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Review

Process integration technology review: background and applications in the chemical process industry

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Abstract: Process integration is a holistic approach to process design and operation which emphasizes the unity of the process. Process integration design tools have been developed over the past two decades to achieve process improvement, productivity enhancement, conservation in mass and energy resources, and reductions in the operating and capital costs of chemical processes. The primary applications of these integrated tools have focused on resource conservation, pollution prevention and energy management. Specifically, the past two decades have seen the development and/or application of process integration design tools for heat exchange networks (HENs), wastewater reduction and water conservation networks, mass exchange networks (MENs), heat- and energy-induced separation networks (HISENs and EISENs), waste interception networks (WINs) and heat- and energy-induced waste minimization networks (HIWAMINs and EIWAMINs), to name a few. This paper provides an overview of some of these developments and outlines major driving forces and hurdles. The fundamental aspects of this approach along with their incorporation in an overall design methodology will be discussed. The paper also highlights several recent applications of process integration to industrial processes.

Keywords: process integration; pinch technology; energy conservation; wastewater minimization

INTRODUCTION

In response to the staggering environmental and energy problems associated with manufacturing facilities, the process industry has recently dedicated much attention and resources to mitigating the detrimental impact on the environment, conserving resources, and reducing the intensity of energy usage. These efforts have gradually shifted from a unit-based approach to a systems-level paradigm. Therefore, the past decade has seen significant industrial and academic efforts devoted to the development of holistic process design methodologies that target energy conservation and waste reduction from a systems perspective. Nonetheless, in order to undertake any holistic modifications that deal with the core processing units, it is inevitable to fully understand and appreciate the integrated nature of the process. Changes in a unit or a stream often propagate throughout the process and can have major implications on the operability and profitability of the process. Furthermore, the various process objectives (eg technical, economic, environmental, and safety) must be integrated and reconciled. These challenges call for the application of a systematic and generally applicable approach that transcends the specific circumstances of the process and views the environmental, energy, and resource-conservation problems from a holistic perspective. The above-mentioned challenges can be addressed via a unique framework of design methodologies that are collectively referred to under the general heading of *process integration* design methodologies.

Process integration is a holistic approach to process design and operation that emphasizes the unity of the process.[1] It can be broadly categorized into mass integration and energy integration. Mass integration is a holistic approach to the generation, separation, and routing of species and streams throughout the process. It has been developed and applied to identify global insights, synthesize strategies, and address the root causes of the environmental and mass-processing problems at the heart of the process. Mass integration is a systematic methodology that provides a fundamental understanding of the global flow of mass within the process and employs this understanding in identifying performance targets and optimizing

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the allocation, separation, and generation of streams and species.[2] In the environmental context, the development of the methodologies for waste reduction (*mass integration*) has been driven by the promulgation of more stringent environmental regulations coupled with the desire to improve industrial competitiveness. In the past, for waste reduction tasks, the industrial goal was to identify a recovery system that would effectively allow the recycle and reuse of certain wastes. This goal was generally accomplished by postulating a variety of process system configurations and operating conditions and then individually screening these alternatives to evaluate their overall economic impact to the company (operating cost, capital investment, etc). Recently, significant progress has been made toward developing systematic design methodologies that not only identify a system that accomplishes the waste reduction task, but also a system that represents the most cost-effective approach. The primary focuses of these efforts have been toward the development of systematic design methodologies for identifying cost-effective wastewater minimization systems, end-of-the-pipe separation and recycle systems and in-plant separation systems. The other important category of process integration is energy integration that deals with the global allocation, generation, and exchange of energy throughout the process.[3,4] The development of the methodologies for energy conservation (*energy integration*) has been driven by the increasing demand for expensive utilities within chemical industries. A review of some of the process integration design tools for addressing energy conservation and waste reduction is provided in the following sections.

PROCESS INTEGRATION TOOLS FOR DESIGNING ENERGY CONSERVATION SYSTEMS

During the past decade, rising energy costs have required operating companies to look for ways to improve energy conservation. Energy integration deals with all forms of energy such as heating, cooling, power generation/consumption, pressurization/depressurization, and fuel. Much of the effort in this area has been directed toward increasing heat recovery in chemical processes. Industrial heat exchange networks, 'HENs', are of particular importance because of their role in recovering process heat. An HEN is a network consisting of one or more heat exchangers that collectively satisfy the energy conservation task. Therefore, in most chemical process industries it is necessary to synthesize cost-effective HENs that can transfer heat among the hot and cold streams (temperature conditions refer to the initial stream state). During the design stage, temperature specifications for the hot and cold streams must be met and a decision must be made regarding the use of a process stream or an external utility (eg steam, cooling water, etc) to accomplish the required heat duty. Even in relatively simple situations, the problem of pairing and sequencing of exchanger streams becomes a large one and the use of systematic techniques is necessary. Figure 1 is included as a general representation of the HEN synthesis task.

