Process integration in pulp and paper mills for energy and water reduction - A review

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SUMMARY

Process integration (including pinch analysis) is a holistic or systems approach to process design and optimisation, which considers the interactions and interdependences between individual unit operations or process elements. Large reductions in both energy and water use in pulp and paper mills has been demonstrated using process integration techniques. A review of the current process integration techniques for energy and water reduction, with a focus on application to the pulp and paper industry is presented in this paper. The concurrent application of heat integration and water/mass integration analysis is discussed. Particular focus is given to published case studies. The integration of biorefineries into existing mills and the energy and water use implications is also receiving much attention and this development is also reviewed.

KEYWORDS:
Pulp and paper, Process integration, Pinch analysis, Water minimisation, Energy efficiency

INTRODUCTION

The pulp and paper industry is a large energy and water user and as resource use becomes more of a concern, the impetus to conserve and minimise the use of energy and water will become even greater. Process Integration (using techniques variously described as pinch analysis, pinch technology or heat integration) was developed in the late 1970's and early 1980's and has since demonstrated large energy reductions across numerous industries including the pulp and paper sector. Initially the focus of process integration was on thermal energy reduction, however this has since evolved to include water reduction and resource use optimisation.

The primary aim of process integration is to ensure valuable resources such as energy and water are used effectively while minimising costs. Specific analysis methods such as pinch analysis are employed to first establish meaningful and achievable targets or benchmarks, such as minimum energy use and maximum heat recovery, followed by techniques to design the heat recovery or heat exchanger network.

Traditional pinch analysis has been extensively used throughout the refining and petrochemical industries for several decades to substantially reduce energy use. Other industries such as chemical, pulp and paper, and the food and beverage industries have also benefited from pinch analysis; however there are some important considerations when applying traditional pinch analysis to the pulp and paper industry. The complex interactions between water and energy use is particularly relevant to the pulp and paper industry and therefore much of the recent progress in process integration is focused on developing methodologies that amalgamate heat integration and mass/water integration.

The concurrent design and synthesis of both heat exchanger and water networks is a complex task due to the co-dependence of the two. Furthermore, graphical methods that have been employed are severely limited and lacking when dealing with optimisation of water and heat exchange networks concurrently. Therefore more complicated mathematical programming and optimisation techniques must be used.

A review of current progress in the field of process integration for energy and water reduction with a focus on application to the pulp and paper industry is presented in this paper. First, the general process integration approach is outlined, followed by a presentation of heat integration and mass/water integration separately. The concurrent application of heat integration and water/mass integration analysis is discussed and the potential to conduct site wide studies for simultaneous reduction of energy and water is examined. Recent developments from leading research groups in the process integration field for pulp and paper, predominantly based in Europe, are reviewed.

PROCESS INTEGRATION

Process integration is a holistic or systems approach to process design and optimisation, which considers the interactions and interdependences between individual unit operations or process elements. The basic methods of process integration or pinch analysis, including both heat and mass/water integration are described at length in Smith *(1)* and Klemeš *et al., (2)*. For a detailed overview of heat integration see Kemp *(3)* or Sieniutycz and Jeżowski *(4)*. Mass or water integration is covered in Mann *(5)* and El-Halwagi *(6, 7)*. The basic process integration approach is described including data extraction, targeting, and heat exchanger and mass/water network design and synthesis stages as illustrated in Figure 1. Klemeš and Varbanov *(8)* discuss some of the more practical aspects of conducting process integration studies and the difficulties that are often encountered in practice.

