SIMULATION MODELING

PEER REVIEWED

Mass-integration analysis: A technique for reducing methanol and effluent discharge in pulp mills

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ABSTRACT

This work illustrates the use of mass-integration methodology, a holistic approach to process design and operation. The method's utility derives from its ability to develop global insights about mass flow within a process. The design engineer can then use these insights to identify optimal strategies for allocating, routing, and separating process streams and targeted species. A case study is presented to illustrate the effectiveness of this approach in reducing methanol and wastewater discharges from a kraft pulp mill. The method targets all sources of a given pollutant simultaneously, allowing the engineer to evaluate opportunities for segregation, mixing, recycling, and interception of in-plant and terminal streams. Several visualization tools are described. These graphs are used to understand the global mass flow and to identify optimal allocation, interception, and recycle/reuse opportunities.

Application:

A case study illustrating the use of analytical tools that the design engineer can use to reduce waste and pollution from a kraft pulp mill.

THE U.S. PULP AND PAPER INDUSTRY is under considerable pressure to reduce both the volume of wastewater discharged and the level of contaminants in effluents. Methanol is among the important organic contaminants. Several studies have addressed this topic for kraft pulping operations.

For example, Johnson and Diehl *(1)* presented techniques for condensate segregation and methanol stripping. The use of steam stripping concentrates methanol-laden streams, but it does not reduce the methanol load in terminal streams. Moreover, the additional use of steam increases the amount of wastewater. Venkatesh *et al. (2)* simulated two mills using the general energy and materials balance system (GEMS) process simulator. They modified GEMS process models to include methanol prediction capability, and then used the models to study the effects of process modifications on methanol contents in air emissions. Their results demonstrated various process modifications that could substantially reduce gaseous emissions of methanol. However, this did not eliminate the problem of methanol in the mill. Rather, it was transferred from the gaseous phase to the liquid phase.

These previous efforts focused on optimizing a particular process. Hence, their findings cannot be readily transferred from one mill to another. Indeed, what is needed is a systematic methodology that can address the problem in a generally applicable manner. In this regard, mass integration provides an attractive framework. Using the mass-integration approach described in this paper, one can evaluate millwide options for reducing methanol and wastewater discharges, including the costs for each option. The solution procedure follows an integrated approach that is based on an analysis of the mass flow of the targeted species in process liquids throughout the process.

OVERVIEW OF MASS INTEGRATION

Definition and objective

Over the past two decades, the industry has made significant progress in integrating pollution prevention with other process objectives. This led to the concept of process integration, which is a holistic approach to design that emphasizes the unity of the entire process. Process integration is based on first understanding the global insights of the process and then addressing design details at the appropriate stage. The first significant success of process integration was in the area of energy integration, a subset of which is the thermal "pinch" technology that is used in designing heat-exchange networks *(3–5)*. Energy integration deals with the optimum allocation, transformation, and exchange of energy throughout the process. This energy-integration methodology has been widely used to optimize energy usage in many process industries, including the pulp and paper industry *(6)*. Mass integration—a more recent development in process integration—is the framework used in this paper.

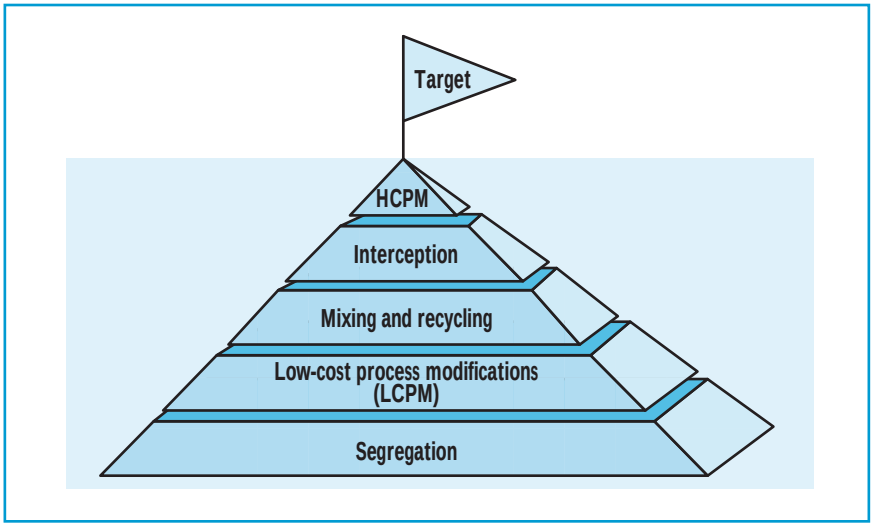
Mass integration is a holistic approach that provides a global understanding of the flow of mass throughout the process. This approach provides insights into the process, which are then used to develop strategies for the allocation, routing, separation, and conversion of streams and targeted species. The method guides designers in routing

all species to their most desirable destinations and allows the designer to establish mass-related cost trade-offs.

The original motivation for mass integration was pollution prevention. In 1989, El-Halwagi and Manousiouthakis *(7)* introduced the problem of synthesizing mass-exchange networks (MENs) with the objective of removing targeted species (in this case pollutants) from streams rich in these species using mass-separating agents (MSAs) that are lean in the targeted species. Over the past few years, the MEN concept has been generalized to the broader framework of mass integration for the global allocation of mass. This includes species utilization and recycle, species interception within the process, species conversion via chemical reactions, stream segregation and mixing, and the manipulation of unit operations through design and operating changes.

Mass integration has been successfully applied to a wide variety of process industries to reduce pollution, enhance yield, reduce costs, and debottleneck the process. A thorough review of the process can be found in a recent textbook by El-Halwagi *(8)*.

The framework of mass integration allows simultaneous consideration of liquid, solid, and gaseous pollutants. A particularly useful concept in mass integration is waste interception and allocation networks (WINs) *(9–11)*. This novel concept identifies optimal strategies for separating and recycling pollutant-laden in-plant streams. Using this approach, the design engineer has the tools needed to tackle the pollution problem at the source and throughout the process. In addition, one can screen several separation technologies for pollutant removal from in-plant streams and then identify the structure of the optimal separation system.



1. Pyramid representing strategies used in mass integration

Strategies of mass integration

After identifying the target of waste reduction (e.g., minimum cost, minimum wastewater discharge), the design engineer can choose among several strategies to achieve that target. These strategies, depicted in **Fig. 1**, include: segregation; low-cost process modifications (LCPM); mixing and recycling; interception (separation); and high-cost process modifications (HCPM). The strategies are integrated to reach the design target.

Segregation. In some industrial applications, dilute streams are mixed with concentrated streams unnecessarily. Segregation of streams at the source provides several opportunities for cost reduction. Segregation can generate environmentally benign streams, and it enhances the opportunities for direct recycling and separation, since it can provide appropriate concentrations for recycle and separation.