For a given system, the synthesis of HENs entails answering several questions including:

- Which heating/cooling utilities should be employed?
- What is the optimal heat load to be removed/added by each utility?
- How should the hot and cold streams be matched (ie stream pairings)?
- What is the optimal system configuration (eg how should the heat exchangers be arranged?, is there any stream splitting and mixing?, etc)?

Numerous methods have been developed for the synthesis of HENs. These methods have been reviewed by Linnhoff,[3] Shenoy,[4] Douglas[5] and Gundersen and Naess.[6]

PROCESS INTEGRATION TOOLS FOR DESIGNING WASTEWATER REDUCTION AND WATER CONSERVATION SYSTEMS

Wastewater reduction and water conservation are becoming increasingly more important issues in process industries. More stringent environmental regulations, concerns over long-term health effects on humans and nature, and the future availability of 'clean' water resources are just a few of the factors that are driving efforts toward improvements in water conservation and wastewater reduction in manufacturing processes. As these issues continue to receive intense government scrutiny and heightened concern from community-organized environmental groups, the ability of industry to address these issues may soon impact their right-to-operate within these communities and their sustainability of future operations.

These critical concerns have refocused efforts over the past decade toward identifying cost-effective wastewater reduction and water conservation process designs, involving direct recycle and reuse of water, that can be implemented within a variety of process industries. Several recent research efforts have focused on the development of process design methodologies and tools that are generic and can be utilized

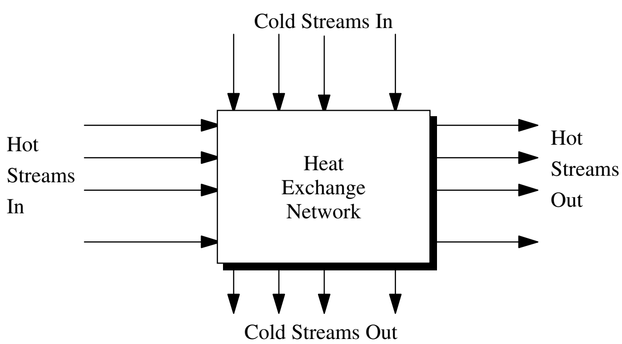

Figure 1. Heat exchange network (HEN) synthesis.

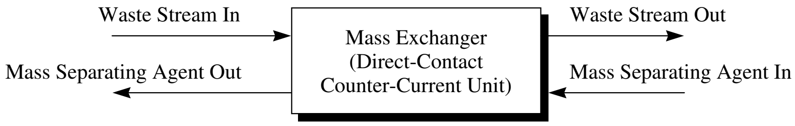

Figure 2. Schematic of a single mass exchanger for environmental process design.

across a wide variety of industries. These industries include petroleum process industries, pulp and paper manufacturing industries, plastics production industries, food products industries, pharmaceutical industries, specialty chemical industries, industrial laundries and fiber dying industries, to name a few. The design methodologies and approaches cover a variety of techniques ranging from graphical based approaches, including 'water pinch' analysis[7–9] the source-sink graphical methodology[10–13] to mathematical optimization-based approaches.[14–16]

For a given system, the synthesis of wastewater reduction and water conservation networks entails answering several questions including:

- Which wastewater streams should be recycled or reused?
- What is the optimal load of each wastewater stream to be recycled or reused?
- What is the optimal allocation of wastewater streams that are to be routed to process water users?
- What is the optimal system configuration (eg how should the water allocation system be arranged?, is there any stream splitting and mixing?, etc)?