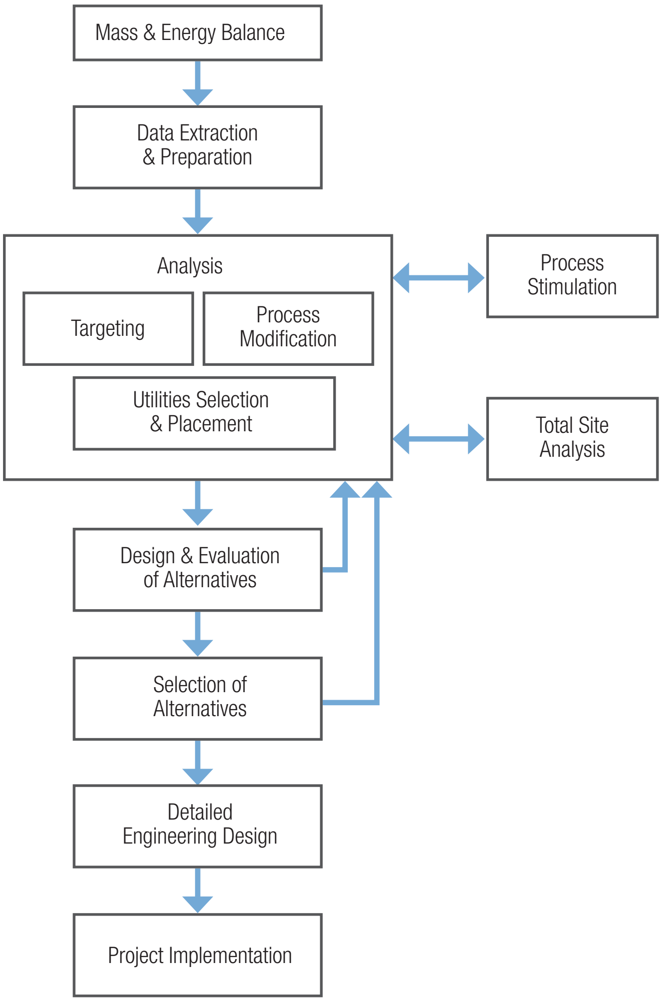

Fig. 1 General outline of methodology in pinch analysis (adapted from Linnhoff March *(9)*).

The several different approaches and methodologies employed in process integration can be broadly described as either insight based methods (such as pinch analysis) or optimisation based methods. Insight based methods often use graphical tools, such as composite curves, to calculate energy targets and provide methodologies for network design to achieve the targets. Networks can then be relaxed or modified to provide flexibility in the design and allow the designer to be involved at every step in the process. Some of the main advantages of these methods are that they are relatively simple, provide graphical representation of the problem, and involve the designer throughout the process. The major limitation is that for complex problems involving many streams or units, optimal solutions may be difficult to achieve without the aid of more rigorous optimisation techniques *(4)*.
Optimisation based methods tend to use some form of mathematical programming to optimise an objective function, such as minimise cost or energy use, and to achieve a global optimum. For multi-variable optimisation two search methods can be employed, deterministic (direct and indirect) and stochastic methods (such as simulated annealing and genetic algorithms). Each technique has advantages and disadvantages and often there is a trade-off between complexity of the formulation and therefore accuracy and computational time.
The basic pinch analysis technique is outlined as follows. Stream data is extracted for a mass and energy balance with supply and target temperatures and heat capacity rates assigned to each stream. For heat integration hot streams (also called source streams) are streams that require cooling, while cold streams (also called sink streams) require heating. Hot streams are added together to form a hot composite curve, and cold streams are added together to form a cold composite curve. These composite curves are graphed together on a temperature / enthalpy plot so that the minimum vertical distance between the curves is equal to the minimum temperature difference for heat exchange (ΔT_{min}). A generic set of composite curves is illustrated in Figure 2. Targets for minimum hot and cold utility requirements are established, along with other important targets such as minimum heat exchanger area.

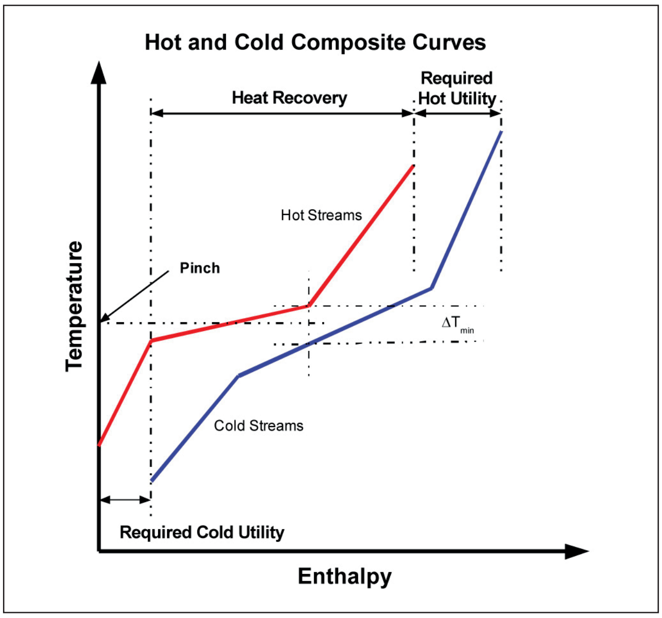

Fig. 2 Schematic of a generic set of hot and cold composite curves with the pinch point shown.

