PINCH ANALYSIS:
For the Efficient Use of Energy, Water & Hydrogen

PULP AND PAPER INDUSTRY
Energy Recovery and Effluent Cooling at a TMP Plant

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PINCH ANALYSIS APPLICATION EXAMPLE

Pulp And Paper Industry

Energy Recovery and Effluent Cooling at a TMP Plant

The following example is based on an actual study conducted in a pulp and paper mill. The example has been simplified to facilitate the description of the Pinch concept. The objective of this presentation is to provide a concrete illustration of the steps involved in the Pinch Analysis of an industrial process.

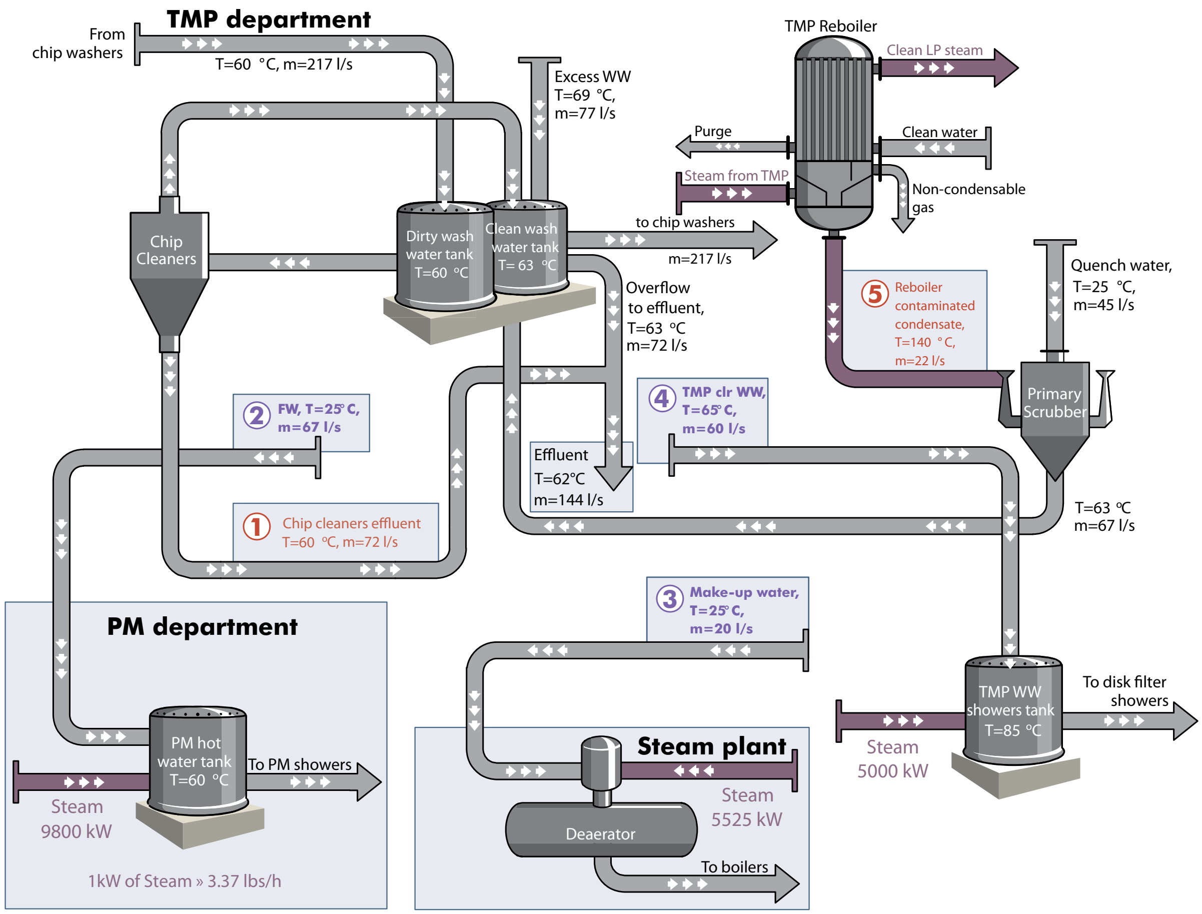
All costs mentioned in this text are in Canadian dollars (Can$).