PROCESS INTEGRATION TOOLS FOR DESIGNING END-OF-THE-PIPE SEPARATION AND RECYCLE WASTE MINIMIZATION SYSTEMS

Separation systems (a combination of unit operations) designed to allow the recycle/reuse of waste streams, or certain constituents in waste streams, are generally envisioned as an end-of-the-pipe process system. The initial thrust to identify the most cost-effective waste separation system from a large group of process options (multiple technologies and/or separating agents for the separation task) resulted in the notion of synthesizing a mass-exchange network, 'MEN'.[17,18] An MEN is a network consisting of one or more mass exchangers that collectively satisfy the waste recovery task. A single mass exchanger is defined as a direct-contact, counter-current unit that employs a mass-separating agent, 'MSA', to effect the transfer of the pollutant from the waste stream to the MSA and a general schematic of a single mass exchanger is included as Fig 2. Examples of mass exchangers would be absorption columns, adsorbents, extraction units, strippers and ion-exchange units and examples of MSAs would be liquid absorbents, adsorbents and extractants such as solvents, activated carbon, liquid extractants, etc. The design task of synthesizing an MEN is to systematically identify a cost-effective network of mass exchangers for the selective transfer of a certain undesirable species from a set of 'rich' (waste) streams to a set of 'lean' (MSA) streams. This undesirable species generally represents a pollutant if it is discharged to the environment, but may be a valuable raw material if it can be recovered for reuse within the plant. Figure 3 is included as a general representation of the MEN synthesis task for end-of-the-pipe waste minimization process design.

For a given system, the synthesis of MENs entails answering several questions including:

- Which mass separating agents should be employed?
- What is the optimal mass load to be removed/added by each MSA?
- How should the waste and MSA streams be matched (ie stream pairings)?
- What is the optimal system configuration (eg how should the mass exchangers be arranged?, is there any stream splitting and mixing?, etc)?

Over the past few years, several important categories of the MEN synthesis task have been identified and addressed:

- MENs for multiple component systems[19,20]
- MENs with regeneration systems[21,22]
- MENs with chemical reactions[23–26]
- MENs with heat integration[27]
- MENs via a structural based approach[28,29]
- MENs for wastewater reduction[7,30]
- MENs with flexibility[31]
- MENs for fixed load removal[32]
- MENs with controllability[33,34]

Synthesis techniques have also been developed for other separations systems that are traditionally used for waste minimization via end-of-the-pipe

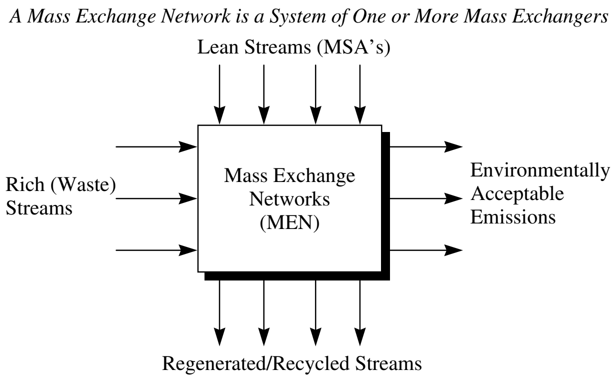

Figure 3. Mass exchange network (MEN) synthesis (El-Halwagi and Manousiouthakis 1989).

recycle/reuse systems. For instance, there is a wide class of separation systems that employ energy separating agents, 'ESAs' (hot and cold process streams and/or utilities such as steam and cooling water), to separate species from a waste stream via a phase change. These include unit operations such as condensers, evaporators, dryers and crystallizers and they are collectively grouped in the category of heat-induced separators. A general schematic of a single heat-induced separator is included as Fig 4. The notion of synthesizing heat-induced separation networks (HISENs) for recycle/reuse waste minimization process design encompasses the task of identifying a cost-effective system of heat-induced separators and heat exchangers that can achieve a specified waste reduction task (single component or multiple component waste streams) by heating/cooling the streams to produce a phase separation.[35–38] Figure 5 is included as a general representation of the HISEN synthesis task for end-of-the-pipe waste minimization process design.

More recently, the HISEN synthesis methodology has been generalized to include pressurization/depressurization equipment in conjunction with heat-induced separation specifically to address gaseous emissions containing volatile organic compounds, 'VOCs' and the resulting recovery system was referred to as an energy-induced separation network, 'EISEN'[39] One of the simplest techniques for VOC recovery is to use heat-induced separation networks to affect condensation via cooling,[35,36,40,41] however, VOC condensation is, in general, a function of both temperature and pressure. Hence, a more general condensation design task should capitalize on the synergism between two energy forms: cooling and pressurization/depressurization. This synergism was

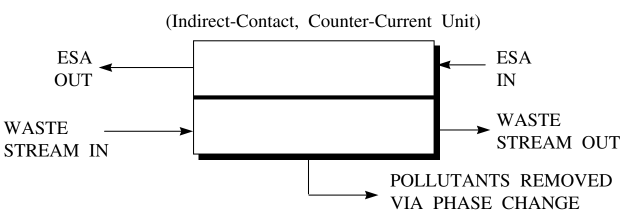

Figure 4. Schematic of a single heat-induced separator for environmental process design.