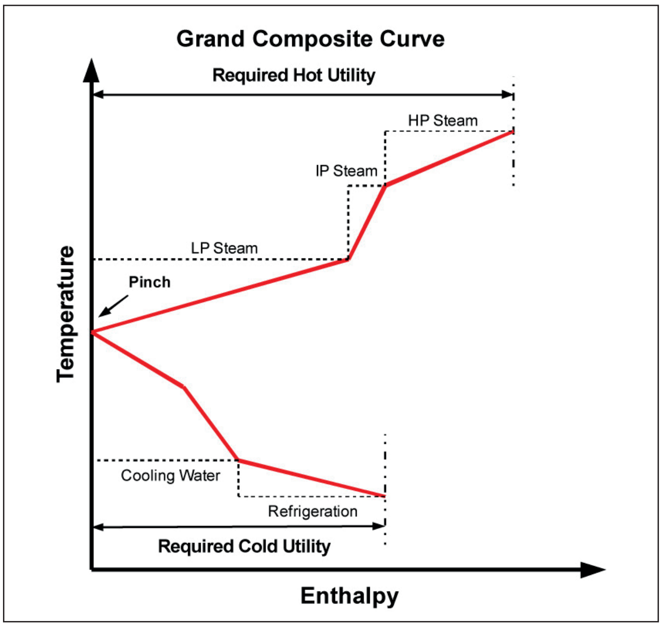

Fig. 3 Schematic of a grand composite curve.

The composite curves can be modified to produce a grand composite curve, which can give a better picture of the utility targets as well as establish individual utility targets. A generic grand composite curve is illustrated in Figure 3. Ultimately, targets are used to guide the design and development of alternative solutions, whether they are in the form of process change or modified heat exchanger networks. Alternative solutions can then be compared to an "ideal" case that meets the targets and the inherent trade-offs between energy and capital can be rigorously assessed. An example heat exchanger network is illustrated in Figure 4.

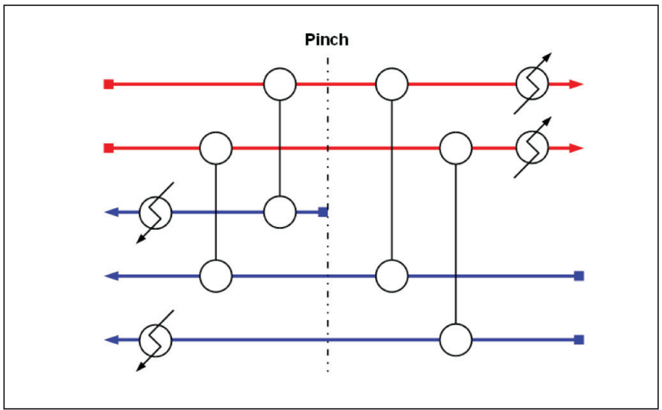

Fig. 4 Schematic of a heat exchanger network.

Several different graphical approaches have been developed for mass and water integration and the same general process outlined in Figure 1 is applied. A generic material recovery pinch diagram is shown in Figure 5.

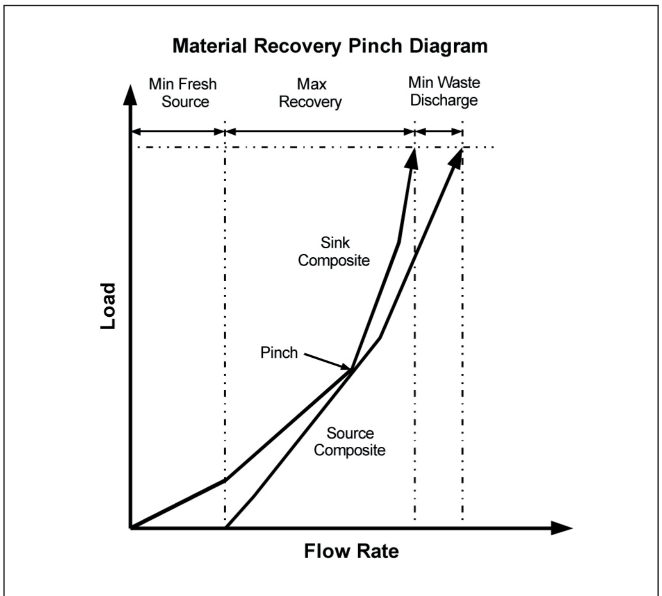

Fig. 5 Schematic of a generic material recovery pinch diagram for mass integration.