Low-cost process modifications. In some cases, waste can be reduced or eliminated by changing the operating conditions (e.g., temperature, pressure, flow rate, composition) of the unit (sink) from which the waste is generated or fed. This is referred to as sink manipulation. In other cases, one might replace a unit with a more environmentally benign unit if the return on investment associated with this change is acceptable.

Mixing and recycling. Discharged waste can be reduced by recycling pollutant-laden streams for reuse in the process or by directing the streams to satisfy nonprocess requirements. In some instances, several streams may need to be mixed together to achieve the desired level of flow rate and composition. The cost associated with this step includes piping and, sometimes, mixing tanks.

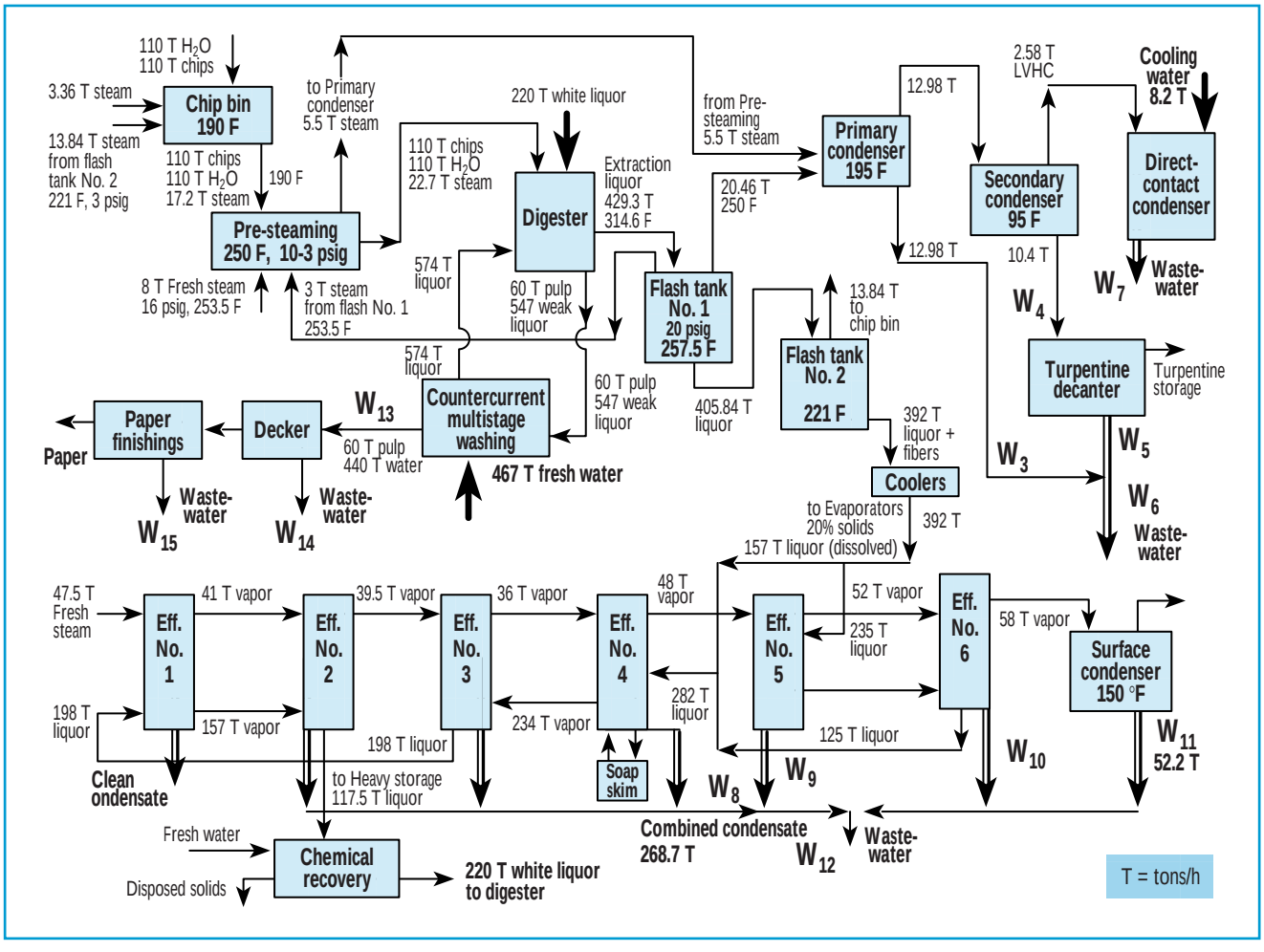
Interception. Interception involves the use of separation technologies to selectively remove the targeted species from the targeted streams. In most industrial applications, interception is needed to enhance the opportunities of recycling, to prevent pollutant buildup, and to generate environmentally benign streams.

High-cost process modifications. HCPM can include the use of new chemistry (such as a new solvent, new reaction path, etc.) or new technology (e.g., new plant).

Process modifications probably will require some experimental work and/or process simulation to demonstrate their validity.

Solution approach

The five identified strategies can be combined and solved optimally using graphical as well as optimization mathematical models *(8, 9)*. The graphical approach refers to the use of visualization tools to systemati-



2. Process flow diagram for unbleached kraft

cally develop optimal solutions. These graphical tools include: path diagrams, source–sink mapping diagrams, and mass–pinch analysis. Together, these tools provide a detailed map of the pollutant's (targeted species) path throughout the process. Moreover, these tools are flexible, allowing engineers to approach the problem using their own preferences while still gaining insights from the design as well.

The following case study is presented to illustrate how these tools can be used to identify optimal strategies for pollution prevention.