Process Description

Figure 1 presents a simplified flowsheet of the process under examination, and includes the mass and energy balance data. The figure shows some components of a thermomechanical pulp (TMP) and paper mill, including:

- A chip wash water tank with cleaners for wash water;
- A reboiler, located in the TMP department, evacuates pressurized fibre-contaminated condensate. The condensate is flashed to atmospheric pressure in a primary scrubber that condenses the flash steam with fresh water showers in order to eliminate any fibre loss to the environment. The resulting mixture is then sent to the clean side of the chip wash water tank;
- The hot white water tank for the TMP pulp washers' showers;
- The hot water tank for the paper machines' showers;
- The steam plant deaerator for the boilers' make-up water.

Figure 1 Simplified Process Diagram of the Thermomechanical Pulping Process (TMP)



The streams numbered 1 through 5 will be used in this example. The steam requirement of this process is a consequence of the heating requirements of some process streams that need a temperature increase. This is the case for stream #4 for the pulp washers' showers, stream #2 for the paper machines' showers, and stream #3 for the steam plant make-up water. The total heating load for these 3 streams is 20,325 kW, or approximately 38 mt/h of steam at typically encountered pressures.

The cost of the steam generated to fulfill the process' heating requirements is 0,015 $/kWh (equivalent to 4,17 $/GJ). The mill is in production 8,400 hours per year. However, for several reasons (especially shutdowns caused by the maintenance schedule or defects in the equipment), the streams used in the process are not always available. When they are, their synchronism is imperfect. Also, continuous fluctuations in the process operation are caused by seasonal changes, grade changes, process control modes and process control stategies, etc. Taking all these factors into account, an annual operating time equivalent to 6,000 hours is used in this example. Consequently, the annual bill for steam usage is $1,830,00/year. (Inefficiencies related to steam production and distribution are not taken into account).

Figure 1 also shows the two hot streams that compose the effluent: line #1, the discharge from the chip wash water cleaners; and line #5, the contaminated condensate coming from the TMP reboiler. This last stream, going to the chip wash water tank, reaches the effluent through the tank's overflow. Streams #2 and #5, composing the effluent, have a combined temperature of 61°C, and must be cooled to 35°C to ensure the proper operation of the secondary wastewater treatment plant. This cooling is effected by cooling towers, located before the secondary wastewater treatment plant. This represents a cooling load of 15,945 kW. The cost of operating these cooling towers is relatively low compared to the cost of steam, and will be disregarded for the purpose of this example.

The Mill's Context and Pinch Analysis Objectives

The mill plans to increase its production by 10% in the upcoming year. However, the steam plant has already reached its full capacity with present needs. The same problem occurs with the capacity of the cooling towers for the effluent, which sometimes is short during the summer period. In order to increase capacity without spending money on new boilers and cooling towers, the mill's management wants to use energy saving projects to reduce the processing cooling and heating requirements. At the same time, the mill wants to reduce its greenhouse gas emissions in a profitable way. Management requires an average payback period of less than 12 months for the combination of projects, and a payback period of less than 24 months on each individual project.

To reach these goals, Pinch Analysis was selected to minimize the process steam usage and to reduce the effluent temperature to as close to 35°C as possible.

Application of Pinch Analysis: Data Extraction

The first step consists in analyzing the process flowsheet and its mass and energy balance data. This allows the extraction of the basic data required for the Pinch Analysis. In ***Figure 1***, the mass and energy balance data appear for each stream, including the value of the CP parameter (flowrates multiplied by heat capacity Cp), which is required for the calculation of the heating load corresponding to a stream temperature change. This is obtained with the following equation:

$$Q = CP\ (T_{init} - T_{final})$$

where Q = heating load (kW)
CP = mass flowrate x heat capacity (kW/°C)
T_{init}, T_{final} = initial and final temperatures (°C)

This data extraction phase is crucial because the figures selected to represent each stream will affect all results arising from the Pinch Analysis. ***Table 1*** is a possible extraction set for our example. Other sets are also possible and could lead to different results. The experience and judgement of the Pinch Analysis expert play a crucial role at this juncture.