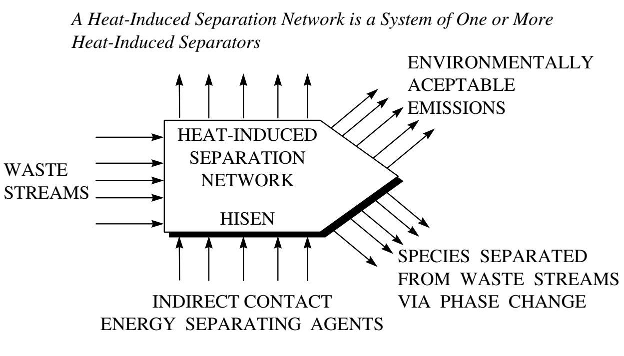

Figure 5. Heat-induced separation network synthesis.[38,25]

addressed by the design methodology of Dunn and coworkers whose objective was to create a cost-effective network of heat-induced separators, heat exchangers and pressurization/depressurization devices, which can separate one or more species from a set of waste streams via phase change.

For a given system, the synthesis of HISENs/EISENs entails answering several questions including:

- Which energy separating agents should be employed?
- Should stream pressurization or depressurization be employed and, if so, to what level?
- What is the optimal mass and heat load to be removed/added by each ESA?
- How should the waste and ESA streams be matched (ie stream pairings)?
- What is the optimal system configuration (eg how should the heat-induced separators, heat exchangers and compressors/turbines be arranged?, is there any stream splitting and mixing?, etc)?

Over the past few years, several important categories of the HISEN and EISEN synthesis task have been identified and addressed as summarized below:

- HISENs for single component VOC condensation systems[35]
- A shortcut graphical approach for HISENs for single component VOC condensation systems[41]
- HISENs for multiple component VOC condensation systems[36]
- HISENs for fixed load removal[42]
- Hybrid HISEN and membrane systems
- A spreadsheet-based approach for identifying cost-effective HISENs and EISENs for condensation-hybrid processes[45,46]
- HISENs for crystallization systems
- HISENs for infinite component VOC condensation systems using clusters[47]

In addition to mass exchange operations and heat- and energy-induced separation systems, systematic design techniques have also be developed for end-of-the-pipe pressure-based membrane systems.[48,49] Also, the application of MEN, EISEN, and membrane synthesis techniques has been illustrated via the design of cost effective VOC recovery systems.[30]

PROCESS INTEGRATION TOOLS FOR DESIGNING IN-PLANT SEPARATION SYSTEMS FOR WASTE MINIMIZATION

Although end-of-the-pipe recycle/reuse systems provide an attractive approach for waste minimization, there may be a greater economic incentive to address pollution prevention from a source reduction perspective. In fact, reducing/eliminating the generation/use of the undesirable species at the source may significantly reduce/eliminate costs associated with end-of-the-pipe separation and recycle. The following four strategies are commonly pursued to address source reduction of pollutants:

1. If the undesirable species *is* generated in the process (via reaction), find an alternative, environmentally acceptable, reaction path. This reaction path should eliminate or minimize the use of raw materials or the production of by-products that are not environmentally friendly.[43,50] This approach is outside of the scope of this paper.
2. If the undesirable species *is not* generated in the process (no reaction), substitute it with a more environmentally benign material. An example of this type of approach could be the substitution of a more environmentally acceptable solvent for use in a chemical process.[51–54] This approach is outside of the scope of this paper.
3. If the emissions are associated with in-plant utility systems (eg blowdowns, greenhouse gas emissions, etc), implement in-plant heat integration modifications to minimize the amount of emissions from thermal pollution or to reduce the amount of emissions associated with utility systems.[55–57]
4. If the undesirable species is not generated in the process and cannot be replaced with a more environmentally benign material, implement inplant modifications to recycle streams with the undesirable species. This design approach has resulted in the novel concepts of the design of wastewater minimization systems, waste interception and allocation networks, 'WINs', heat-induced waste minimization networks, 'HIWAMINs', and energy-induced waste minimization networks, 'EIWAMINs'.[7,10,33,34,58,59] The HIWAMIN and EIWAMIN design approaches simultaneously address waste reduction and energy conservation process design to further improve economics.