Many papers in the process integration area are presented at the annual International Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction or PRES conference with the peer-reviewed proceedings being published as *Chemical Engineering Transactions*. Over the years several excellent case studies have been presented at the conference, many in the dedicated pulp and paper session and selected papers from the conference are selected for high impact peer review journals such as *Applied Thermal Engineering*.

HEAT INTEGRATION

Pinch analysis for thermal energy reduction has been widely used throughout the pulp and paper sector with studies being conducted at well over 100 mills *(10)*. Many commercial studies (mainly unpublished) have been undertaken by consultants such as Linhoff-March (a division of KBC Process Technology Ltd) to identify or explore options for improved energy efficiency and heat recovery.

Many process integration studies have utilised model mills as the basis for examination. A model of an average Scandinavian kraft pulp mill developed as part of a nation Swedish research programme called "Future Resource Adapted Pulp Mill" or FRAM has been used in numerous studies conducted primarily at the Chalmers University, Sweden *(11-17)*. This approach has been highly beneficial when examining long term and strategic issues in the industry, especially as several technoeconomic studies have been performed to consider the best configuration for kraft mills producing excess steam *(16)*. For example, Jönsson et al., *(17)* compared the profitability and associated carbon emission reduction of several different technology pathways for utilising excess steam at a typical Scandinavian kraft mill. Pathways included increased electricity production, district heating, sales of biomass in the form of bark and/or lignin, and carbon capture and storage (CCS). The newer and emerging technologies (i.e. lignin separation and CCS) provided the largest carbon emissions reduction, but the profitability of these pathways were highly sensitive to both energy and carbon prices. The traditional pathways (i.e. electricity, district heating, biomass) provided more robust profitability scenarios and were much less affected by carbon costs, while representing much less risk than the emerging technologies, such as CCS.

More recently a Heat Load Model for Pulp and Paper (HLMPP) has been developed and applied to Scandinavian TMP mills to assess potential thermal energy savings *(18-20)*. The steam demand and pinch temperature for the mill was severely affected by the amount of freshwater use and theoretical steam savings ranged from 2 to 20% depending on the mill considered *(20)*. When summer and winter operation of these TMP mills are considered separately, the demand and potential efficiency measures changed significantly, mainly due to the change in temperature of the air and freshwater streams *(19)*.

Mathematical programming techniques have been employed in the design of heat recovery systems from paper machine dryer exhausts *(21-23)* and the wider process *(24)*. Both greenfield and retrofit situations have been considered. Similar approaches have also been used to optimise mill hot water systems *(25)* and site wide utility systems. Atkins *et al., (26)* used traditional pinch analysis methods to examine each individual part of a paper mill including changes in heat demand due to changes in product grade. The entire paper mill and heat exchange network was also considered as a whole and substantial savings were identified by resolving pinch violations and removing non-isothermal mixing of streams *(27)*.

Variability in process stream properties (e.g. mass flow rate, temperatures), ambient conditions, and production rate and product grade changes can have a large effect on the design and operation of the heat exchange network and the amount of heat recovery possible. Several studies have considered or raised these issues *(26-31)*. Persson and Berntsson *(30, 31)* have studied the effect of both seasonal and short-term variations on potential heat recovery. Approximately a 10% decrease was found when seasonal and short-term variations were considered individually, and the choice of reference conditions (e.g. summer, winter, or average values) determined the effectiveness of the heat exchanger network.

example, Marinova et al., *(39)* considered the potential impact on steam demand at a Canadian hardwood kraft mill including hemicelluloses extraction and conversion stages. Steam demand increased 13.1% and total steam production capacity decreased 5.9% when hemicelluloses extraction and conversion were included. However after conducting a heat integration study on the kraft mill only, practical and economic energy efficiency measures such as improved heat recovery, condensate recovery, water system closure, and integration of an absorption