CASE STUDY: COST-EFFECTIVE REDUCTION OF WATER USE, DISCHARGED WASTEWATER, AND METHANOL LOAD IN EFFLUENT

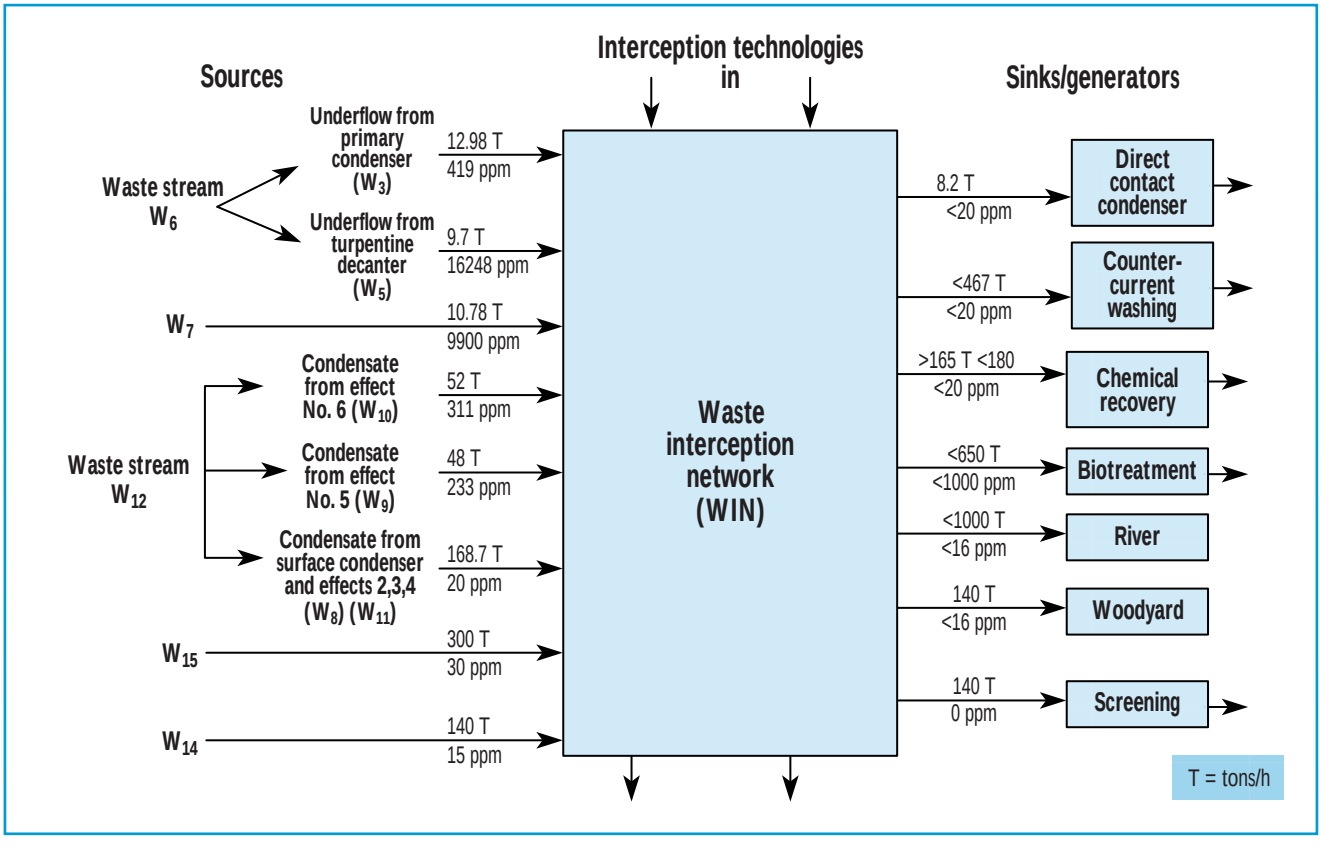
Objectives of case study

The EPA's recently promulgated Cluster Rule contains specific requirements for kraft mill condensates *(12)*. Certain condensates from the digesters, turpentine recovery, and evaporator system will have to either be steam stripped, "hard-piped" directly to a "well operated" biotreatment system, or reused in a totally enclosed unit process. The case study presented in this paper shows how the mass integration technique can be used to identify the most cost-effective option for reducing methanol loading in the plant effluents by 97% as well as optimizing fresh water usage and wastewater discharge. The approach presented here assumes that methanol emissions are to be incinerated.

Process description

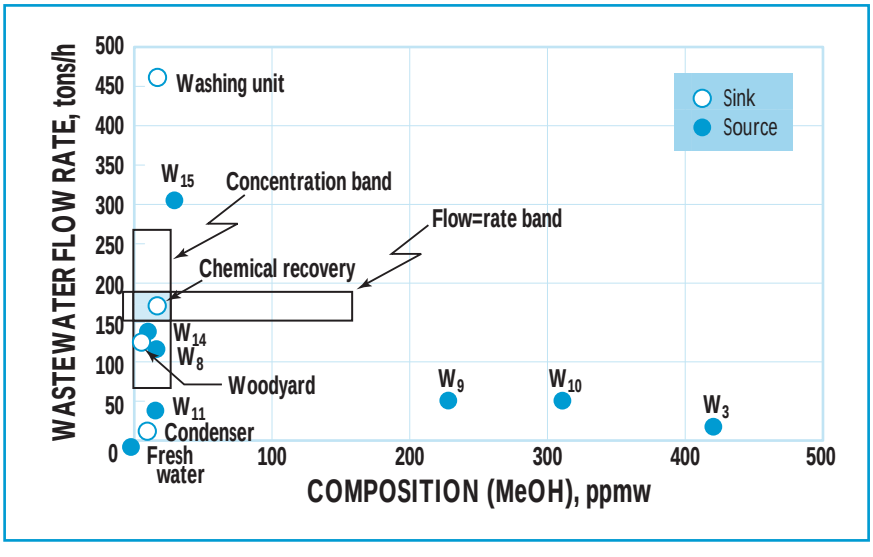
A kraft mill producing 60 tons/h of unbleached pulp was selected to illustrate the mass-integration technique. The basic features of the process are shown in **Fig. 2**. The following key features are worth mentioning:

- The black liquor from the continuous digester is flashed twice. Part of the steam generated is used in the steaming vessel. The excess steam joins the steam from the presteaming vessel in the primary condenser.
- The noncondensables from the primary condenser go to the secondary condenser, the downflow of which is taken to the turpentine decanter. After recovery of turpentine, we get wastewater stream W_5.
- The noncondensables from the secondary condenser form wastewater stream W_7 after passing through a direct-contact condenser.



3. WIN representation of the sources and sinks of the pulping process

- The pulp passes through a countercurrent multistage washer that uses fresh water. Decker filtrate is sewered (open screen room). The weak liquor generated goes to the digester for a countercurrent washing stage before the contents are blown.
- The black liquor is concentrated in multieffect evaporators. Six countercurrent effects and surface condenser are utilized. All evaporator condensates except those from effect No. 1 are sewered.
- Fresh water is used in the recausticizing area for makeup.



4. Source–sink diagram for the case study. (Shaded area represents the acceptable range of recycle for the chemical recovery unit.)

SOLUTION METHODOLOGY

Tools used in mass integration

Source–sink mapping diagram. From the process, one can identify the "sources" of the targeted species (i.e., streams that carry the targeted species) and the "sinks" of these sources (i.e., units that can, under particular conditions of concentration and flow rate, process these sources). The sink is also called a generator, since in most cases it generates a source that can be used in the analysis. **Figure 3** shows the flow rates and methanol concentrations of the liquid sources and sinks of the case study. Figure 3 also includes processing composition and flow-rate constraints for each sink.