Reaction-path modifications and/or material/solvent substitutions generally have a greater potential to tackle waste reduction at the source and are important design approaches to pursue during the overall process identification/conception phase; however, in-plant modifications may be a more readily acceptable option for an existing process. In-plant modifications are generally less capital intensive and easier to retrofit within an existing process than the modifications generally required by reaction/material substitution. Furthermore, in a manufacturing environment, reaction/material substitution usually involves several years of research and development and, in some cases, could also depend on an invention. Thus, source reduction via in-plant modifications is an attractive approach towards tackling waste minimization for existing process plants.

Recently, there have been several systematic methodologies developed for the design for cost-effective waste reduction systems based on in-plant modifications, such as the synthesis of waste interception and allocation networks, 'WINs'[1,58] the synthesis of heat-induced waste minimization networks, 'HIWAMINs'[59] and the synthesis of energy-induced waste minimization networks, 'EIWAMINs'.[60] The WIN synthesis methodology is based on tracking streams containing an undesirable species within a process, and identifying the optimal location(s) to intercept one or more in-plant streams with mass-exchangers to achieve a specified waste reduction task. The WIN design technique features the use of direct-contact *mass separating agents* to intercept the undesirable species. Figure 6 is included as a schematic representation of the WIN design methodology. The HIWAMIN methodology is also based on tracking streams containing an undesirable species within a process and identifying the optimal location(s) to intercept one or more streams with heat-induced separators and heat exchangers to achieve a specified waste reduction and heat integration task. However, the HIWAMIN design technique features the use of indirect-contact, *energy separating agents* to intercept the undesirable species. Furthermore, the HIWAMIN design approach simultaneously addresses the waste minimization and process heat integration (heat exchange network) design tasks. The EIWAMIN design technique extends the HIWAMIN approach to include the use of pressurization and/or depressurization devices in addition to heat-induced separators and heat exchangers to further improve separation efficiencies and the cost effectiveness of the final design. Figure 7 is included as a schematic representation of the HIWAMIN and EIWAMIN design techniques.

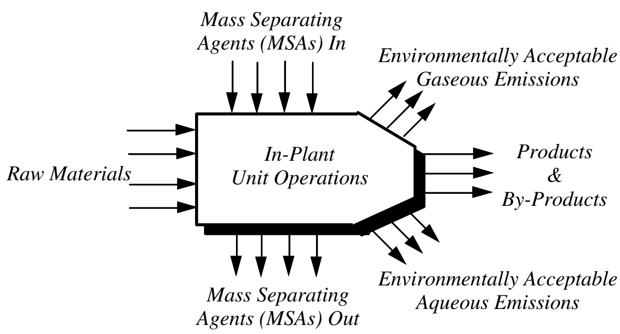

Figure 6. WIN synthesis representation.

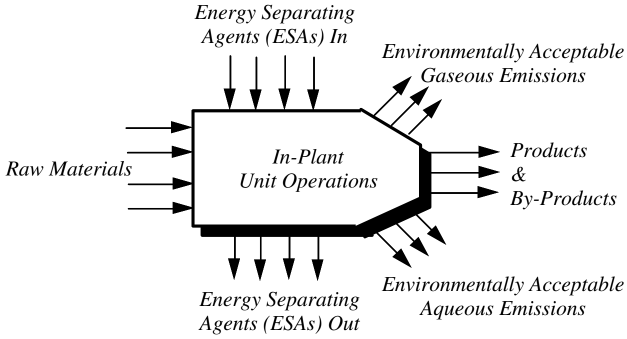

Figure 7. HIWAMIN and EIWAMIN synthesis representation.

MATERIAL SUBSTITUTION, MOLECULAR DESIGN[56] AND REACTION SYNTHESIS OF ENVIRONMENTALLY BENIGN SPECIES

So far, the previous strategies have focused on the process aspects of pollution prevention. Another important element of mass-integration strategies is based on material substitution and chemistry changes. Examples include the selection of environmentally-benign chemical reactions, raw materials, solvents and products. Over the past few years, significant progress has been made in this area. This section provides a brief overview of the recent advances in synthesizing 'green' reactions and species. For more detailed discussion, the reader is referred to El-Halwagi,[1] Anastas and Williamson,[62] Anastas and Farris,[63] and Chase.[64] In the following, we discuss some of these advances.

