating and low pressure stream generation can be used.

Another important step in pinch analysis was the development of targets for the minimum number of heat-transfer units and also the minimum heat-transfer area, which allowed minimum capital cost targets to be set. These can be traded off against energy costs in order to find the optimum $\Delta T_{\min}$ value and is termed supertargeting and essentially optimizes the network ahead of any design. More details of all these areas of pinch analysis concepts and methods are provided by Linnhoff (2).

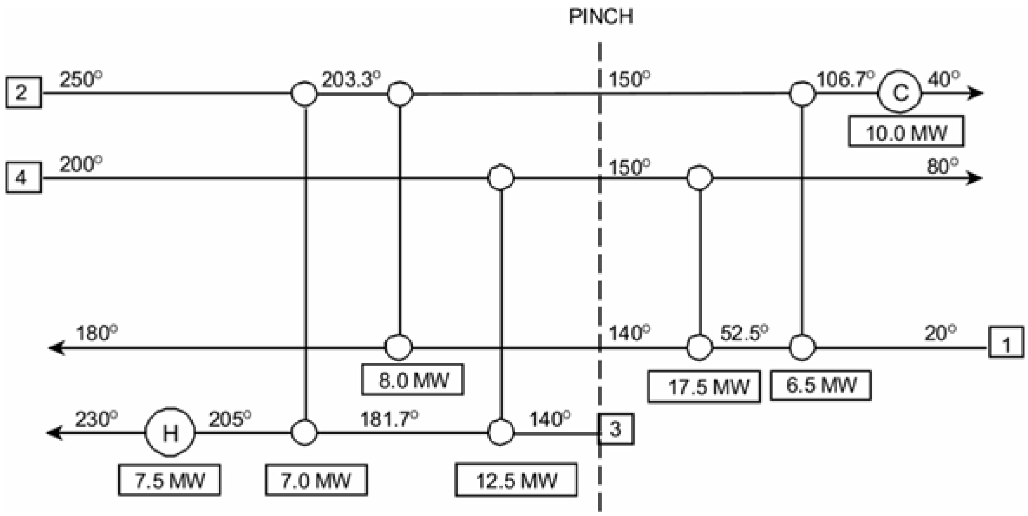


Fig. 3. The grid diagram representation of a heat exchanger network.

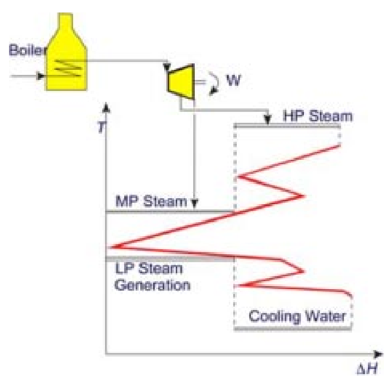


Fig. 4. The grand composite curve is used to determine the best mix of utilities.

2. Mass Integration

More recently, researchers at University of California in Los Angeles (UCLA) and Auburn University pioneered the development of mass integration technology, which is a holistic approach to address the conversion, routing, and separation of mass. Mass integration began with the concept of a mass exchange network (MEN), which is a system of mass-transfer operations that transfers certain targeted species from a set of rich process streams into a set of mass separating agents (See also MASS TRANSFER). El-Halwagi and Manousiouthakis (4) showed how mass-transfer composite curves can be developed in order to give targets for the minimum mass separating agent (MSA) flowrate required to effect a given separation (Fig. **6a**). Both internal (process) MSAs as well as external (utility) MSAs can be minimized. This effectively minimizes the operating cost and is analogous to the minimum utility target in a heat exchanger network. They also showed how to design mass exchange networks to meet these targets exactly.

In a later paper, El-Halwagi and Manousiouthakis developed an automated linear programming approach to MEN synthesis (5). They also considered the case where MSAs are not used on a 'once-through' basis, but

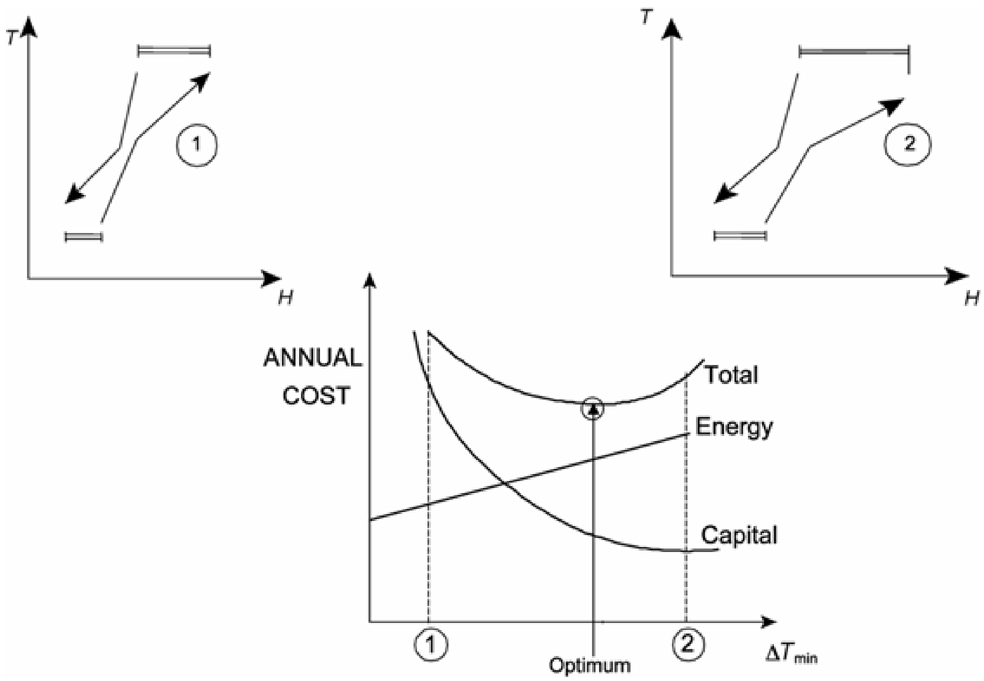


Fig. 5. Supertargeting involves trading-off capital and energy costs in order to optimize the minimum approach temperature before design.

are treated using a regenerating agent (6). They showed how the total operating cost (MSAs plus regenerating agents) can be minimized while using a minimum number of units.

In some problems, physical mass exchange is accompanied by chemical reaction and often results in overall equilibrium relations that are strongly nonlinear. El-Halwagi and Srinivas (7) showed how to deal with problems in which the equilibrium relations are nonlinear.

Srinivas and El-Halwagi (8) discussed problems in which there is a strong interaction between mass and energy. For example, the mass exchange equilibrium relation of an MSA may be affected by its temperature and so heating and/or cooling may be beneficial to the MEN. However, heating and/or cooling may incur additional costs. Srinivas and El-Halwagi showed how MENS and HENS concepts may be combined to minimize the total operating cost (MSAs plus hot and cold utilities).

The original MEN problem involved removing fixed amounts of mass from a given set of streams. El-Halwagi and co-workers (9) expanded the problem and considered a waste interception network, which involves the use of mass exchange operations to intercept streams within a process flowsheet in order to achieve the desired pollution reduction. In this type of problem, the rich stream data are not fixed and must be determined as part of the synthesis procedure. The use of targets is extremely valuable for screening the multitude of process options that need to be considered. El-Halwagi and co-workers showed that intercepting streams within the process can give solutions that are significantly cheaper than simply treating the effluents.

El-Halwagi's textbook (10) provides an excellent coverage of the above-mentioned developments. Most of the work was aimed at minimizing operating cost rather than total cost, because until recently, systematic methods for targeting and designing for minimum capital cost were not as well developed.

Hallale (11) developed a new plot, termed the *y–x* composite curve diagram, which is used to target the minimum mass exchanger sizes required to achieve the operating cost targets. It consists of a composite

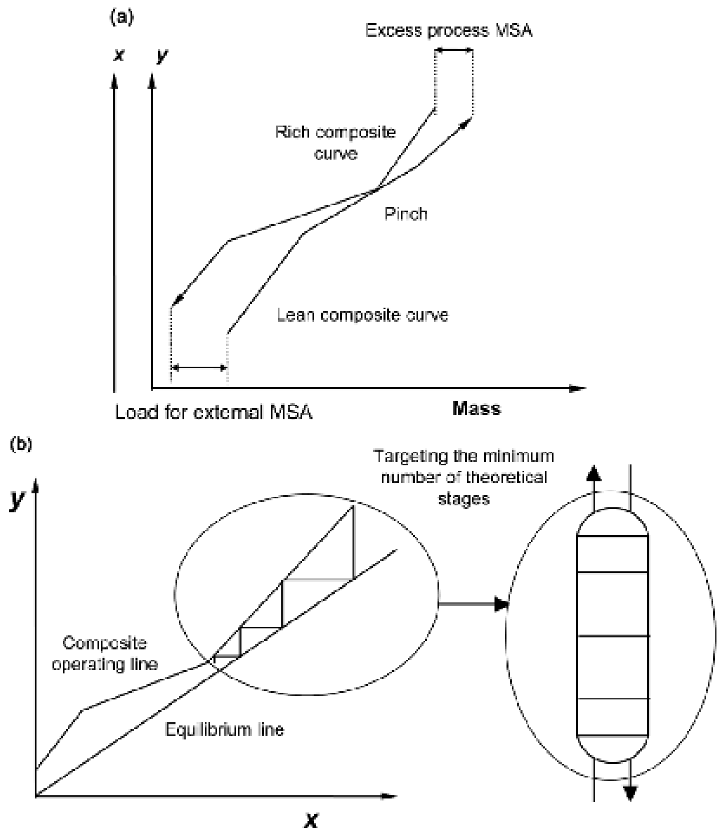


Fig. 6. (**a**) Mass exchange composite curves for targeting the minimum mass separating agent requirement. (**b**) The x–y composite curves for targeting the minimum mass exchanger size.

operating line and an equilibrium line, so that the familiar McCabe–Thiele method can be used to target the minimum number of stages (Fig. 6**b**). The ability to set capital as well as operating cost targets means that powerful supertargeting can be performed as for heat exchanger networks. Hallale (11) has shown how this new approach gives mass exchange networks with costs significantly cheaper than previously published solutions.