The data in ***Table 1*** is based on the assumption that it is not desirable to flash the TMP reboiler's condensate in the scrubber because this operation cools the stream. The basis for this assumption is the thermodynamic rule of keeping a hot stream at its maximum temperature as much as possible. Thus, we preserve the maximum potential for energy recuperation in this process stream since its energy quality (temperature) is not degraded. By applying this axiom, we eliminate the scrubber's fresh water usage. Moreover, we do not alter the fibre load of the total effluent since, in the actual design, the fibre content of the reboiler condensate is already sent to the effluent through the chip cleaners rejects and the chip wash water tank overflow.

The final temperature given for hot streams #1 and #5 corresponds to the process requirement of 35°C for the effluent going to the secondary treatment plant (maximum allowable temperature for proper operation of the treatment process). In the same way, the final temperatures for the cold lines that must be heated are selected to meet process requirements (chests' temperatures, and maximum preheating temperature at the deaerator inlet, to ensure an adequate deaeration process).

Table 1: Data Extraction - Summary of Streams Data

no	Description	Type	$T_{initial}$ (°C)	T_{target} (°C)	Q (kW)	h (kW/m²-°C)	CP (kW/°C)
1	Chip cleaners effluent	hot	80	35	7,500	3.0	300
2	Paper machine hot water	cold	25	60	-9,800	3.5	280
3	Make-up water to boilers	cold	25	90	-5,525	3.7	85
4	Water from TMP disk filters' showers	cold	85	85	-5,000	3.1	250
5	Reboiler condensate	hot	140	35	9,776	2.9	93

Table 1 also contains the heat transfer coefficients (h) of each stream. This allows the preliminary design of the exchangers required to recover heat (evaluation of the heat transfer surface of each heat exchanger). The heat transfer coefficients are usually

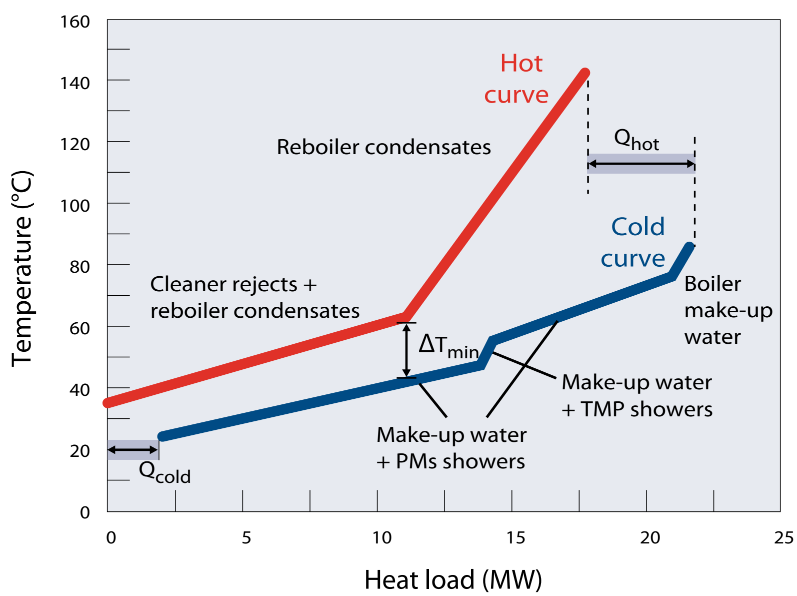
calculated by using generalized correlations, applicable to a precise heat exchanger technology, or may be provided by the manufacturer of the heat exchanger.

Establishing Energy and Capital Cost Targets

A powerful feature of Pinch Analysis is its ability to predict, even before the design of a heat-recovery exchanger network, the process' minimum energy requirements, and the minimum capital cost of reaching this minimum level of energy usage. These energy and capital cost targets are functions of a key parameter: the minimum temperature difference ΔT_{min} allowed to recover energy through a heat exchanger.

Energy and capital cost targets are established using the composite curves built from the data of ***Table 1***. ***Figure 2*** shows the contribution of each process stream in the composite curves.