In many cases, it is possible to replace environmentally hazardous chemicals with more benign species without compromising the technical and economic performance of the process. Examples include alternative solvents, polymers and refrigerants. Group contribution methods have been commonly used in predicting physical and chemical properties of synthesized materials. Two main frameworks have been employed to synthesize alternative materials: knowledge base and computer-aided optimization. Knowledge-based approaches depend on understanding the criteria of the materials to be replaced along with general rules and algorithms that link properties with structure. Examples of this approach can be found in literature.[58,65,66] Furthermore, software can be used to screen solvents based on their properties and performance. An example of this

Table 1. Summary of some methodologies for environmental process design

Design methodology	Description	Example technologies targeted
Heat integration systems	The identification of heat recovery devices that minimize environmental emissions resulting from utility generation systems.	• Heat exchangers • Heat pumps • Boilers/cooling towers
Wastewater minimization systems	A design strategy for reuse, regeneration reuse, and regeneration recycling of wastewater streams that minimizes water usage and minimizes wastewater discharge.	• Direct recycle opportunities • Regeneration reuse and recycling opportunities
Mass exchange networks (MENs) and reactive mass exchange networks (REAMENs)	A network of process units that removes pollutant(s) from end-of-pipe streams via the use of physical or chemical, direct-contact, mass separating agents (MSAs).	• Adsorption • Absorption • Liquid–liquid extraction • Ion exchange
Heat-induced separation networks (HISENs) and energy-induced separation networks (EISENs)	A network of process units that removes pollutant(s) from end-of-pipe streams via the use of indirect-contact energy separating agents (ESAs), including stream pressurization and/or depressurization.	• Condensation • Evaporation • Drying • Crystallization • Compressors • Vacuum pumps
Membrane separation networks	A network of process units that removes pollutant(s) from end-of-pipe streams via the use of membranes and stream pressurization and/or depressurization.	• Reverse osmosis • Pervaporation
Environmentally acceptable reactions (EARs)	The development of an alternative reaction path that will no longer result in the generation of the pollutant.	• Reactions
Solvent selection systems	The identification of alternative solvents and/or solvent combinations that can be used to provide a desired effect (solubility, material transport, separating agent, etc).	• Substitute refrigerants • Substitute coating constituents • Simultaneous solvent and separation unit selection
In-plant separation design via waste interception and allocation networks (WINs)	A network of process units that removes pollutant(s) from in-plant streams via the use of physical or reactive direct-contact mass separating agents (MSAs) and/or rerouting of in-plant process streams.	• Direct recycle opportunities • Adsorption • Absorption • Liquid–liquid extraction • Ion exchange
In-plant separation design via heat-induced waste minimization networks (HIWAMINs) and energy-induced waste minimization networks (EIWAMINs)	A network of process units that removes pollutant(s) from in-plant streams via the use of indirect-contact energy separating agents (ESAs) with stream pressurization and/or depressurization and/or rerouting of in-plant process streams. Full site heat integration is simultaneously addressed by this technique.	• Direct recycle opportunities • Heat exchange/heat integration • Condensation • Evaporation • Drying • Crystallization • Compressors • Vacuum pumps • Heat pumps

Table 2. Examples of discouraging attitudes about process integration and suggested responses

Discouraging attitudes	Response
We don't have the resources to support this process integration initiative.	Let us create resources that match the anticipated results or let us do the best we can within the available resources.
We have tried something similar before and it did not work.	Let us study the previous effort and see indeed if no more progress can be made.
These concepts will not work in my plant. We have a very unique operation.	There is now a track record of tens of very successful process integration projects that have applied to a wide variety of industrial processes; each of which is unique in its own right.
Has anyone else applied it before?	See previous response.
Our process is too big/too small for this approach.	See previous response.
I am the process expert; there is no way that someone else can do better.	Let us incorporate your experience in a process integration framework. Time and again, track record has indicated that when proper process experience is incorporated into a process integration framework, significant and intuitively non-obvious benefits have accrued.
You really don't understand the issues and problems that we face.	See previous two responses.
Sounds great but you need to speak to someone else.	Get suggestions on 'the someone else' but also see if there is a legitimate role for the individual.
I don't wish to participate in an initiative where I don't feel comfortable with the tools and techniques.	Provide appropriate training to develop the proper comfort level and understanding.
Not now! We will include it in our long-term strategic planning.	Each day without process integration implies missed opportunities.