3. New Developments

Until recently, process integration was virtually synonymous with pinch analysis. However, over the past few years, there have been two significant trends that change this picture:

(1) First, a wider range of solution techniques is now used. Rather than using only thermodynamic, or pinch methods, the advantages of mathematical programming and optimization have been combined. The insights from thermodynamics have been retained and combined with the power of mathematical methods for data handling, optimization, and automatic design. The approach used as far as possible is to develop as deep an understanding of the physical principles underlying problems, and only then to develop practical methodologies that employ the necessary mathematics. The wider range of available methods has given rise to the second trend.

(2) A much wider range of problems can now be addressed. Until the early 1990s, process integration was almost exclusively devoted to the study of energy efficiency, ie, the third and fourth layers of the onion. Now, however, it can be considered to cover four major areas: Efficient use of raw materials, energy efficiency, emissions reduction, and process operations.

It should be clear from the discussion above that process integration is now far more concerned with material (mass) processing issues than earlier due largely to the efforts of researchers at UCLA and Auburn. Mass integration and energy integration, in fact, complement one another and this article will discuss how the two are brought together in the latest research. Owing to space limitations, only selected areas will be discussed in detail.

3.1. Efficient Use of Raw Materials

3.1.1. Reactive Systems

Over the past few years, significant progress has been made in the development of methods to select clean and profitable chemical reactions, raw materials, solvents, and products. Crabtree and El-Halwagi (12) introduced a method for synthesizing environmentally acceptable reactions. For a reactor of known size and functionality, and a desired product and flowrate, they were able to synthesize an overall chemical reaction that features maximum economic potential while complying with environmental and thermodynamic constraints.

The technology can consider potential raw materials and by-products, stoichiometry, thermodynamics, and environmental requirements. It is based upon formulating an optimization problem. More details are given elsewhere (12).

Often, it is possible to replace hazardous chemicals with more benign species. Group contribution methods have commonly been used in predicting physical and chemical properties of synthesized materials. Constantinou and co-workers (13) developed an algorithm to synthesize molecules subject to a set of property constraints. For more detail on how this product synthesis can be integrated with process design, see El-Halwagi (10).

3.1.2. Design of Novel Reactor Systems

For the design of industrial reactors, the most appropriate choice of configuration and mixing pattern, arrangements for feed and recycling of raw materials and arrangements for handling the energy effects in the reaction system have not only a critical effect on the performance of the reactor but that of the process as a whole (see Reactor technology). The problem is made more complex by the fact that many industrial reactors involve multiphase systems.

Design choices are made on the basis of past experience and trial and error using laboratory tests and repeated simulation. Very often, a reactor is chosen because it reminds designers of a similar system, because it has been used before, or simply because there is no time to search properly and the proposed design is known to work. Heuristics and expert systems can help, but these will often lead back to conventional designs.

A methodology has been developed for the systematic design of chemical reactors that sets performance targets, predicting the maximum yield and selectivity for a given reaction system with its catalyst (14). The technology was developed specifically to address industrial reactor problems rather than academic or “textbook” ones.

This method makes strong use of mathematical programming and is a good illustration of the use of newer tools. A superstructure consisting of generic reactor units and a network of interconnected streams that account for different layouts, arrangements, and mixing patterns is created (Fig. 7**a**), which is then subjected to stochastic optimization and/or mathematical programming in order to give a target for the theoretical best performance (eg, conversion, yield, selectivity, cost etc). However, many physical insights must be included in the problem formulation to obtain solutions.

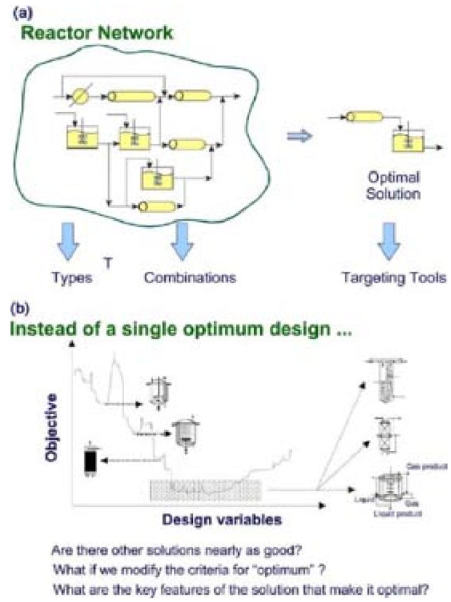


Fig. 7. (**a**) A superstructure with all possible combinations of reactor types and connections is optimized to give a target for the best performance. (**b**) The method gives a range of targets and design options rather than a single point.

Even the most complex systems can be analyzed, involving multiphase reactors and complex heat-transfer arrangements. When dealing with multiphase systems, a network is constructed for each phase and these are linked using understanding of mass transfer. The mixing patterns and heat-transfer arrangements associated with the target provide the basis for the design to achieve the target. Optimum catalyst distribution patterns can also be predicted. For new processes, the technology is capable of identifying the optimal reactor configuration and operation. For existing processes, it can be used to determine the potential for modifying the design.

The application of this technology leads to the development of novel reactor schemes that would be virtually impossible to derive using an approach based on trial and error. The technology has either led to designs with very significant improvements in the yield of the process when compared with those based on conventional reactor designs, or significantly reduced capital investment. This approach does not simply give one solution as being "the optimum". Rather, it provides the designer with a range of targets and design options (Fig. 7**b**).

The power of the approach can be illustrated with a study involving the chlorination of butanoic acid to form α-monochlorobutanoic acid (MBA) and an undesired by-product, α,α-dichlorobutanoic acid (DBA). The objective is to maximize the yield of MBA, which is a difficult problem because first there are two phases—gas and liquid—and second because the reactions and kinetics are complex. Further details are given elsewhere (14).

Let us first consider the performance of three of the most widely used conventional gas–liquid reactors, namely, a packed bed reactor, a mechanically agitated reactor, and a bubble column reactor (Fig. 8**a**). As shown, the mechanically agitated reactor has the apparent highest yield (73.8%) and would probably be selected for the application. However, optimizing the problem using the new methods—and without any commitment to a preferred or conventional reactor type—gives the design shown in Figure 8**b**. This has an MBA yield of 96.9%, which is a step change in performance, compared with the conventional designs. Note the reactor volume is smaller than those of the conventional designs. Of course, the design on the left is an ideal situation, which

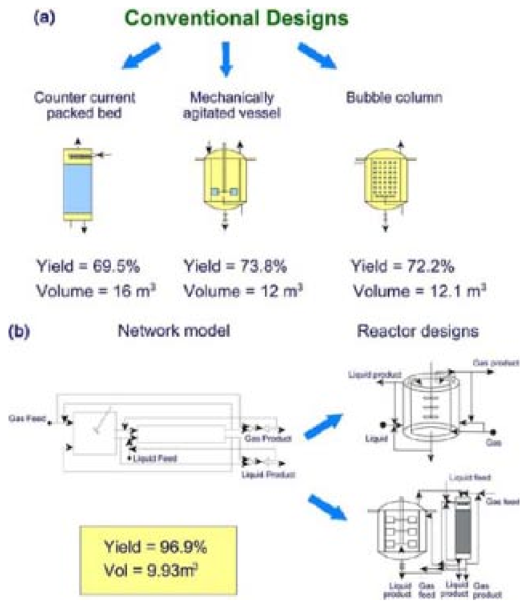


Fig. 8. (**a**) Conventional reactor performance for the chlorination of butanoic acid. (**b**) A novel solution shown as a network representation and as combinations of real reactors.

must then be translated into a workable design. Two possible designs using existing reactor types are shown on the right.

3.1.3. Design of Reactor–Separator–Recycle Systems

In most chemical processes, the effluent from the reactor is separated into products, by-products, and unreacted feed. The unreacted feed (and in some cases the by-products) can be recycled back to the reactor system. Until recently, very few systematic procedures have been proposed for the synthesis of reactor–separator–recycle systems. A newly developed approach proposes a general superstructure of different reactors and separation tasks and features all the potential interconnections among the proposed units. The approach has highlighted the importance of the coupling between the reaction and the separation system and confirmed the potential benefits of an integrated approach (15).

3.1.4. Reactive Distillation

Reactive distillation not only removes a step in a flowsheet by carrying out two operations in one unit, but also allows reactions with unfavorable equilibria to achieve higher reactor conversions and to improve reaction selectivity. The design issues in reactive distillation are significantly more complex than conventional distillation. Both homogeneous and heterogeneous catalysts can be used. In some applications the whole of the column is reactive. In others, only part of the column is reactive with conventional separation occurring in the nonreactive zones. Many design options are possible with different feed and product take-off arrangements. Intermediate heating and cooling can be carried out and recycles between different parts of the arrangement might be advantageous. This research identifies the optimal structural configuration and operating conditions for reactive distillation (16). Again, a more mathematical approach is adopted to deal with the complexities of such problems, incorporating physical insights into the problem formulation.

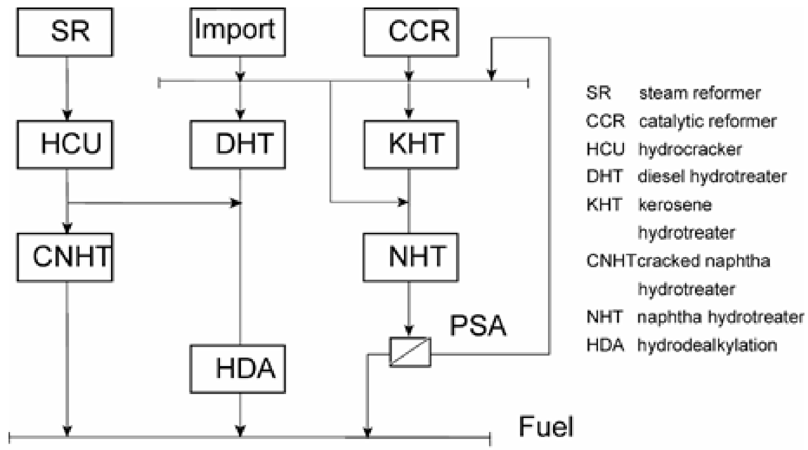


Fig. 9. A hydrogen distribution system in an oil refinery.

3.1.5. Design of Solvent-Based Separations

Previously, the selection of solvents has normally been left to experience or trial and error. A new approach has been developed for designing separation agents (17). Representing materials as a combination of functional groups identifies promising molecular structures. The most appropriate combination of functional groups is optimized to give material with the most desirable properties. Once a solvent has been selected, a flowsheet structure needs to be developed. The appropriate configuration with its recycles has a profound influence on the efficiency of the process and the potential for solvent losses. Systematic methods are now available developed for the design of optimum solvent-based separation processes such as MEN (18).