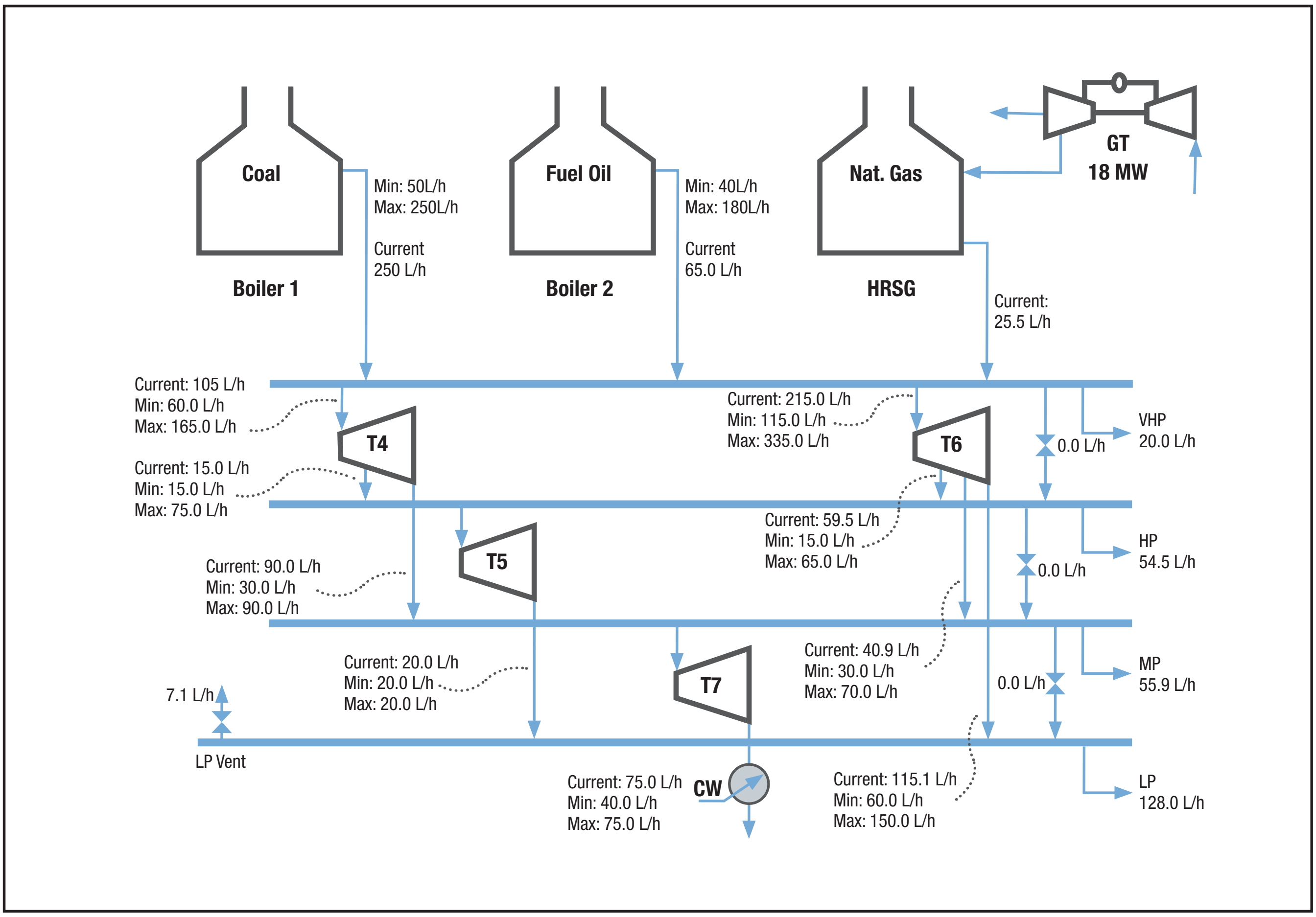

Fig. 6 Typical utility system schematic adapted from *(50)*.

The usefulness of detailed process integration studies is that longer term, strategic and decision making assessments can be considered *(10, 32)*. Future opportunities and production pathways can also be compared and assessed from both technological and economic perspectives *(16, 17, 33, 34)*. Biorefineries, biofuel production and advanced lignin separation processes, such as the ethanol organosolv process and how these types of processes are integrated into current pulp mills and the consequences for energy use and production are now being considered by several researchers *(35-41)*. The inclusion or conversion to a biorefinery significantly alters the total heat balance of the mill and excess steam is substantially reduced or in the case of a mill without an initial excess, additional external fuel would be needed to compensate for the additional load *(38, 39)*.

The potential integration of biorefineries may help assist traditional energy efficiency projects to be indentified and undertaken in order to allow more effective integration of the various biochemical and thermochemcial processes. For heat pump, total steam demand could be decreased by 23.7%. These savings more than offset the additional steam demand from the biorefinery. In fact, if only these efficiency measures were implemented, it would substantially reduce the amount of external fuel needed by the mill for steam production.