approach is the PARIS (Program for Assisting in the Replacement of Industrial Solvents) software (eg US EPA 1994; Cabezas and Zhao.[67] Computer-aided optimization approaches are based on formulating the molecular design problem as an optimization program that seeks to maximize a performance function or minimize deviation from desired properties subject to various constraints including structural feasibility, property-structure correlations and environmental criteria. Examples of this approach include synthesis of solvents,[39,53,61,66,67] polymers[39,53] and refrigerants.[68,69,70] Table 1 is included as a summary of the design methodologies that have been discussed in this paper.

PUTTING IT TOGETHER: HOW TO DEVELOP AND SUSTAIN PROCESS INTEGRATION INITIATIVES WITHIN A COMPANY?

The foregoing discussion has focused on process-integration tools. These are key elements for identifying opportunities and developing sound strategies. Nonetheless, tools alone will not deliver solutions; people, work processes, and working cultures and environments will. The authors have been involved in working with many companies to develop teams, work process, and environments that are conducive to the success of process integration applications. Towards this end, the following are key building blocks:

- Articulate a clear vision of the broad goals of the company.
- Perform a preliminary targeting analysis to determine priority areas of work.
- Develop a preliminary framework of tasks needed and the required human, technical, and financial resources.
- Establish realistic expectation and targets of what process integration can deliver and what resources it will take to perform the tasks.
- Describe anticipated constraints, corporate unique aspects, and challenges.
- Get enthusiastic support from senior management.
- Recruit local champions from among the process experts and the stakeholders.
- Form task-driven teams.
- Encourage an open environment which fosters creativity and out-of-the-box integrated thinking where the dominating culture is 'how do we make it happen?' instead of 'why it won't work'.
- Measure, analyze, use process integration tools to develop, improve, synthesize, feedback, refine, and sustain projects and strategies.
- Present the proposed changes in an way which focuses on gained insights, is easy to follow, and highlights the key characteristics of the findings.
- Give focus to important issues.
- Consult with relevant individuals all along to capture process know-how, ensure that appropriate details are included and hurdles are overcome.
- Start now!

Another important aspect is to take initiative and not be discouraged by resisting responses. Table 2 lists the 'top ten' statements and attitudes that the authors have encountered, along with positive responses.

EXAMPLES OF INDUSTRIAL APPLICATIONS OF PROCESS INTEGRATION TOOLS

Over the past decade, the authors have been active in applying the tools previously mentioned to improve process performance via productivity enhancement,

Table 3. Summary of industrial applications of process integration tools

Type of process	Project objectives	Motivation	Approach	Key results
Specialty chemical process	Debottlenecking of the process and hydrogen management	Soldout product with no additional capacity and significant cost for hydrogen consumption	Systematic elimination of two primary bottlenecks and sitewide integration of hydrogen generation, usage, and discharge	12% additional capacity and 25% reduction in hydrogen cost with a payback period of less than one year
Kraft pulping process	Water management and conservation	High usage of water and buildup of non-process elements upon recycle	Sitewide tracking of water and non-process elements followed by a mass integration study for water minimization	Key results: 55% reduction in water usage with a payback period of less than two years
Resin production facility	Production debottlenecking	Soldout product with more market demands but a capped production capacity (bottleneck)	Mass integration techniques to determine subtle causes of process bottlenecks and eliminate them at minimum cost	Increase in capacity by process debottlenecking: 4% (>$1 million/year additional revenue)
Organic chemicals production process	Identification of sitewide water stream recycle opportunities to reduce river water discharges	Pressure from local environmentalists and the need to meet more stringent environmental permit requirements	Sitewide tracking of water followed by a mass integration study for water recycle opportunities and potential land treatment and reverse osmosis treatment of select wastewater streams	Nine process designs selected for implementation, including one separation system resulting in 5% wastewater reduction with a payback period of one year
Polymer and monomer production processes	Identification of sitewide energy conservation opportunities to reduce energy costs	Reduction in operating costs for manufacturing processes and the need for additional steam generation for production capacity expansion	Sitewide tracking of energy usage followed by a heat integration study to identify energy conservation opportunities	A heat-exchange network and utility optimization process design implemented, resulting in a 10% reduction in site utility costs, a 10% reduction in site wastewater hydraulic load and a 5% production capacity increase; annual savings are in excess of $2.5 million/year
Specialty chemicals production process	Identification of sitewide energy conservation opportunities to reduce energy costs	High operating costs for utilities	Sitewide tracking of energy usage followed by a heat integration study to identify energy conservation opportunities	Five process designs implemented leading to a 25% reduction in energy usage with a payback period of less than one year
Metal finishing process	Reduce cost of industrial solvent	Major solvent losses leading to a large operating cost and environmental problems	Synthesis of an energy-efficient heat-induced separation network	Recovery of 80% of lost solvent with a payback period of three years
Papermaking process	Recovery of lost fibers and management of water system	7% losses of purchased fibers during processing and high usage of water	Integrated matching of properties of broke fibers with demands of paper machines (property integration)	Recovery and reuse of 60% of lost fibers and reduction in water usage by 30% with a payback period of less than one year
Polymer production processes	Identification of sitewide wastewater stream recycle opportunities	Future expansion (wastewater discharge system expected to exceed its maximum capacity during the production process expansion)	Sitewide tracking of water followed by a mass integration study for water recycle opportunities and reverse osmosis treatment of select wastewater streams	24 process designs implemented resulting in a 30% reduction in site wastewater discharge and with a payback period of less than one year
Petrochemical facility	Develop power co-generation strategies and optimize utility systems	Significant usage of steam for process uses and high cost of power usage	Energy integration with emphasis on combined heat and power optimization	25% reduction in steam cost and cogeneration of 20% of power requirement for the process. Payback period is four years.