Hamad and co-workers (19) showed how to simultaneously synthesize MSAs and waste interception/mass exchange networks. Candidate chemical groups (eg, UNIFAC functional groups) are chosen as building blocks for the MSAs. Property structure correlations and thermodynamic models are used in order to predict mass exchange equilibrium. Finally, MSA solvent constraints are integrated with a network synthesis formulation in a mixed-integer nonlinear program that minimizes the cost of MSAs and network subject to technical requirements as well as safety and environmental constraints.

3.1.6. Hydrogen Integration in Oil Refining

Hydrogen is an important and very valuable utility in oil refining and petrochemicals processing. It is required for many operations such as hydrotreating (where it is used to remove impurities such as sulfur from streams and to hydrogenate aromatics and olefins) and hydrocracking (where it breaks down large hydrocarbons into smaller, higher value molecules). The hydrogen required is usually obtained as a by-product of catalytic re-forming or else imported or produced in a hydrogen plant such as a steam reformer. It is distributed among the consumers as illustrated in Figure 9.

Until recently, hydrogen availability was not a major issue for most refineries. However, several trends in the oil industry are leading to an increased demand for hydrogen in refineries and this changes the picture drastically. First, stricter legislation on sulfur content in fuels increases the need for hydrotreating. At the same time, regulations on gasoline aromatic composition are constraining re-former operation and removing some of the sources of hydrogen traditionally available to refineries. Second, the move to processing of heavier crude oils and the reduced market for heavy fuel oil is forcing greater use of hydrocracking for upgrading. Simply increasing the throughput of a refinery will also lead to increased hydrogen requirements, with the existing hydrogen production capacity often being a bottleneck.

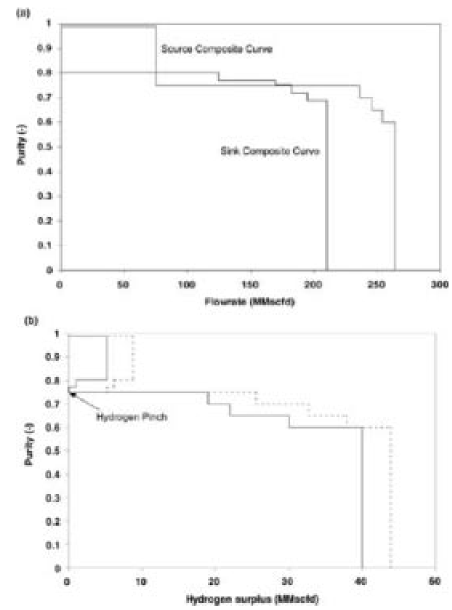


Fig. 10. (**a**) The hydrogen composite curves. (**b**) The hydrogen surplus diagram is used to target the minimum supply requirement. The dotted profile shows the existing case which is unpinched (ie, uses excess hydrogen). The supply flowrate is reduced until the surplus diagram just touches the vertical axis (ie, becomes pinched). This is the minimum feasible flowrate.

All of these factors can lead to a deficit in the hydrogen balance of a refinery, resulting in the need for investment in additional hydrogen production facilities (eg, steam re-forming) or else importing from outside suppliers—often involving expensive contracts. The requirements for additional production capacity or imports can be decreased—or even eliminated—by using the available hydrogen resources more efficiently.

A methodology has recently been developed for assessment of hydrogen resources, based on an analogy with the problem of process heat recovery (20). This method constructs hydrogen composite curves, showing the demands and sources of hydrogen on the site in terms of stream purities and flowrates (Fig. 10**a**). These are used to construct a hydrogen surplus diagram (Fig. 10**b**), which is analogous to the grand composite curve for energy systems. This diagram allows the engineer to find the “hydrogen pinch” and to set targets for hydrogen recovery, hydrogen plant production and import requirements.

This method also gives insights into the effective use of hydrogen purification units. It has been shown that a purification unit (eg, a pressure-swing adsorber, a membrane, or a cryogenic separator) should not be placed below the hydrogen pinch. Purifying gas above the pinch may have some benefits, but placing the purifier across the pinch is the best option (20).

The pinch approach is useful for conceptual purposes, but has some limitations when applied to real systems. For example, it does not take account of stream pressures and thus assumes that any source can be fed to any sink even if there is insufficient pressure. An improved approach has recently been developed (21), which can account for pressure and makes best use of the existing compressors in a refinery. This approach is mathematically based and can account for all important costs and tradeoffs including hydrogen production, compression power, fuel value and piping costs. It is well suited to both new design and retrofit studies.

3.1.7. Integrated Combined Cycle Gasification Processes

As a result of the worldwide trend toward stricter environmental regulations and increased demand for better quality products, Integrated gasification combined cycle (IGCC) technology has become an attractive option for the refining industry. Gasification converts the "bottom of the barrel" into valuable products such as hydrogen, clean fuel, and power. The major issues involved to establish IGCC as an economically viable process include selection of the best IGCC feedstock and better utilization of existing facilities. Methods have been developed to identify and remove bottlenecks to enhance throughput and also to optimize the unit connections, allocation of utilities and operating modes. This is aimed at increasing refinery economic margins.

3.2. Energy Efficiency

As mentioned earlier, this research theme really represents the roots of process integration. Much work involves separation systems with distillation being the most significant. Others are still concerned with heat recovery and utility systems, but now make far more use of mathematical methods than was previously the case. Specialized methods for retrofit have been developed.

3.2.1. Design of Complex Distillation Systems

It has become clear in recent years that complex column arrangements can significantly reduce distillation costs compared to systems comprising only simple columns (columns with one feed and two products) (see Distillation). Complex arrangements include prefractionators (and preflashes), side strippers, side rectifiers, and fully thermally coupled (Petlyuk and dividing wall) columns. Once these options are included, the number of possible configurations to be considered explodes and solving the problem by exhaustive enumeration becomes out of the question, even for small numbers of products. In addition, if thermal coupling is applied, then this introduces further constraints into the problem, as thermally coupled columns are most often constrained to work at the same pressure.

A screening method has been developed that allows promising structures to be synthesized for distillation systems ahead of any detailed design or simulation. It allows systematic development of performance targets and automated development of novel designs (22).

This approach is based upon a new representation, which incorporates all possible design alternatives. Figure 11 shows how this representation is used to synthesize sequences of simple columns to separate out five components. Note that discrete "tasks" are used instead of units and/or networks. All possible simple column sequences can be generated from this representation. For example, the direct sequence (ie, where the lowest boiling component is removed in each column) can be generated by selecting tasks 1, 8, 15, and 20, in that order.

As shown in Figure 12, complex column configurations can be derived by forming "hybrids" of separation tasks, which can be extended to systems performing sloppy or nonsharp separations by including more tasks in the hybrids. Where column pressure is another degree of freedom, this can be dealt with by introducing "clone" tasks at discrete pressure levels for all simple and hybrid tasks.

The reason for using the task representation is that a combination of tasks (supertask) is easier to model than a composite network of sequences. Also, the number of possible tasks increases much slower than the number of possible sequences when the number of components to be separated increases, which prevents the problem size from exploding.

Shortcut column calculations and cost correlations are used with a mixed-integer linear program (MILP) in order to generate a spectrum of cost-effective designs. Both capital and operating (energy) costs can be considered in the objective function. Promising structures can then be subjected to more detailed simulation and design.

A case study supplied by MW Kellogg will be used for illustration (23). This problem involved the separation of the effluent from a catalytic reformer. There were 22 components in the mixture and the product

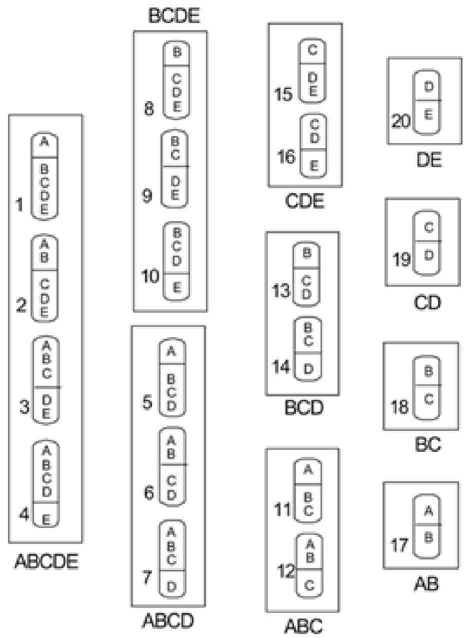


Fig. 11. A five-component separation problem shown as a task representation.

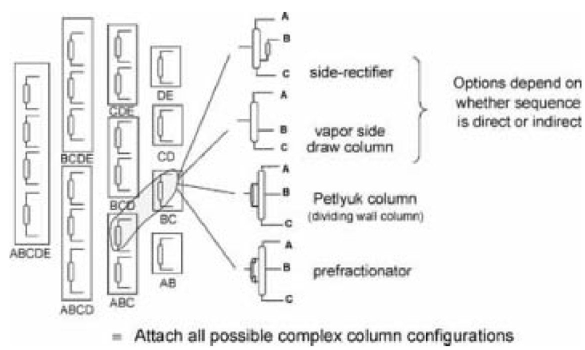
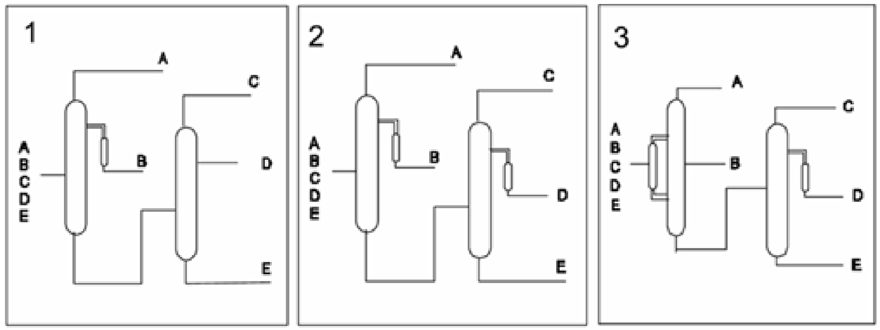


Fig. 12. Tasks can be merged to form hybrids to allow for complex configurations.

streams were also to be multicomponent. The new method generated the spectrum of design alternatives shown in Figure 13 in $<$ 2 min of computer time, even though the number of components was so large. The solutions are ranked in terms of energy cost, and it can be seen that they all offer significant benefits over the best sequence of simple columns. This approach has also been applied to subambient systems such as ethylene cold-end separation to give significant reductions in the refrigeration shaftwork requirements (24).