Next, the source–sink mapping diagram *(13–15)* is constructed as

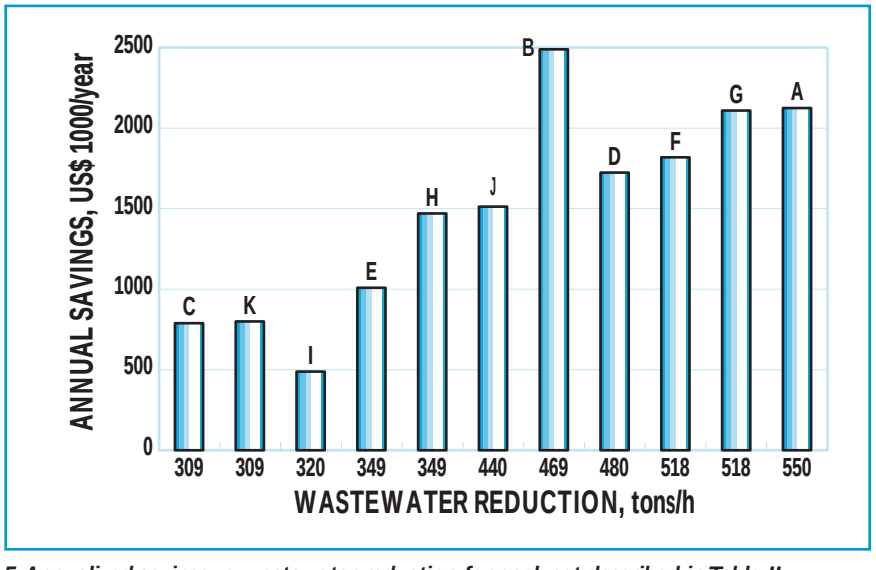
Project	Mixing tank cost, US$/year	Piping cost, US$/year	Waste water reduction,[a] tons/h	Reduction in wastewater treatment cost, US$/year	Reduction in river water cost,[b] US$/year	Total savings, US$/year
1	24,000	82,500	169	980,000	31,000	904,500
2	27,000	88,000	180	232,000	33,000	150,000
3	27,000	88,000	180	695,500	22,000	602,500
4	24,000	68,500	140	0	26,000	–66,500 (net cost)
5	72,000	187,000	338	1,397,000	70,500	1,208,500
6	72,000	214,000	338	1,710,500	81,000	1,505,500
7	72,000	147,000	300	1,739,000	55,400	1,575,400
8	72,000	82,500	169	980,000	31,000	856,500
9	72,000	68,500	140	0	26,000	–114,000 (net cost)

[a] River water reduction
[b] Cost of river water = US$ 0.021/ton

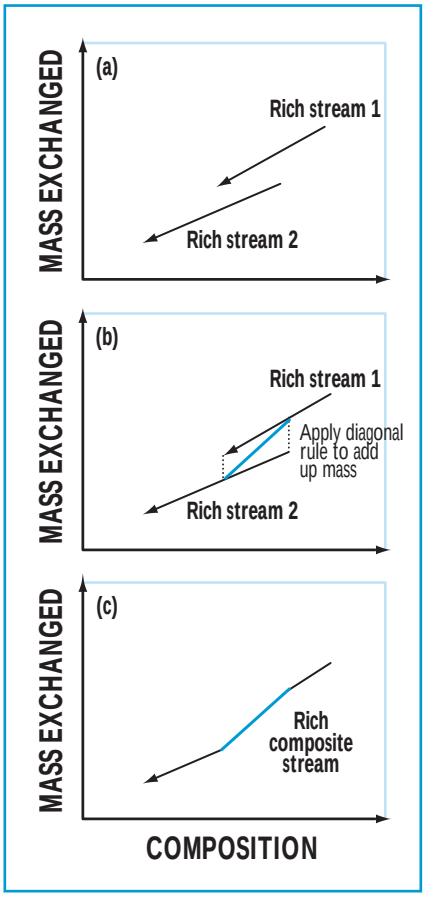
I. Details of the direct recycling projects

Set	Projects involved	Total wastewater reduction, tons/h	Total savings, US$/year
A	1 and 5	550	2,113,000
B	1 and 7	469	2,479,900
C	1 and 9	309	790,500
D	2 and 7	480	1,725,400
E	2 and 8	349	1,006,500
F	3 and 5	518	1,811,000
G	3 and 6	518	2,108,000
H	3 and 8	349	1,459,000
I	3 and 9	320	488,500
J	4 and 7	440	1,508,900
K	4 and 8	309	790,000

II. Sets of mutually exclusive direct recycling projects



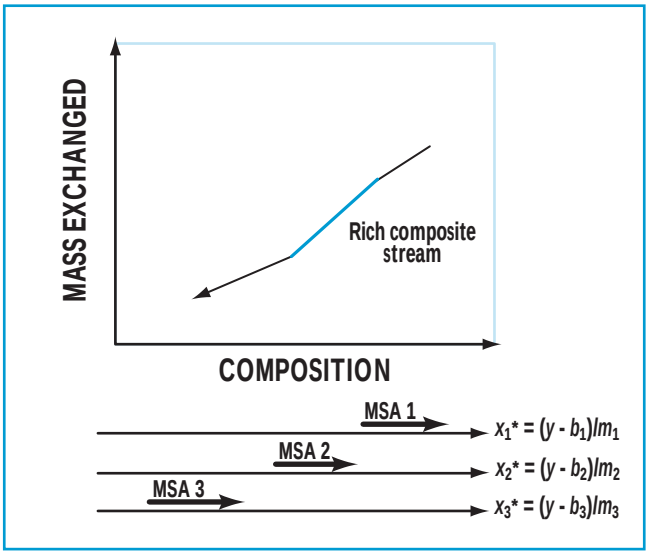
5. Annualized savings vs. wastewater reduction for each set described in Table II