energy conservation, and pollution prevention issues at various industrial sites. Table 3 is a snapshot summary of the positive results achieved through some of these projects. The names of the companies or products are not provided to protect the proprietary nature of the projects. Instead, the type of the process is described.

OBSERVATIONS ON INDUSTRIAL APPLICATION OF PROCESS INTEGRATION TECHNOLOGY

The authors' experience in applying process integration methodologies in the process industries has led to the following insights:

- These methodologies are well suited for a variety of chemical processes including, but not limited to, the chemical, polymer, petroleum, pulp and paper, food products, and pharmaceutical industries.
- These methodologies work equally well for small, medium and large size chemical processes. Obviously application to larger processes often results in a greater magnitude of savings and a greater magnitude of capital cost for the implementation of identified designs.
- These methodologies are applicable for both continuous and batch processes; however, batch processes are more difficult to analyze and to implement the identified solutions as they typically involve dynamic performance and require an additional layer of scheduling solutions.
- These methodologies are well suited for both retrofit and grassroots process designs. Utilization of these tools during grassroots plant design can allow the added flexibility of locating equipment to be 'integrated' within a close proximity of each other. In addition, personal experience has shown that even relatively 'new' plants that are analyzed for retrofit process integration designs can offer substantial cost savings and waste minimization opportunities.
- Companies involved in applying process integration methodologies must be prepared to pay for the implementation of identified solutions. The process designs may often be low cost but almost none are free. It is true that 'it takes money to make money'. If no capital funds are available, the potential results of the process integration study can be severely limited. The good news, however, is that most process integration projects enjoy a very attractive payback period (typically less than two years) and can 'pay for themselves'.
- Implementation of identified process designs can be sequenced as a part of a master-plan investment strategy for the company. Implementation may start with the low-cost projects and proceeds to the high-cost projects as the financial resources become available. However, process integration provides an overarching framework for sequencing the implementation.
- The nature of the problems calls for the use of specific tools within the process integration methodology. A basic knowledge of the entire methodology and set of tools referenced in this paper is recommended.
- Process integration tools are systematic and the application of these methodologies often identifies process designs that are not intuitively obvious even by experienced engineers employing heuristics and brainstorming. Equally important to the tools is the overall integration approach and mindset.

CONCLUSION

Process integration is an attractive framework for the holistic analysis of process performance and the development of cost-effective and sustainable solution strategies. It is based on fundamental chemical engineering and systems principles and therefore provides a set of generally-applicable tools. The paper has presented an overview of salient process integration tools and overall methodology. The paper has also presented examples of industrial applications, driving forces, hurdles to implementation, common features, and key results. These process integration design tools can be used to address and reconcile a wide variety of process objectives including productivity enhancement, resource conservation, and long-term planning. All of these objectives translate into a positive impact on the sustainability of the companies and the ability to remain competitive in a global market. This is an active research area that promises to lead to significant contributions on the engineering principles of integrated systems.

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