3.2.2. Dividing Wall Distillation Columns

The dividing wall column is a fully thermally coupled design, which combines a prefractionator with a main distillation column in a single shell. It has been established that energy savings of 30% are typical because of the prefractionation effect. In addition, the dividing wall column can in new designs save up to 30% of the capital cost compared with a conventional arrangement. Despite these benefits, industry has largely been reluctant



Order of solutions	Simulation energy cost Best simple sequence = 100%
1	74%
2	80%
3	82%

Fig. 13. Spectrum of design options for the catalytic re-former effluent separation problem.

to exploit this technology because it is unconventional. Until recently, there was a lack of reliable design procedures and a fear of control and operational problems. New design methods have recently been established (25) for fully thermally coupled designs, which optimize the design for minimum energy consumption and allow initialization for rigorous simulation. They also consider the heat integration potential of the configurations as well as the implications for control.

3.2.3. Separation of Azeotropic Mixtures

Many industrial distillation problems involve mixtures that form azeotropes (see Distillation, azeotropic and extractive). Several methods can be used to break the azeotrope, of which the most common is to add a mass separation agent, known as an entrainer. The choice of entrainer depends on the phase-equilibrium behavior of the system and the choice of compounds available. Pioneering work in the area of azeotropic distillation design includes that of Doherty, Stichlmair, Wahnschafft, and others. A comprehensive review is given by Widagdo and Seider (26).

More recent work (27,28) has developed automated design methods for the synthesis of azeotropic distillation sequences. These consider mass-transfer rates as well as equilibrium and can create new possibilities for column sequences that require less energy and lower entrainer flows. The techniques developed can be applied to any mass-transfer model or method of azeotropic distillation sequence design.

3.2.4. Thermodynamic Analysis of Distillation

Once the structure of the separation sequence has been determined, thermodynamic analysis can be applied to individual separators to improve both their inherent efficiency and their heat integration potential (29). The methods can now be applied to all types of column design including columns with multiple feeds and side draws and side strippers/rectifiers. Even the most complex arrangements such as those used in petroleum refining can now be analyzed (30).

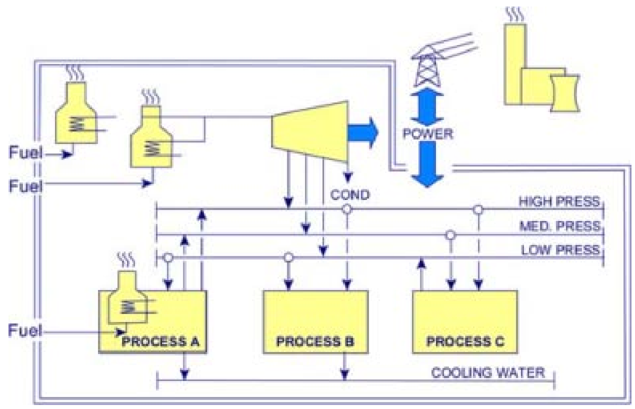


Fig. 14. A total site.

3.2.5. Design of Absorption Separation Systems

Physical absorption is the most commonly used alternative to distillation for the separation of light gases (see Absorption). Chemical absorption is an important operation for the separation of acid gases. New arrangements have been developed for the separation of acid gases to achieve extremely low outlet concentrations at low capital and energy cost and removes the need for downstream treatment (31). These include several different double-loop arrangements.

3.2.6. Cogeneration and Site Utility Systems

Processes operate in the context of a total site, in which a number of processes are linked to the same utility system (Fig. 14). The utility systems of most sites have evolved over a period of many years without fundamental questions being addressed as to the design and operation of the utility system. The picture is complicated by the growing trend of individual production processes on a site belonging to different business areas, each assessing investment proposals independently of one another and each planning for the future in terms of their own business. Yet the efficiency of the site infrastructure and the required investment is of strategic importance and must be considered across the site as a whole, even if this crosses the boundaries of different business areas.

Total site pinch analysis provided an overall picture of the site and utility system (2). The grand composite curves for each individual process were combined to produce site source and sink profiles (Fig. 15), which show clearly the site utility requirements in terms of temperature and enthalpy. These profiles allow targets to be set for utilities, fuel, emissions, cooling, and cogeneration.

This approach has seen many successful applications throughout the world. However, it does not completely account for the interactions between improved heat recovery on an existing site and the efficiency of cogeneration. A new site revamping methodology has recently been developed to achieve this and this is known as top-level analysis (32).

The original methods for site analysis required heat exchange data for every individual process and the data extraction for the whole site could therefore take several months. Also, the method often led to projects that could not be implemented because of constraints in the utility system, meaning a waste of effort. Finally, an expert user was needed to carry out the analysis.

In top-level analysis, the problem is literally flipped upside-down and uses the following strategy:

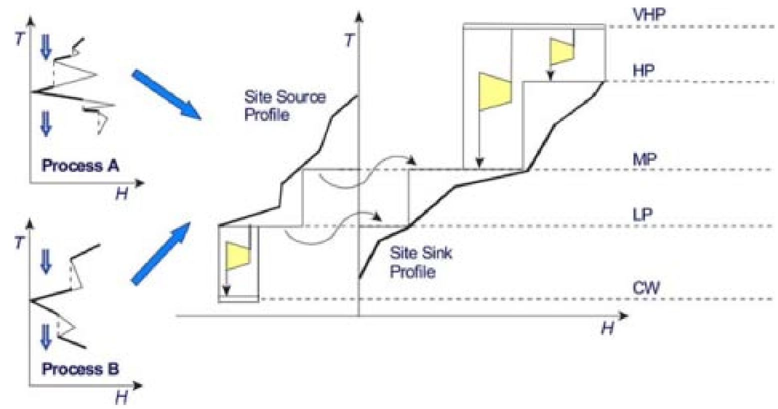


Fig. 15. The individual process grand composite curves are combined to produce the site source and sink profiles, giving targets for the site utilities, fuel, emissions, cooling, and cogeneration.

- Start with the *utility* system to establish the scope for improvement and economic directions in terms of specific energy saving targets.
- Use the economic directions to undertake process heat exchanger network retrofit and identify projects with minimum capital investment. (Incidentally, new methods for heat exchanger network retrofit have been developed in a separate project and will be mentioned later in this article.)

The procedure requires only utility data to begin with, which can usually be obtained in a matter of days. Once this has been obtained, the analysis then looks at the benefits that would be achieved by saving a certain utility (eg, steam at a particular pressure) in the processes. It is important to note that these energy savings cannot be directly converted to fuel savings and therefore cost savings as they can result in lower power generation on the site. Therefore, the tradeoff between fuel consumption and power generation needs to be studied.

To illustrate, consider the utility system shown in Figure 16. We would like to know the benefit of saving an amount, Q_{P}, of high pressure (HP) steam. As the diagram shows, this would result in a surplus of Q_{P} in the HP steam header. Now, there are two ways in which to exploit this surplus. It can either be saved (giving a fuel saving), or it can be used to generate extra power. Which is the better option will depend on fuel costs, power costs and the efficiency of the power generation equipment (eg, steam turbines). All the possible heat flow paths in the utility system are then analyzed and the surplus heat is shifted between these paths in order to find the most efficient option (Fig. 17). Note that limits on the utility system hardware are included here.

This analysis is carried out for all the utility levels and the results used to construct a financial benefits chart (Fig. 18), which sets out very clearly which steam levels are worth saving. It gives the maximum potential and financial benefit for saving steam and also includes the turbine performance and limitations. In this diagram, we see that HP steam is the most worthwhile to save and that a maximum saving of 30 t/h is possible or economic. After saving this, we see that we should then turn our attention to saving medium pressure (MP) steam, this time up to 35 t/h. It also shows that saving low pressure (LP) steam is not worth much, especially if the existing condensate return system is efficient.

Having found the correct directions, we can then extract the heat exchanger network data judiciously. We need only consider processes using HP and MP steam, but we will not even bother to collect data for those processes using LP steam. Bearing in mind that heat exchanger network data is by far the most time consuming to gather, this approach can save weeks or months of effort. Once this is done, methods exist for

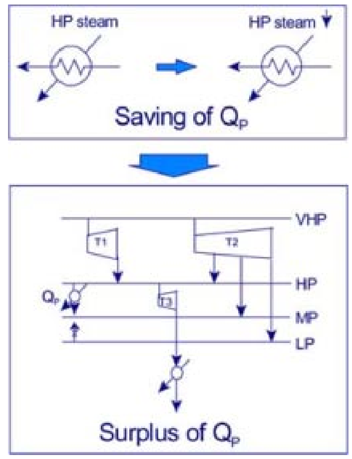


Fig. 16. Saving Q_P of HP steam means that there is a surplus in the steam header. How can we best exploit this surplus?

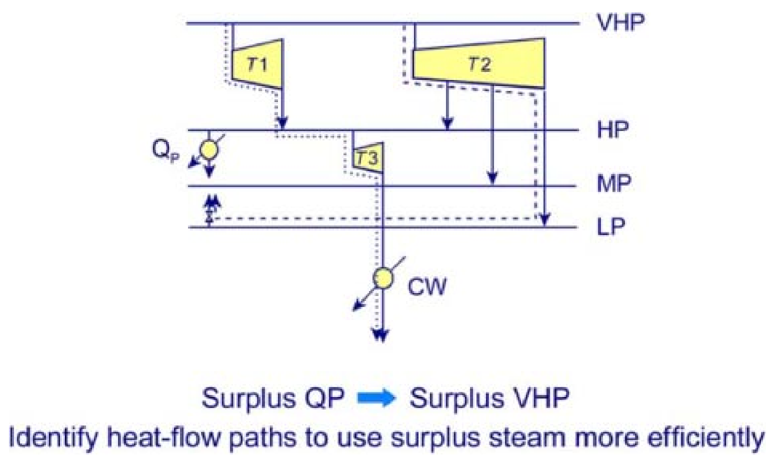


Fig. 17. Steam of a given level can be produced by several different routes or paths, which link boilers, turbines, and throttling valves. We can improve the performance of the utility system by maximizing steam flow through the most efficient paths. This figure shows an example of two paths.

achieving the steam savings, either by switching steam in utility exchangers or by improving the process heat recovery (33).