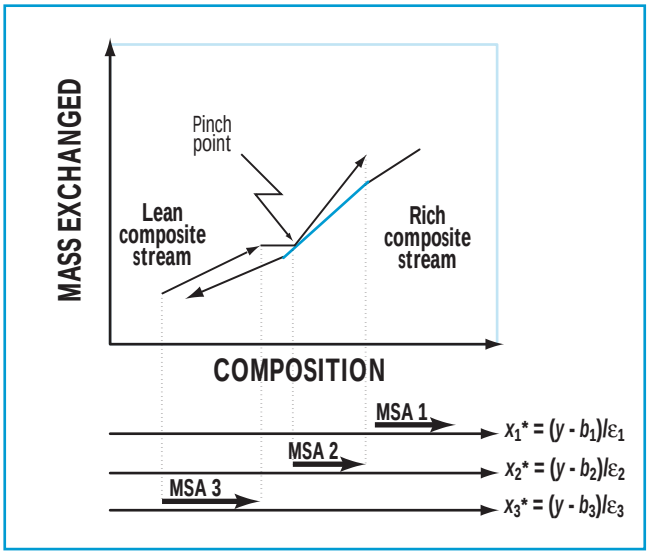
6. a: Representation of rich streams; b: application of "diagonal rule" to add up mass in overlapping regions; c: composite rich stream

follows: Mass load (or the flow rate) of all sources (shaded circles) and sinks (blank circles) are plotted on the same diagram as functions of their composition (in this case, methanol or MeOH). The source–sink mapping diagram of the case study is shown in **Fig. 4**. The acceptable ranges for the recycling concentrations and flow rates for each sink are drawn as horizontal and vertical bands, respectively. The sample bands shown in Fig. 4 are for the chemical recovery unit. The intersection of the two bands defines the region of permissible recycle. Any stream that is located within the concentration band can be totally or partially recycled. In some instances, multiple streams outside the permissible region can be mixed to produce a stream located within the permissible region. Moreover, this tool identifies some sinks that can process some sources after reducing the composition and mass load of those sources via interception.

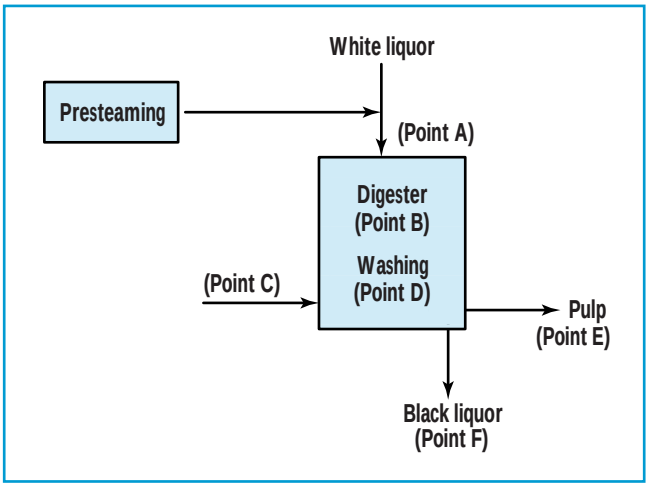
Using the source–sink mapping diagram, several mutually exclusive projects for direct recycling can be identified. To determine which projects should be pursued, one needs to develop an impact diagram that shows the economic impact of each set of mutually exclusive projects vs. their total waste reduction. From the source–sink mapping diagram, the



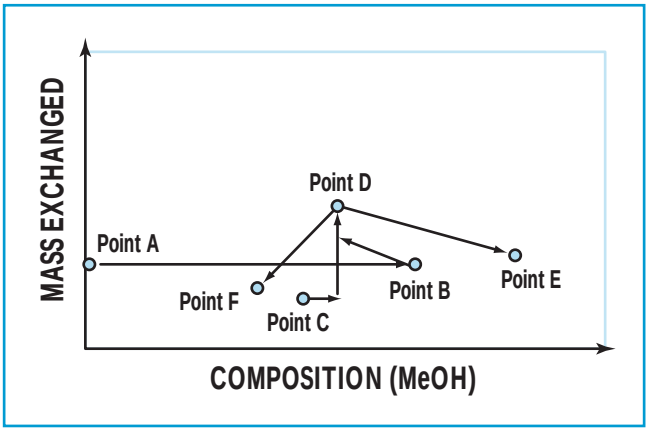
7. Screening MSAs for pinch analysis



8. Pinch diagram for the example in Fig. 7



9. Generic process used in discussion of path diagram



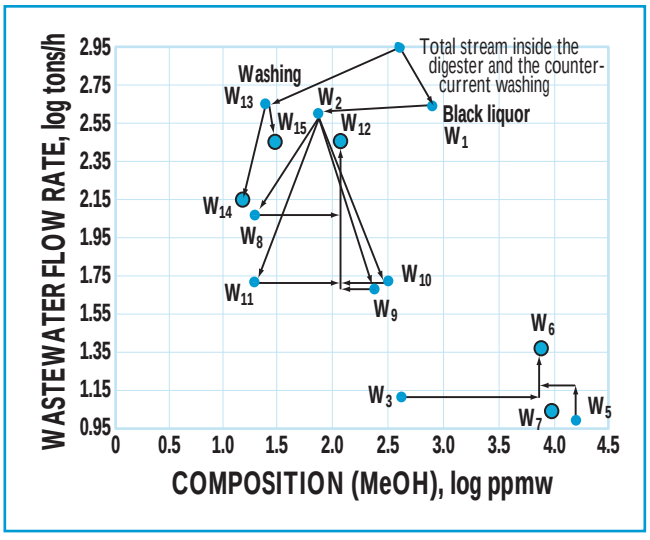
10. Path diagram for the generic example

following (nonmutually exclusive) direct recycling projects can be proposed. (A source–sink mapping diagram should be evolved for each sink.):

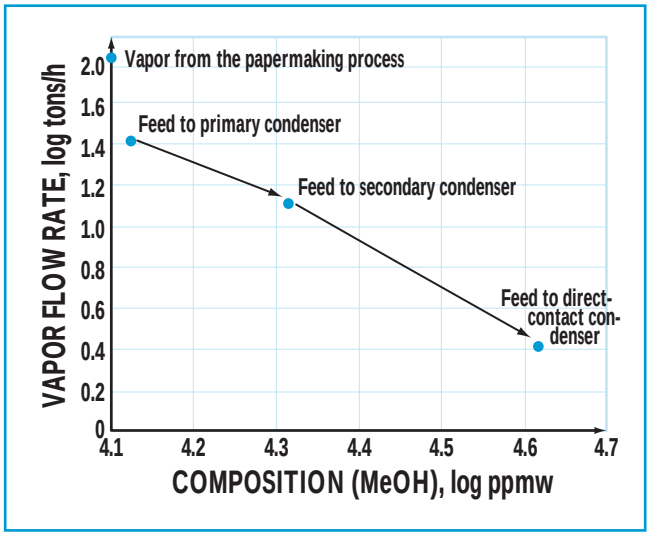
1. Recycle W_8 and W_{11} to the chemical recovery unit.
2. Recycle all W_{14} and 40 tons/h from W_{15} to the chemical recovery unit.
3. Recycle 120 tons/h from W_{15} and 60 tons/h fresh water to the chemical recovery unit.
4. Recycle W_{14} and 40 tons/h fresh water to the chemical recovery unit.
5. Recycle W_{14}, 241 tons/h from W_{15}, and 86 tons/h fresh water to the brownstock washers.
6. Recycle W_{14}, W_8, W_{11}, 129 tons/h from W_{15}, and 29 tons/h fresh water to the brownstock washers.
7. Recycle W_{15} and 167 tons/h fresh water to the brownstock washers.
8. Recycle W_8, W_{11}, and 298 tons/h fresh water to the brownstock washers.
9. Recycle W_{14} and 327 tons/h fresh water to the brownstock washers.