The integration of individual unit operations has received much attention, especially large energy consumers such as distillation columns and evaporators. The integration of multi-effect evaporators for concentrating black liquor has been the focus of several studies *(15, 42, 43)*. The integration of various types of heat pumps into pulp mills has also been considered *(39, 42, 44, 45)*.

Total site analysis can be used to integrate entire processing sites or groups of sites often utilising the utility system as a means of indirectly transferring heat between processes *(46, 47)*. Combined Heat and Power (CHP) or cogeneration systems are also designed and optimised using the total site approach and methodology *(48-50)*. The design and optimisation of reliable and flexible utility systems, including cogeneration, is a well developed subset of process integration and there is much that could benefit the pulp and paper industry. The inclusion of

total site analysis is vitally important when strategic studies are conducted as external fuel expenditure or excess steam can be minimised and best utilised *(11, 12, 17)*.
Much of the current focus is on design and optimisation of cogeneration from a reliability and redundancy perspective *(51)*. An example schematic of a site utility system is illustrated in Figure 6. Trigeneration systems integration (generation of heat, power, and cooling) to a pulp mill has also been examined *(52)*. There have also been several studies focused on the optimisation and integration of cogeneration to provide both steam and power to large sites or industrial parks with multiple users *(53-55)*.

MASS/WATER INTEGRATION

Following the development and application of pinch analysis for thermal energy reduction and heat exchanger network synthesis, the methodology was adapted to consider mass exchanger and water network synthesis and water minimisation *(56)*. This evolution is often called mass integration, mass pinch, and water pinch or water minimisation. For a recent review of the state-of-the-art in water network synthesis see Foo *(57)*. Bagajewicz *(58)* detailed progress in water management for processing plants and refineries and reviewed the mathematical programming techniques and algorithms that have been developed.
Far fewer mass and water integration studies have been applied directly to the pulp and paper industry and numerous variations in methodology have been employed *(59-61)*. One of the main difficulties is that the methodology is highly dependent on the complexity of the problem under consideration. There have been several graphical techniques developed including the limiting composite curves *(56)*, material recovery pinch diagram *(62)*, and water surplus diagram *(63)*. These techniques are more easily applied where only a single contaminant is considered; however the complexity of an integrated pulp and paper mill may require complex mathematical programming techniques to be employed.
Where multiple contaminants are considered mathematical programming techniques are superior, although more complex, and they also remove some of the design control away from the design engineer. If water or mass exchange network design and synthesis are considered then optimisation algorithms are more easily applied with mathematical programming techniques *(64)*. Total suspended solids *(65)* and dissolved solids concentration *(66-68)* are often used depending on the contaminants under consideration. The extraction of reliable stream data and setting realistic values of limiting contaminant concentrations is crucial *(69)*, however there exists few guidelines for the pulp industry *(66)* and limits will be very process and mill specific *(70)*.
Jacob *et al., (66)* applied both graphical and linear programming techniques to the cases of a de-inking plant and integrated newsprint mill. The authors concluded that the graphical method had merit for single contaminant problems and for visualisation of the results but lacked the capability to handle multiple contaminant problems. For the de-inking plant there was no freshwater reduction, although a filtration stage could be removed from the process. The integrated newsprint mill had potential for a two thirds reduction in freshwater use by redesigning the water network.
Parthasarathy and Krishnagopalan *(71)* optimised a kraft mill water system using a non-linear optimisation program. Chloride concentrations were considered in the study. The targeting process indicated that freshwater usage could be reduced by 78%, however the proposed water network only achieved a 57% reduction due to practical and economic constraints. Despite the importance of these optimisation studies, the importance of good housekeeping and engineering practice cannot be overstated *(60)*.