New tools have also been developed to determine the most appropriate number and levels of steam for the site and simultaneously the most appropriate cogeneration system of steam turbines and gas turbines. The total site technology can be used to reduce operating costs for an existing system, to determine and assess new investment proposals or to provide long-term investment plans for the infrastructure to allow for projected changes in the pattern of production.

3.2.7. Design of Cooling Water Systems

Recirculating cooling water systems are the most common method used to reject waste heat to the environment. The majority of designs employ networks of cooling water coolers that operate in parallel. Novel arrangements allow lower recirculation rates and better cooling tower performance. In debottlenecking situations, where

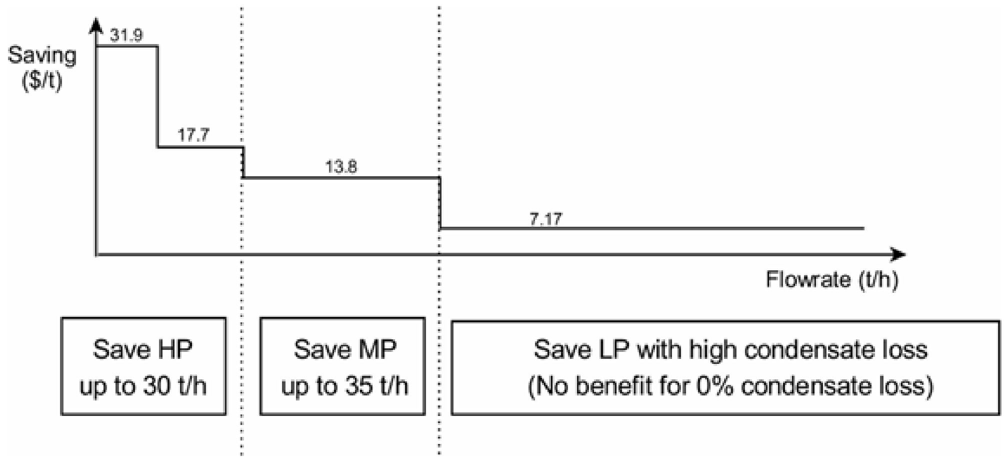


Fig. 18. The financial benefits chart shows which steam levels are most worth saving.

cooling tower capacity is limiting, it can allow increased capacity without investment in new cooling tower capacity. New methods have been developed for the design of cooling networks. Coupled with new models for the cooling tower, the interactions between the design of the cooling tower and the cooling network can now be explored systematically.

3.2.8. Design of Low Temperature Systems

The operating costs for low temperature (subambient) processes are usually dominated by the cost of power to run the refrigeration system. New methods have been developed recently to predict power requirements for refrigeration systems prior to design to within 3% of detailed simulation. The approach works for all refrigerant fluids and for all of the complex features found in refrigeration systems (eg, multiple levels, subcooling, economizers, presaturators, intermediate heat rejection, etc). Multiple levels of refrigeration and cascaded systems can also be considered. Even mixed-refrigerant compositions can now be optimized to achieve minimum power in mixed refrigerant systems (34).

El-Halwagi and Dunn (35, 36) discuss in detail how refrigeration systems can be designed to remove volatile organic compounds or "VOCs" from gaseous process streams. Their methodology considers integrating dehumidification of a VOC laden gas, process cooling, and refrigeration in order to minimize operating costs. Multiple refrigerants can be used and the best one(s) are selected using thermodynamic or mathematical methods. In addition to conventional refrigerants, new ones can be synthesized using methods discussed earlier (13).

3.2.9. Automatic Design of Heat Exchanger Networks

It is well known that rigidly following the pinch design method for heat-exchanger networks can lead to designs that are overly complex and potentially difficult to operate and control (see Heat-exchange technology, Network synthesis). This is not surprising, since the Pinch method is based on thermodynamics only and is essentially aimed at minimizing energy consumption. It is difficult to include considerations like constraints, equipment limitations, etc., in a thermodynamic approach and it was understood that the design method would need to be tempered with an engineer's insight, judgement, and common sense. Some attempts have been made to modify the pinch method, but these were all essentially still thermodynamic methods and suffered from the same inherent limitations.

A new, practical method has been developed for the automated synthesis of new heat exchanger networks. The new approach is based on a concept known as block decomposition (37). This concept uses physical insights from pinch analysis and decomposes the composite curves into a number of blocks, such that the streams in each block have similar characteristics. Each block will usually encompass several sections of the composite curves. In each block, a superstructure is used to represent the possible matches between streams. As a result, the combined superstructure for the overall problem is much simplified and thus the dimensions of the mathematical models are greatly reduced. The superstructure is then subjected optimization, which allows the automatic generation of optimal or near-optimal networks with a low number of units. These new techniques not only significantly enhance design capability but also allow for interaction. The designer has full control over network complexity to avoid impractical designs. In addition to trading off energy and capital costs, the new methods allow for multiple utilities, constrained matches, variable heat-transfer coefficients, and different cost laws for exchangers, producing designs that combine low cost with simple structures.

3.2.10. Retrofit of Heat-Exchanger Networks

Traditional industrial practice has been to use pinch analysis concepts, or a variation of these, to retrofit heat exchanger networks. However, this is not ideal as these methods in one way or another treat retrofit as a pseudo-new design, which does not account for the existing layout and equipment limitations.

New methods have been developed that are quite different from previous approaches in that the design starts from the *existing* network rather than the stream data. New approaches to retrofit have been developed both of which automate the procedures using a combination of thermodynamics and mathematical programming. One approach that has been applied successfully in industry locates the network pinch, which is the bottleneck on heat recovery in the existing network structure (38). This is not the same as the original Pinch (Fig. 2) and actually corresponds to a heat exchanger unit in the system. Structural changes to the network are required to overcome the network pinch. The retrofit design proceeds one modification at a time from the existing network. In this way, the designer can develop retrofit projects in full control with the number of network changes (eg, adding a new exchanger, exchanger relocation, stream splitting, etc) kept to a minimum.

3.2.11. Heat-Exchanger Network Design Using Intensified Heat Transfer

Heat transfer operations can be intensified through the use of compact heat exchangers and the use of heat-transfer enhancement techniques in conventional exchangers. The use of heat-transfer enhancement in heat-exchanger network retrofit is well established. Retrofit often calls for increased heat transfer area on existing units, which can, in principle, be achieved using heat-transfer enhancement techniques. We are now able to examine the use of intensified heat transfer—whether through the use of compact exchangers or heat-transfer enhancement techniques—as part of the overall approach for network design, such that they are used in a completely systematic way (39).

3.2.12. Power Station Design

The design of stand-alone power plants is significantly different from the design of cogeneration power plant. In the design of stand-alone power plants the efficiency of power generation is of paramount importance and even small percentage improvements in efficiency are important. Such power plant design is normally carried out by experienced power station designers, making extensive use of simulators to evaluate designs. A new systematic methodology has been developed, which uses a combination of thermodynamic analysis and mathematical programming for the conceptual design of power stations. Both new design and retrofit are considered. Applications have included gas turbine integration into existing power stations (40).

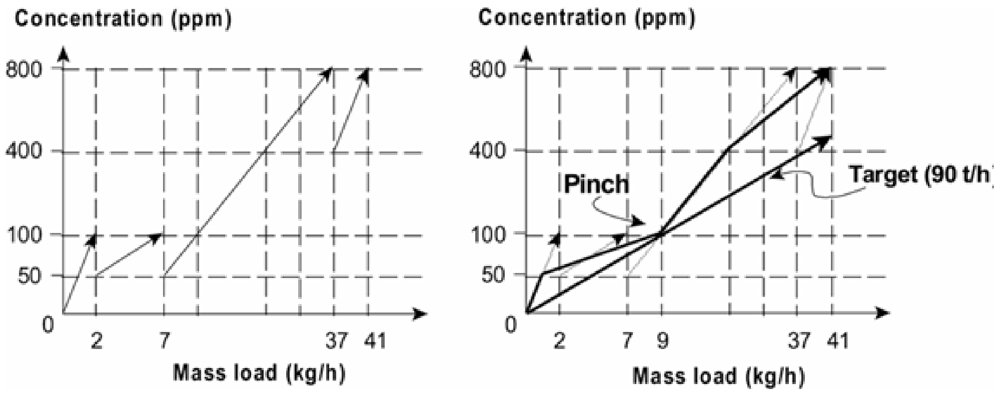


Fig. 19. In the graphical water pinch approach, the individual operations are combined to give a composite curve. The minimum water target is given by the inverse slope of the steepest line that can be drawn against the composite curve.

3.2.13. Heat Induced Separation System Design

Earlier, this article mentioned simultaneous heat and mass-transfer methods (8). These have been extended to design optimum heat induced separation networks. Examples include condensation, crystallization, and drying. The primary objective of these processes is to deliver a required mass recovery. However, heat is a key element in achieving the objective. It has been shown (41,42) how vapor pressure relations can be used to convert mass-transfer problems to heat transfer problems, which can then be solved using existing heat integration methods.

Pressure is an important factor in designing heat induced separation systems, particularly condensation. Streams can be pressurized in order to induce additional condensation. In some cases, streams following condensation can be throttled using turbines in order to recover work and may induce additional separation. These effects are discussed by Dunn and others (43,44) who investigate the tradeoffs between the cost of cooling, compression, and depressurization.

3.2.14. Emissions Reduction

Many environmental issues can be dealt with using recent process integration technology. In fact, El-Halwagi's book (10) places great emphasis on how process integration is used for pollution prevention.

3.2.15. Water System Design

In the past water, has been assumed to be a limitless low cost resource. However, there is now increasing awareness of the danger to the environment caused by overextraction of water. As a consequence, the price of fresh water for the process industries is escalating. In some locations it is likely that future increases in its use will be restricted. At the same time, the imposition of ever-stricter discharge regulations has driven up effluent treatment costs, requiring capital expenditure with little or no productive return. There is now considerable incentive to reduce both freshwater consumption and wastewater generation.