Economic justification determines which projects should be implemented. To account for piping and pumping, the cost is taken to be US$ 4/(ft·lb/s). This cost includes power, labor, and maintenance. Details of the costs and savings associated with Projects 1–9 are presented in **Table I**. Sets of mutually exclusive projects and associated savings are presented in **Table II** and **Fig. 5**.

It is apparent from Fig. 5 that Set B provides the greatest annual savings. These projects could also be ranked using a more detailed profitability analysis. As already mentioned, the source–sink mapping diagram can also identify sources that need interception in order to be recycled or discharged. For example, the stream from the primary condenser underflow (W_3) requires interception to be recycled or dis-



11. Path diagram for liquids in the pulp mill



12. Path diagram for gases in the pulp mill

charged, as can be seen from Fig. 4. After identifying interception opportunities, other tools such as mass–pinch and path diagrams can be used to explore the optimal network for in-plant interception.

Mass–pinch analysis. Mass–pinch analysis *(7, 8)* is another tool that can be employed in mass integration to synthesize the optimal mass-exchange networks (MENs). The problem of synthesizing MENs can be described as follows: Given a number of rich streams (streams containing targeted species, also called sources) and a number of lean streams (mass-separating agents, MSAs), the desired outcome is to synthesize the optimal mass-exchange network. Such a network would selectively transfer the targeted species from the rich streams to the lean streams so as to meet environmental or process requirements. Examples of mass-exchange operations include stripping, absorption, extraction, washing, adsorption, etc. To optimize the cost of mass separating agents, the pinch analysis is utilized.

As a first step in constructing the pinch diagram, each rich (waste) stream is represented as an arrow whose tail and head represent the supply and target compositions of the stream, respectively (**Fig. 6**a). The vertical distance between the head and the tail of the arrow represents the mass load to be removed of the targeted species from the stream, and the slope of the arrow gives the flow rate of the stream. Next, the "diagonal rule" for superposition is used to provide a combined representation of both rich streams by adding up mass load in overlapped regions of streams (Fig. 6b). This representation results in the rich composite stream (Fig. 6c). The same procedure can be adapted for all the rich streams to develop a global rich composite stream. The rich composite stream represents the cumulative mass of targeted species to be removed using mass-separating agents (MSAs). The MSAs are superimposed on the *x*-axis, as seen in **Fig. 7**. The position of each MSA represents the feasible operational region of this MSA with respect to composition (i.e., thermodynamics). Thermodynamic feasibility can be represented through Eq. 1:

$$y = m_i x_i^* + b_i \qquad (1)$$

where

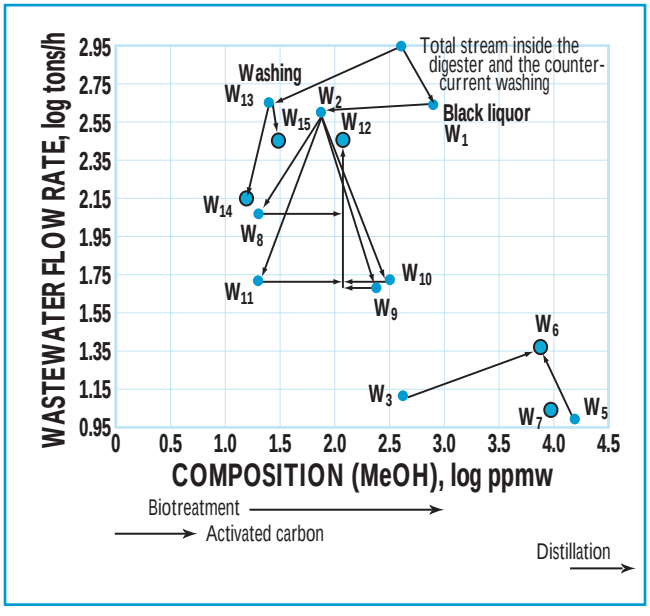
y = composition of the rich stream
m = distribution coefficient (e.g., Henry's constant)
x^* = maximum possible composition of the MSA
b = a constant

and the subscript i refers to MSA i.

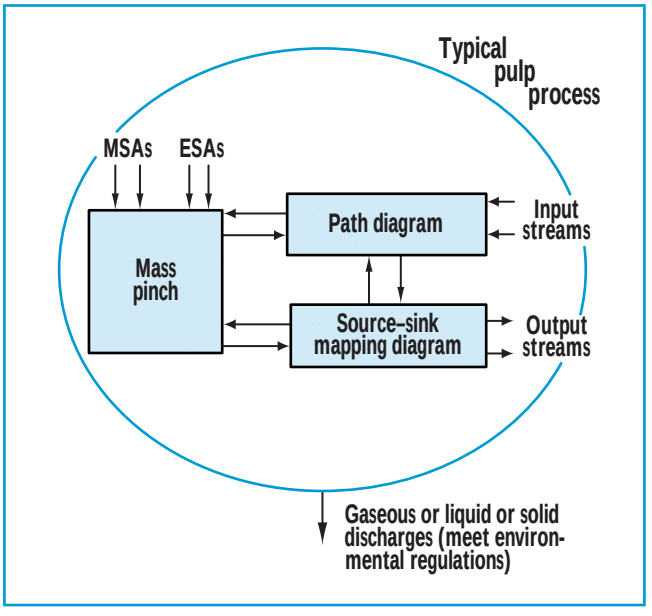
To avoid an infinite unit (e.g., column) size, a minimum allowable composition difference (ε) is required. This parameter is used to trade off capital vs. operating costs so as to minimize total annualized cost. Details on selecting (ε) are described in the literature *(7, 8)*. Hence, the equilibrium equation is depicted as follows:

$$y = m_i(x_i^* - \varepsilon_i) + b_i \qquad (2)$$

A shortcut method was described by El-Halwagi *(8)* to determine the optimal operating cost of MENs by identifying the pinch location. In this method, one needs to identify the cost of each MSA per unit mass removed of the targeted species. Based on thermodynamic feasibility and the unit costs of each MSA, the optimal pinch diagram can be constructed. For example, if stream MSA 2 is to the left of stream MSA 1—and if MSA 2 costs less than MSA 1 per unit mass of targeted species removed—then MSA 1 can be removed from the analysis. However, if the cost of MSA 1 is cheaper, then both MSAs should be retained. For the purpose of clarification, let us assume that the cost of MSA 2 is the cheapest among the three MSAs per unit mass removed of the targeted species. To minimize the cost of MSAs, then MSA 2 should be used to



13. Superimposed interception technologies on the path diagram (including segregation)



14. Iterative scheme to identify optimal solution for case study

its maximum capacity. Since thermodynamics prevent MSA 2 from doing all the separation job, MSA 3 is required to accomplish the remaining separation job.