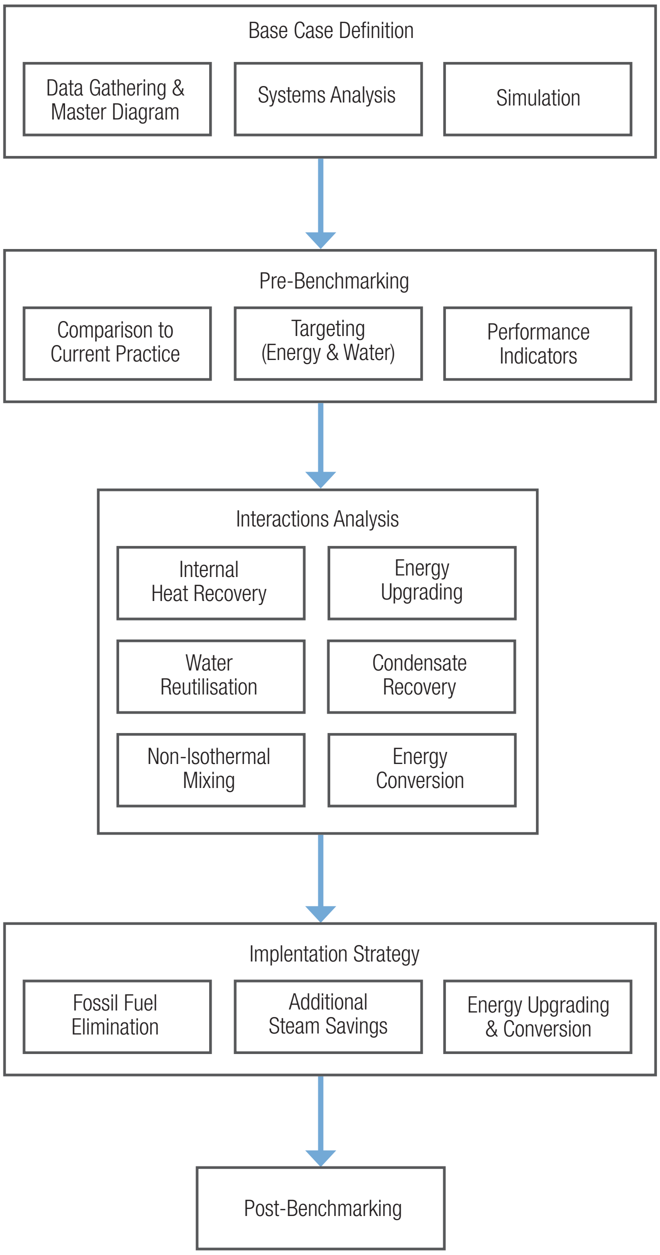

Fig. 7 Unified methodology for process integration at pulp mills (adapted from *(68)*).

SIMULTANEOUS HEAT AND MASS INTEGRATION

Although there have been numerous studies into heat and mass integration, the application of process integration methodologies for simultaneous energy and water reduction has only recently received much attention. The complex co-dependence between energy and water use makes the targeting process and designing heat exchanger networks and water networks difficult when both factors are considered together.

Several different approaches have been developed *(68, 72-75)*, although only a few detailed case studies focused on the pulp and paper industry have been published *(67, 68, 76-79)*. Mathematical programming and optimisation techniques have been extensively employed, usually to optimise the water network first followed by the heat exchange network. One issue is that any modifications to the water network and demand will directly affect the heat integration problem and vice versa. Multiple options for integrated solutions are possible which adds to the complexity of the problem.

Mateos-Espejel *et al., (67, 68, 78, 79)* have recently presented a so called "unified method" specifically applied to a kraft mill that attempts to systematically examine, quantify and implement mass and energy integration simultaneously. The interactions between internal heat recovery, water utilisation, non-isothermal mixing, energy upgrading, condensate recovery, and energy conversion form the basis of their analysis. Aspects of total site integration and utility systems optimisation are also incorporated. The major steps of the methodology are outlined in Figure 7.

FUTURE DEVELOPMENTS

Energy and water use implications of biorefineries and their integration into pulp mills will continue to be a focus and it is likely that future pulp and paper mills will become more highly integrated. The application of optimisation techniques will be more widely applied to both heat exchange and water networks. Simultaneous mass and heat integration will become more widely applied in the pulp and paper industry and techniques and procedures will become more refined and industry specific. A holistic, systems approach, including the concurrent reduction in energy and water, for strategic planning for the evolution of current mills and the development of future mills will be needed if the industry is to stay competitive and be seen to be reducing its environmental impact.

CONCLUSIONS

Process integration techniques are numerous and range from the relatively simple to extremely complex. Advanced methodologies in both heat and mass integration have been successfully applied to the pulp and paper industry, resulting in large identified reductions in energy and water use. Simultaneous mass and heat integration techniques are developing rapidly and if applied, promise to further optimise pulp and paper mills in the future.

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