Water consumption can be minimized by maximizing the reuse of water (see Water supply and desalination). The approach is based upon analogies between heat and mass transfer (45). Figure 19 illustrates how various water-using processes can be combined to give a composite curve for the whole system, allowing targets to be set for minimum water supply. These targets can be met by following certain rules that give a network design (Fig. 20).

This conceptual work opened up an entirely new chapter for pinch analysis, but the original approach very rapidly ran into problems. First, it is very difficult to extend this method to deal with multiple components.

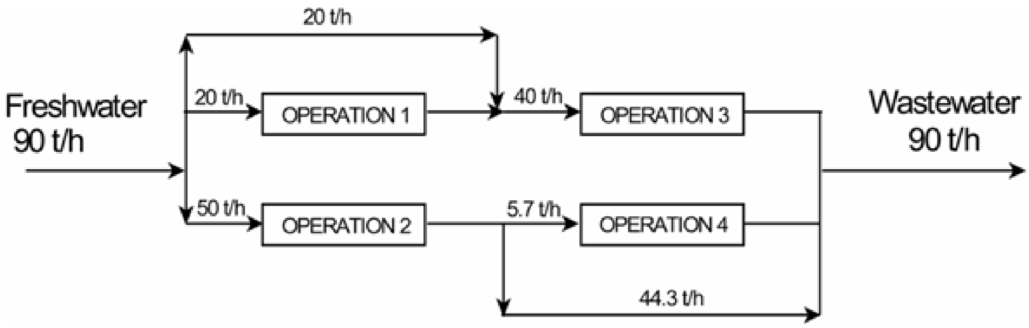


Fig. 20. One possible network design to meet the target of 90 t/h.

The two-dimensional graphical method works very well for heat transfer where there is only one transferred quantity—namely, energy—but real water systems feature several or even tens of species that are transferred simultaneously.

Also, flowrate constraints (ie, processes that demand a fixed or minimum flowrate of water) are also difficult to account for. Another problem is that of operation modeling. Some operations, eg absorbers, can be modeled as having a fixed mass-transfer load. However, other operations, such as reactors or hosing operations cannot be modeled as primarily mass-transfer operations. Add to this the need to include practical constraints (eg, forbidden matches, forced matches, complexity constraints, etc) as well as capital costing (eg, for pipes, sewers, treatment plants, etc) and the simple water pinch approach simply cannot cope.

A recently developed approach uses mathematical programming. First, each water-using operation is described by a model, which can be different for different contaminants. Then, a superstructure containing all possible connections is set up as shown in Figure 21**a**. Note that this structure includes all conceivable use, reuse, recycling, and discharge alternatives, which is then optimized as a mathematical program, which is usually a combination of a MILP and a nonlinear program (NLP). This gives an optimum network design as in Figure 21**b**. Details of the optimization are given elsewhere (46). This approach can handle all the difficulties mentioned earlier, which the pinch approach could not. Furthermore, the use of mathematical programming does not mean that the insights from the graphical method need to be sacrificed. It has been shown (46) how the output from the optimization can be used to build up a composite curve for the water system, thus retaining the graphical representation.

Industries such as specialty chemicals, pharmaceuticals, textiles, food and beverage, brewing, distilling, and dairies, make extensive use of hot water for washing and sterilization operations. In these industries it is most effective if energy and water management are considered together. Methods now exist for simultaneous energy and water minimization (47). These consider isothermal and nonisothermal mixing of water streams with indirect heat recovery to ensure that energy and water targets are met with the simplest possible design.

Effluent treatment can also be handled. A similar approach can be used to design optimum treatment processes for a set of effluent streams. The essence of the method is to use distributed treatment instead of centralized treatment. In this approach, effluent streams are combined for treatment where necessary, but segregated if that is appropriate. This can reduce the volume to be treated, and hence the cost.

More recent work has considered the water use and treatment networks as one total water system, which is important because water treatment does not have be limited to effluent streams. A treatment process can instead be used to regenerate water so that it can be reused or recycled within the water use network. Once again, a superstructure approach is used, but this is now a far more comprehensive and complex structure (see Fig. 22). As before, all relevant costs and constraints can be included.

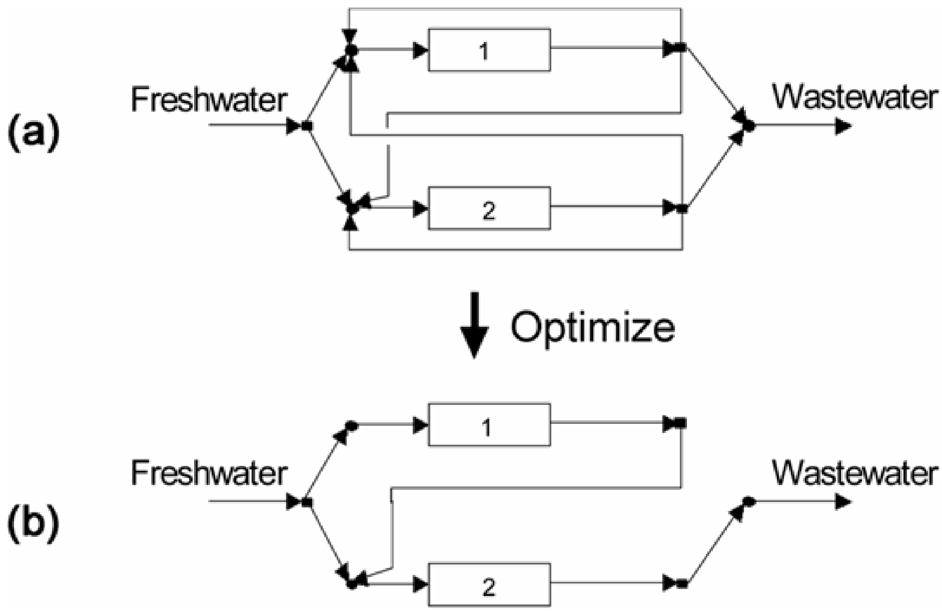


Fig. 21. (**a**) Superstructure for two water-using operations and one freshwater source. (**b**) Final design following mathematical optimization.

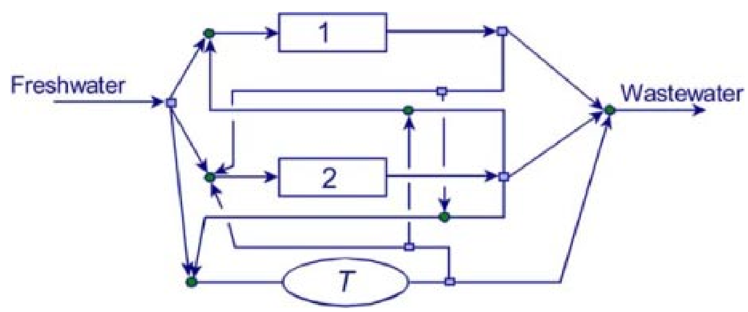


Fig. 22. Superstructure including the use of treatment/regeneration.

Dunn and other workers recently published a very good review of the available water network design methods from an industrial point of view. They have discussed single contaminant systems (48) and multicomponent ones (49) and have presented several industrial case studies.

3.2.16. Minimization of Flue Gas Emissions

Environmental concerns now require that the flue gas emissions resulting from the supply of energy to processes should be minimized. A method now exists for site utility system design to meet the appropriate discharge regulations at minimum cost (50). This uses a combination of physical insights and mathematical programming is used to find the best strategy, which will be a combination of changing fuel, modifying the utility system, process changes, improved heat recovery, cogeneration, and chemical treatment. The emphasis of the method lies in achieving flue gas limits with lower capital investment compared with conventional approaches and potentially making operating cost savings at the same time. Both new design and retrofit are considered.

It seems likely that there will be many more applications for reduction in flue gas emissions in the future as governments seek to reduce national levels for the emissions of greenhouse gases.

Many of the developments that were discussed earlier in this article can have environmental benefits even though they do not fall under emissions reduction. An excellent case is the design and optimization of chemical reactors. Better reactor design can without a doubt be used for waste minimization, if it increases the conversion and yield of desired products and thus reduces the unreacted feed or waste by-products that might ordinarily be emitted. El-Halwagi (10) shows many cases where better process integration leads naturally to pollution prevention. Technologies such as waste interception networks are aimed directly at reducing emissions. The technology developed for VOC recovery also has strong environmental benefits.

3.3. Process Operations

Early process integration work was concerned largely with conceptual design and did not really concern itself with day-to-day operations and planning. Now, however, major contributions have been made in this area too.

3.3.1. Process Optimization for Commodity Chemicals

A significant problem with the design and optimization of commodity chemical processes is that the prices of feeds and products fluctuate over time. This project provides an analysis that is simple to carry out and can be used to design flexible processes that achieve maximum profitability under a wide range of conditions. Variations in prices are represented in a simple, graphical manner that rapidly identifies the economic conditions that a process is likely to encounter while eliminating the need for price forecasts. This graph can be used to suggest alternative designs that offer flexibility if certain conditions are likely to occur. It can also be used to find the optimum capacity for a new plant and the optimum size of expansion for an existing one (51).

3.3.2. Refinery Optimization and Debottlenecking

An oil refinery is an extremely complex process (Fig. 23) (see Petroleum refinery processes). Profitable operation of a refinery requires an optimization of stream flows and process feeds. Most crude oils offer considerable flexibility in cut points, and many refineries are also able to handle a number of different crude oils. The optimization of the stream flows is constrained by the capacities of the refinery equipment and by the desired specifications of the refinery products. A new methodology has been developed involving three levels of analysis and optimization, which takes into account all of the utility and process interactions (52). As shown in Figure 24, the refining processes, heat-exchanger networks, utility system, and hydrogen network are all considered as one system. The aim is not simply to *save* energy or hydrogen, but rather to use these more efficiently in order to improve profitability, which can take the form of throughput increases, better product slates, or reduced feedstock costs.

Current operations are first optimized using models of the operations that allow for discrete (on–off) effects as well as continuous changes. The second level identifies major bottlenecks and near-bottlenecks. The third level provides a strategy for debottlenecking by considering changes in operating conditions, transferring bottlenecks from expensive to less expensive equipment, and making structural changes. The optimization provides an investment strategy for the short, medium, and long term.