The flow rate of each MSA is determined by dividing the mass load of the targeted species to be removed by the MSA by the composition difference of the MSA. Composition difference is the difference between target and supply compositions of the MSA. After determining the mass load to be removed by each MSA and the flow rate of each MSA, the pinch diagram can be constructed as shown in **Fig. 8**. The slope of each MSA in Fig. 8 represents the flow rate of this MSA. Extensive details on how to rigorously develop the pinch diagram and how to optimize overall cost of MENs is beyond the scope of this paper. Instead, the reader is referred to the literature *(7, 8)* for broad details.

Other technologies such as heat-induced technologies can also be used. In such cases, energy-separating agents (ESAs) such as cooling, heating, pressure, and vacuum are employed to induce separation. Examples include condensation, distillation, crystallization, and evaporation.

	Supply composition (x_s), ppmw	Target composition (x_t), ppmw	Slope (m)	Minimum allowable composition for MSA (ε), ppmw	Cost of MSA (c), US$/lb
Activated carbon	2	10	0.65	4	120

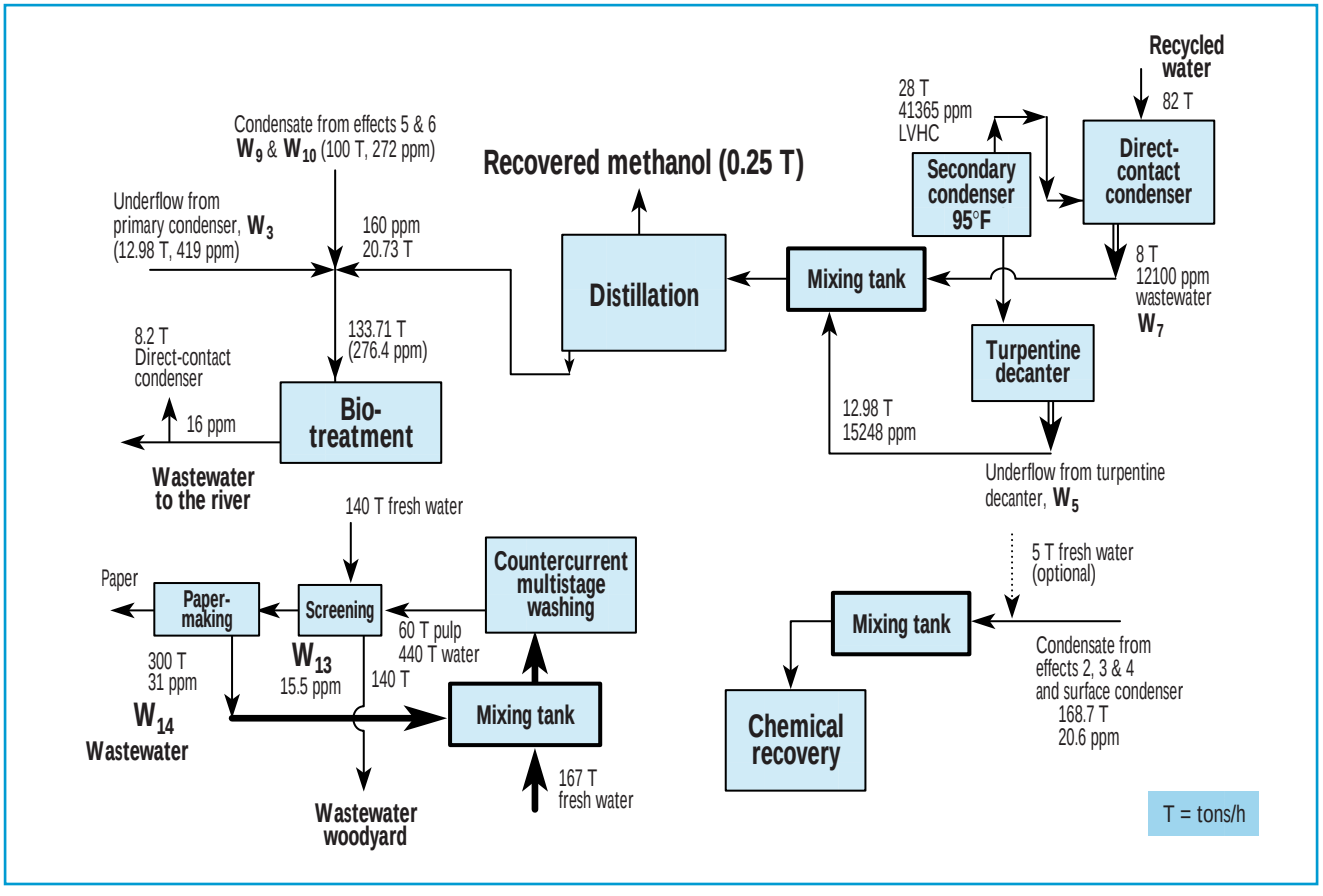
III. Mass-separating agent (MSA) data for methanol removal from liquid streams

Recycling and interception of in-plant streams affect the composition and flow rate of other streams. To study their effect on the paths of other streams, the path diagram is used.

Path diagram. The path diagram *(8, 9)* presents the composition and flow rate of all streams (sources) carrying the targeted species throughout the process. A path diagram should be evolved for each targeted species in each carrier. The composition and flow rate of each targeted species-laden in-plant stream are required to construct the path diagram.

Let's consider a generic process that consists of a presteaming vessel and a digester and washing system, as illustrated in **Fig. 9**. The stream leaving the presteaming vessel and the white liquor are assumed to have no methanol (the targeted species in this example). For simplicity, both streams are assumed to be mixed and fed to the digester. This stream is represented by Point A in Fig. 9. The cooking process inside the digester generates methanol. The changes in load and composition of the stream move the stream to Point B. Stream C (water) is mixed with Stream B inside the digester/washer system to produce Point D. Stream D is split into two streams, E (black liquor) and F (pulp). The path diagram for this example is presented in **Fig. 10**. Note that we considered the washing process as a mixing operation, with the output of the digester/washing system split into black liquor and pulp streams E and F, respectively.

Each node on the path diagram denotes a pollutant-laden stream that has the opportunity to be inter-



15. Optimal solution for the case study

cepted and/or recycled/discharged. The nodes on the path diagram are related to each other through process modeling correlations. Modeling correlations include mass balances and unit performance. Nodes are connected with each other by linear profiles (arrows), which represent the orientation of the mass flow. The tail of the arrow emerges from the input of the associated unit, while the head points toward its output. If the unit possesses more than one input and/or more than one output, the number of arrows associated with corresponding nodes would increase.