3.3.3. Optimal Scheduling, Design, and Operation of Batch Processes

The technology for the scheduling and planning of batch operations should, in general, take account of many issues in the supply chain. These include the supply of raw materials, through to the process units to be used in the manufacturing, the storage and packaging operations, the transportation systems used for delivery of the products, and the delivery schedules for the customers. A novel method has been developed to solve such problems (53). It uses system information and novel representations that exploit the process logistics,

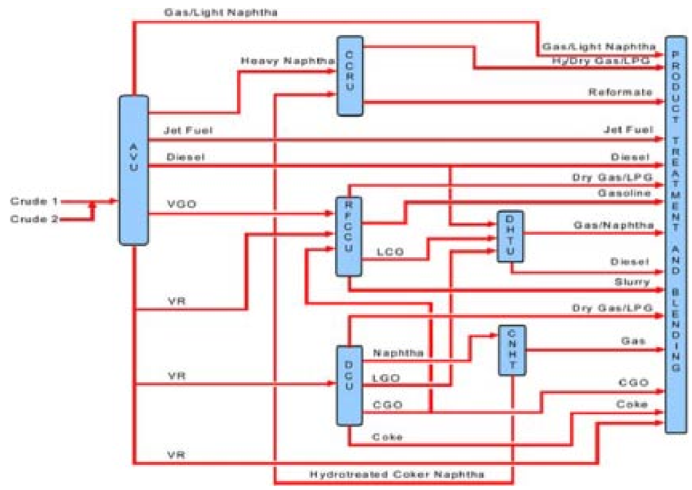


Fig. 23. Schematic diagram of an oil refinery.

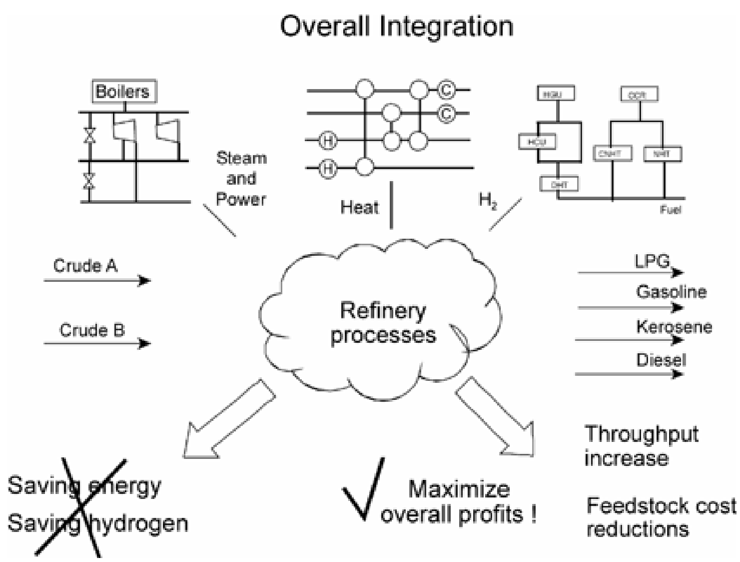


Fig. 24. The refinery comprises several subsystems, which must be optimized together, not in isolation in order to exploit the synergies between them.

resulting in dramatic improvements in the potential of the mathematical methods. It is capable of providing rapid solutions where conventional technology completely fails.

3.3.4. Operability of Cogeneration and Site Utility Systems

Variation in operation is the norm for many processes, whether continuous, semicontinuous, or batch. Such variations may be the result of a different feed, a change in the operating conditions, decrease or increase in throughput, shutdown of units for maintenance, etc. These variations will create varying demands on the utility system. As the utility system is required to supply the heat and power demands, it is important that the utility system is flexible enough to meet varying process demands in a cost-effective way. The design of site utility systems can now take account of operational variations (54). Optimized maintenance schedules for the utility system can also be developed.

4. Technology Transfer and Application

The challenge with research in process integration is always to ensure that it works in practice. The only way to achieve this is to follow research through to application. The applications experience then needs to feed back into the research.

The UMIST group has achieved this via the process integration research consortium. In this model, a group of 30 major companies from around the world sponsor the research and work closely with the researchers on the first applications of the new technology. AspenTech is a member company and has become the world leader in the application of process integration technology.

The consortium provides considerable financial and technical support for the UMIST research program, and in return receives a number of significant benefits, including specialized software packages. As this article has tried to emphasize, process integration technology now makes significant use of mathematical programming and optimization methods. The power of these methods is undeniable, but these are virtually impossible to apply without the use of computer software. It is worth mentioning that member companies including AspenTech have developed several commercial packages from the research.

The close industrial links and feedback ensure that the research is practically oriented and is able to help engineers solve real problems. AspenTech's advanced process design group offers consulting services in many of the areas discussed in this article. Major projects include ethylene plant debottlenecking, refinery-wide energy and hydrogen management as well as utility system optimization. The group has been very successful in enhancing the technology developed by UMIST thanks to Aspen's actual industrial project experience as well as software development resources.

For those interested in finding out about education in process integration, Gundersen (55) provides a comprehensive and up-to-date review of standard curricula, conferences, and textbooks.

4.1. Some Applications

Pinch analysis itself has had an enormous amount of application, with thousands of projects having been carried out all over the world in a wide range of industries such as chemical, petrochemical, petroleum, food and drink, pulp and paper, steel, etc. Motivations have included energy cost savings, debottlenecking for increased throughput, and reduction in flue gas emissions (2). Such companies as Shell, Exxon, BP-Amoco, Neste Oy, and Mitsubishi have reported fuel savings of up to 25% and similar emissions reductions, worth millions of dollars per year. Here, we will look at how some of the state-of-the-art technologies discussed in this article are being applied.

The distillation design work has seen successful industrial applications by consortium members. The dividing wall column technology was recently applied to BP-Amoco's Coryton refinery in the United Kingdom. The application, carried out in collaboration with MW Kellogg, was featured in *European Chemical News* (56), who reported that "successful trials ··· indicate that MW Kellogg's divided wall column distillation technology can provide a significant increase in fractionation performance at a lower capital cost than conventional alternatives. The modification doubled the capacity of the column and increased the middle distillate yield by 50% with a payback < 1 year and *with no operating and control problems*. In addition, the azeotropic distillation techniques have been applied in several successful joint projects with other members.

Although the reactor system design technology is very new, it has already seen two main applications. These were both carried out jointly with UOP.

The new heat integration and utility system work has also already seen several applications. Top-level analysis has had successful applications even though it is relatively new. The low temperature system design has been applied to ethylene and LNG systems. The new heat exchanger network retrofit methods are well established and are now included in commercial software packages. Powergen has collaborated on the application of the power station design technology.

The water system design methodology has met with very impressive success, with Unilever reporting reductions of 50% in freshwater demand and 65% in wastewater production (57).

The newest member of the pinch family, hydrogen pinch, has already been taken on board by AspenTech and has been applied successfully on projects in Europe, the United States, the Far East, and South Africa. The technology can be used to achieve several objectives. First, it can be used simply to save hydrogen and has given benefits of hundreds of thousands if not millions of dollars per year. However, it can also be used to meet new fuel specifications with a minimum level of capital investment. Similarly, it can be used to increase the refinery throughput as well as to provide the flexibility to process various oils and to change the product spectrum for improved profitability. This is done by optimizing the partial pressure of hydrogen in the appropriate reactors. AspenTech has powerful software tools for kinetic reactor modelling (eg, Aspen Hydrotreater, Aspen Hydrocracker) as well as refinery optimization (eg, Aspen PIMS). These tools are now used alongside hydrogen pinch software in order to carry out true optimization. Again, these benefits can be worth millions per year.

Mitsubishi Chemical Corporation report that using the new methods developed for process scheduling and supply chain optimization, the company "can reduce delivery cost by 20–30 million Yen ($\sim$ $200,000–300,000) per year" (58).

The mass integration work pioneered by UCLA and Auburn University has also seen very successful applications in many industries. A recent article by El-Halwagi and Spriggs (59) discusses some of them.

5. Conclusions

In this article, we have seen two major recent trends, first, the use of a wider range of solution methods and second, the broader scope of problems that are addressed. Clearly, process integration technology has come a long way over the last few years and can no longer be thought of as being synonymous with pinch analysis. However, there are still some areas for future development (60).

The first relates to the philosophy of targeting before design. Current methods still attempt, where possible, to use a two-step approach to design. First, performance targets are set to scope and screen options. Then, once the important options have been screened a design method is used to achieve the targets. In the future, it seems probable that the boundary between targets and design will be blurred and that these will be based on more structural information regarding the process network.

Second, it is likely that we will see a much wider range of applications of process integration. There is still much work to be carried out in the area of separation, not only in complex distillation systems but also separation systems involving mixed types of separation, which includes processes involving solids, such as flotation and crystallization. The use of process integration techniques for reactor design has seen rapid progress, but is still in its early stages. Further work on simultaneous reaction and separation is needed. Process integration will be increasingly applied to process operations. Safety and control have still to be addressed adequately. Also, we should also not lose sight of the work still left to do in energy efficiency and emissions reduction.

Third, a new generation of software tools is expected. The emergence of commercial software for process integration is fundamental to its wider application in process design. While simulation tools are now becoming quite mature and well developed, process integration software is less developed. AspenTech is a world leader in providing simulation software, and also continues to develop process integration packages. Developments in open architecture (Fig. 25) are allowing process integration software to interact on-line with simulation

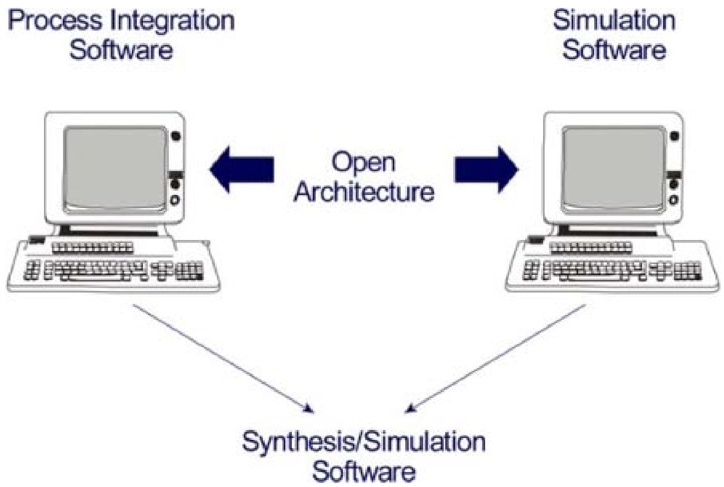


Fig. 25. In the future, process integration software should fit seamlessly with process simulation software.

software to access physical property data and simulation models. This will make a wider range of models available to process integration algorithms and reduce the amount of work and expertise required to use process integration.

A recent discussion at the PI'99 Conference on Process Integration in Copenhagen (61) concluded the following:

- The awareness of the public with regard to process integration should be increased.
- The significantly broadened scope of process integration should be disseminated. Emphasis should no longer be on energy savings in isolation. Hopefully, this article will go some way to exposing users to the wider range of tools and applications.
- There is a need for introductory courses in industry that make engineers familiar with, but not necessarily experts in process integration. Universities and companies such as AspenTech do provide these for a range of topics.
- Software packages are essential for process integration to be usable by nonexperts and AspenTech has been heavily involved in this for some time.
- There is a need for new methods and software tools with respect to cost estimation. This is particularly true in retrofit situations, where piping and layout considerations are important.
- There is a fear that heavily integrated processes will be impossible to operate, which is a misconception. In the experience of AspenTech engineers, there is no inherent link between integration and operability. Poorly designed processes are hard to operate, regardless of integration. Process integration technology combined with practical knowledge and experience has consistently led to processes that are efficient, but also operable, controllable and flexible.
- A diversity of applications should be collected and disseminated as a track record. (This article goes some way toward doing this.)
- Demonstration projects should be carried out in industries where there has been little use of process integration in order to establish new success stories or alternatively identify limitations of current methods and software tools.

BIBLIOGRAPHY

Cited Publications

1. R. Smith, *Chemical Process Design*, McGraw-Hill, Singapore, 1995.
2. B. Linnhoff, *Chem. Eng. Progress*, **90**(8), 33 (Aug. 1994).
3. I. Grossman, J. Caballero, and H. Yeomans, *Advances in Mathematical Programming for Automated Design, Integration and Operation of Chemical Processes*, presented at PRES ′99, 2nd Conference on Process Integration, Budapest, Hungary, May 1999.
4. M. M. El-Halwagi and V. Manousiouthakis, *AIChE J.*, **35**(8), 1233 (1989).
5. M. M. El-Halwagi and V. Manousiouthakis, *Chem. Eng. Sci.*, **45**(9), 2813 (1990).
6. M. M. El-Halwagi, and V. Manousiouthakis, *AIChE J.*, **36**(8), 1209 (1990).
7. M. M. El-Halwagi and B. K. Srinivas, *Chem. Eng. Sci.*, **47**(8), 2113 (1992).
8. B. K. Srinivas and M. M. El-Halwagi, *Chem. Eng. Sci.*, **49**(13), 2059 (1994).
9. M. M. El-Halwagi, A. A. Hamad, and G. W. Garrison, *AIChE J.*, **42**(11), 3087 (1996).
10. M. M. El-Halwagi, *Pollution Prevention through Process Integration: Systematic Design Tools*, Academic Press, San Diego, Calif., 1997.
11. N. Hallale, Capital Cost Targeting for the Optimum Synthesis of Mass Exchange Networks, Ph.D. Thesis, University of Cape Town, 1998.
12. E. W. Crabetree and M. M. El-Halwagi, *AIChE Symp. Ser.* **990**, 117 (1995).
13. L. Constantinou, C. Jacksland, K. Bagherpour, R. Gani, and L. Bogle, *AIChE Symp. Ser.* **990**, 105 (1995).
14. V. Mehta and A. Kokossis, *A Systematic Framework for Development of Novel Multiphase Reactor Designs*, presented at IChemE Research Event, Newcastle, U.K., April 1998.
15. P. Linke, V. Mehta, and A. Kokossis *Synthesis of Reaction / Separation Systems Using a Systematic Approach*, presented at AIChE Spring Meeting, Houston, Tex., Mar. 1999.
16. P. Linke, V. Mehta, and A. Kokossis, *A Novel Approach for Synthesis of Reactive Distillation Systems*, presented at AIChE Spring Meeting, Houston, Tex., Mar. 1999.
17. E. Marcoulaki and A. Kokossis, *Computers Chem. Eng.*, **22**, Suppl., S11 (1998).
18. N. Hallale and D. Fraser *Computers Chem. Eng.*, **23**, Suppl., S165 (1999).
19. A. A. Hamad and M. M. El-Halwagi, *Trans. IChemE* (Part B), 376 (1998).
20. J. Alves, *Analysis and Design of Refinery Hydrogen Distribution Systems*, Ph.D. Thesis, UMIST, U.K., 1999.
21. N. Hallale and F. Liu, *Adv. Environ. Res.*, **6**, 81 (2001).
22. P. Shah and A. C. Kokossis, *Conceptual Programming: Towards the Development of New Targeting and Screening Technology Using Engineering and Optimization Methods*, presented at IChemE Research Event, Newcastle, U.K., April 1998.
23. P. Shah and A. Kokossis, *Computers Chem. Eng.*, **23**, Suppl., S137 (1999).
24. P. Shah and A. Kokossis, *Computers Chem. Eng.*, **23**, Suppl., S895 (1999).
25. K. Amminudin, *Design and Optimisation of the Dividing Wall Column*, Ph.D. Thesis, UMIST, U.K., 1999.
26. S. Widagdo, and W. Seider, Azeotropic Distillation, *AIChE J.*, **42**(1), 96 (1996).
27. F. Castillo, D. Thong, and G. Towler, *Ind. Eng. Chem. Res.*, **30**(3), 987 ().
28. D. Thong, *Multicomponent Azeotropic Distillation Design*, Ph.D. Thesis, UMIST, U.K., 2000.
29. F. Soares Pinto, *Thermodynamic Analysis of Distillation*, Ph.D. Thesis, UMIST, U.K., 1998.
30. K. Liebmann, *Integrated Crude Oil Distillation Design*, Ph.D. Thesis, UMIST, U.K., 1997.
31. G. Towler, H. Shethna, B. Cole, and B. Hajdik, *Improved Absorber-Stripper Technology for Gas Sweetening to Ultra-Low H_2S Concentrations*, presented at the Gas Processors' Association Annual Meeting, San Antonio, Tex., Mar. 1997.
32. Y. Makwana, R. Smith, and X. Zhu, *Computers Chem. Eng.*, **22**, Suppl., S793 (1998).
33. X. Zhu and L. Vaideeswaran, *Recent Research Development of Process Integration in Analysis and Optimization of Energy Systems*, presented at PRES '99, 2nd Conference on Process Integration, Budapest, Hungary, May 1999.
34. G. Wu *Design and Retrofit of Integrated Refrigeration Systems*, Ph.D. Thesis, UMIST, U.K., 2000.

35. R. F. Dunn and M. M. El-Halwagi, *Waste Mgt.* **14**, 103 (1994).
36. R. F. Dunn and M. M. El-Halwagi, *J. Haz. Mtls.*, **38**, 187 (1994).
37. X. Zhu, B. O'Neill, J. Roach, and R. Wood *Trans. IChemE* (Part A)., **73**(8), 919 (1995).
38. N. Asante and X. Zhu *Trans. IChemE* (Part A), **75**, 349 (1997).
39. X. Zhu, M. Zanfir, and J. Klemes, *Heat Transfer Enhancement for Heat Exchanger Networks Retrofit*, presented at CHISA '98, 13th International Congress of Chemical and Process Engineering, Czech Republic, Aug. 1998.
40. J. Manninen and X. Zhu, *Computers Chem. Eng.*, **22**, Suppl., S537 (1998).
41. M. M. El-Halwagi, B. K. Srinivas, and R. F. Dunn, *Chem. Eng. Sci.*, **50**, 81 (1995).
42. R. F. Dunn and B. K. Srinivas, *Adv. Environ. Res.*, **1**, 275 (1997).
43. R. F. Dunn, M. Zhu, B. K. Srinivas, and M. M. El-Halwagi, *AIChE Symp. Ser.* **990**, 74, (1995).
44. R. F. Dunn, A. A. Hamad, and A. M. Dobson, *Clean Products Processes*, **1**(2), 91 (1999).
45. Y. Wang and R. Smith, *Chem. Eng. Sci.*, **49**(7), 981 (1994).
46. S. Doyle and R. Smith, *Trans. IChemE* (Part B), **75**, 181 (1997).
47. L. Savalescu and R. Smith, *Simultaneous Energy and water Minimization*, presented at AIChE Annual Meeting, Miami Beach, Fla., Nov. 1998.
48. R. F. Dunn and H. Wenzel, *Clean Products Processes*, **3**(3), 307 (2001).
49. R. F. Dunn, M. Overcash, and H. Wenzel, *Clean Products Processes*, **3**(3), 319 (2001).
50. H. Singh, R. Smith, and X. Zhu, *Computers Chem. Eng.*, **33**, Suppl., S917 (1998).
51. K. Boccara and G. Towler, *Ind. Eng. Chem. Res.*, **36**, 3727 (1997).
52. J. Zhang, *Refinery Optimization and Debottlenecking*, Ph.D. Thesis, UMIST, U.K., 1999.
53. S. Mokashi and A. Kokossis, *A Tailored Graph-Based Method for the Optimal Scheduling of Product Distribution Lines*, presented at the IChemE Research Event, Newcastle, U.K., April 1998.
54. S. Mavromatis and A. Kokossis *Chem. Eng. Sci.*, **53**(7), 1405 (1998).
55. T. Gundersen, *From Gothenburg '92 to Copenhagen '99—Major Trends and Developments in Process Integration*, presented at PI'99 International Conference on Process Integration, Copenhagen, Denmark, Mar. 1999.
56. *European Chemical News* (28 September 1998).
57. R. Hamilton, and D. Dowson, *The Chem. Eng.*, 566, 21 (1994).
58. Y. Yokomizo, Mitsubishi Chemical Corporation, 1996.
59. M. El-Halwagi and H. Spriggs, *Chem. Eng. Prog.*, **94**(8), 25 (Aug. 1998).
60. R. Smith, *State of the Art in Process Integration*, presented at PRES '99, 2nd Conference on Process Integration, Budapest, Hungary, May 1999.
61. Group Discussions, PI'99 International Conference on Process Integration, Copenhagen, Denmark, Mar. 1999.

NICK HALLALE
AspenTech Ltd.

Related Articles

Reactor Technology; Heat Exchanges, technology network Systems; Energy management; Process control; Process energy conservation, Pinch technology