The path diagram provides engineers with a tool to understand the global mass flow of the targeted species without having to deal with complicated process flow diagrams. The path diagrams of methanol in liquid (water) and gaseous streams for the whole pulping operation are shown in **Figs. 11 and 12**, respectively. The equations (specific for this process condition) representing the liquid path are shown in the Appendix at the end of this paper.

Insights from the path diagram

As mentioned previously, one purpose of the graphical tools is to provide engineers with insights on the optimal solution. The path diagram provides the following insights:

Segregation opportunities. The path, composition, and flow rate of each stream carrying the targeted species is illustrated in the path diagram. In addition, the path diagram shows streams that are mixed or split and tracks the generation or loss of mass. Potential segregation opportunities can be identified for any two or more streams with different compositions shown in the path diagram to be mixed. For example:

1. Streams W_8, W_9, W_{10}, and W_{11} are mixed with each other to form the combined condensate (W_{12}). Segregation of these might be advantageous from a recycling viewpoint, as will be illustrated later in this paper.
2. Streams W_3 and W_5 are mixed to produce stream W_6. Since W_5 is more concentrated in methanol, its segregation may present cost-effective recovery of methanol (by-product recovery).

Interception opportunities. Interception opportunities can be identified by screening candidate MSAs using the hybrid path and pinch diagrams *(8, 9)*. After developing the path diagram, the candidate interception technologies are superimposed through horizontal projection, as shown in **Fig. 13**. This is similar to the pinch diagram (Fig. 7). Each interception technology is represented vs. its thermodynamic feasibility range.

The following insights can be obtained from Fig. 13. First, similar to

the pinch diagram, the interception technology with cheapest cost per unit mass removed should be used to intercept streams within its thermodynamic feasibility range. Furthermore, intercepting in-plant streams using cost-effective technologies may eliminate waste problems in terminal streams. For example, mixing streams W_5 and W_3 removes W_5 from the range of distillation by producing stream W_6 (Fig. 11). Intercepting stream W_5 might eliminate the problem associated with stream W_6. The following section describes candidate interception technologies.

Candidate interception techniques Interception of methanol might be needed to supplement the strategies of segregation, mixing, and recycle. Candidate interception technologies include activated-carbon adsorption, membrane separation, biotreatment, and distillation. The data for activated carbon are given in **Table III**. The variables m, ε, and c in Table III are the slope of the equilibrium line, the minimum allowable composition for the mass-separating agent (MSA) between equilibrium and operating lines *(7, 8)*, and the cost of the MSA, respectively.

Membrane vapor separation. Polydimethyl siloxane membrane is considered here for the separation of water and methanol from air. The permeability coefficients of methanol and water in the membrane are 11,000 and 14,000 Barrer *(16)*, respectively. For membrane cost data, the reader is referred to the literature *(17)*.

Biotreatment. For end-of-pipe treatment, biotreatment is considered.

Maximum inlet concentration = 1000 ppmw (parts per million by weight) methanol

Outlet concentration = 16 ppmw methanol (always)

$$\text{Operating cost (US\$)} = 0.025M + 0.0003G$$

where

M = mass load of methanol, lb/h
G = flow rate of wastewater, lb/h.

Distillation. Distillation will be considered only for recovery of methanol from liquid streams. To guarantee economic benefits of methanol recovery, distillation cannot be used for streams with less than 10,000 ppmw methanol.

After identifying all opportunities for the previously mentioned strategies, the optimal solution is tackled by iterating among the path diagram, source–sink mapping diagram, and the mass–pinch diagram, as shown in **Fig. 14**. The iterative scheme is necessary to study the mass propagation through interception and recycling. The reader is referred to the literature for rigorous mathematical formulation of the problem *(8, 9)*.

Optimal solution of case study By using the suggested iterative scheme, the optimal solution was determined and is shown in **Fig. 15**:

- The condensates from the multiple-effect evaporators are segregated, and the condensates from effects 2, 3, 4 and the surface condenser are recycled to the chemical recovery process.
- The untreated effluent from the screening process is used in the woodyard, since it meets environmental specifications.
- The effluent from the paper machine is mixed with fresh water and recycled to the countercurrent washing process.
- Distillation is utilized to recover methanol from the effluents from the direct-contact condenser and the turpentine decanter effluent. The effluent from the distillation column is routed to biotreatment.
- The effluent from the primary condenser is sent to biotreatment.
- Part of the effluent from biotreatment is used in the direct-contact condenser, and the rest is discharged to the river.

The proposed solution leads to a 0.25-ton/h reduction (recovery) in methanol losses and a wastewater reduction of 477 tons/h. These values correspond to recovery of 80% of methanol generated, 61% reduction in fresh water usage, and 64% reduction in wastewater discharge. Methanol discharged represents less than 2% of the methanol generated in the digester.

The distillation column was simulated (Aspen PLUS software). The number of theoretical plates was set at 12 with a diameter of 6.6 ft. With an efficiency of 66%, the total cost of the column with all the auxiliaries required for the project was determined to be US$ 1,125,000. The value of methanol recovered is approximately US$ 550,000/year. Hence, the payback period for this project—based solely on methanol recovery—is about two years. Other savings include US$ 88,000/year in fresh water and US$ 2,950,000/year in biotreatment cost.

CONCLUSIONS

Mass-integration methodology was used to identify opportunities for waste reduction in a pulp mill. The approach was demonstrated through a case study that targets reduction in methanol and water discharge. Based on strategies of segregation, recycle, mixing, and interception, several solution options were systematically generated. The results of the case study indicate that the mass-integration technique can identify solutions to environmental problems while also generating cost savings. TJ

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APPENDIX: EQUATIONS FOR THE LIQUID PATH IN THE CASE STUDY

The following set of equations represents the liquid path of methanol in the process:

Total mass generated in digester:

$$m_g = 0.311591 \text{ tons/h}$$

Mass in black liquor leaving the digester

$$m_b = 0.964 m_d$$

where

m_d = total mass in the digester

Mass in the underflow from primary condenser (W_3)

$$m_3 = 0.018 m_b$$

Mass in the underflow from turpentine decanter (W_5)

$$m_5 = 0.524 m_b$$

Mass in the underflow from indirect condenser (W_7)

$$m_7 = 0.355 m_b$$

Mass in the condensate from effects 2,3,4 (W_8)

$$m_8 = 0.011 m_b$$

Mass in the condensate from effect 5 (W_9)

$$m_9 = 0.037 m_b$$

Mass in the condensate from effect 6 (W_{10})

$$m_{10} = 0.538 m_b$$

Mass in the underflow from the papermaking process (W_{14})

$$m_{14} = 0.811(m_d - m_b)$$

Mass in the underflow from the screening unit (W_{13})

$$m_{13} = 0.189(m_d - m_b)$$

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