Composite Curves **Figure 2**



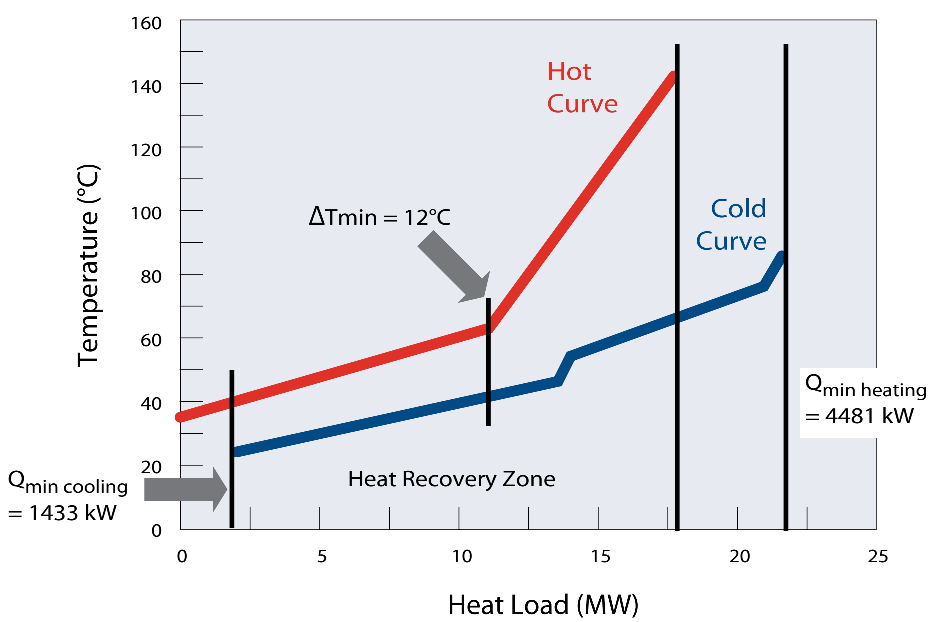
As discussed in **section 3.2** of the technical guide and titled *Pinch Analysis for an Efficient Use of Energy, Water and Hydrogen* produced by Natural Resources Canada, the composites curves represent the overall process in a global way and allow us to identify current inefficiencies, and the best opportunities for energy recovery.

The minimum energy target is given by overlaying both composite curves on the Temperature vs. Heat Load graph (***Figure 3***). The zone in which both curves overlap indicates the amount of energy that can be recovered between the hot and the cold streams of the process, and indicates where heating and cooling needs can be mutually satisfied. The overshoot of the curves on the left and right sides of the graph indicate the minimum heating and cooling loads of the process to be supplied by the utilities, that is, the energy targets.

The minimum cold and hot utility targets and the energy recovery load are related to the position of the two composite curves, relative to one another. This positioning is characterized by the minimum admissible temperature difference ΔT_{min} between both curves. Consequently, the minimum utility targets for process heating and cooling are directly related to the choice of ΔT_{min}. For our example, a value of 12°C has been chosen and is used to build ***Figures 2*** and ***3***. The procedure used to select the appropriate value of ΔT_{min} will be presented further. Other approaches, often based on the experience of the Pinch Analysis practitioner, are also possible.

The composite curves are also used to estimate the minimum capital costs (capital cost target) required for the purchase and installation of new heat exchangers that will bring the utility loads to their minimum values. This cost evaluation has two main components: the minimum number of heat exchangers to be installed, and the total minimum heat exchange area required by all heat exchangers in the network. For additional information on how to determine the minimum number of heat exchangers and the minimum heat exchange area, see the references at the end of this document. Commercial software also allows us to perform these calculations automatically.

Figure 3 Determination of Minimum Energy Consumption Targets



In this example, the minimum number of heat exchangers required to reach the cold and hot utility targets (N) is 4, and the minimum total heat exchange area is 549 m^2.

Once these values are known, a costing equation is used to evaluate the purchase and installation costs for the required heat exchangers. This equation depends mainly on the type of heat exchangers required by the process (spiral, shell and tubes, plates, etc.), the operating pressure, and the metallurgy. For the purposes of this example, the following equation has been used (A is the minimum exchange area in m^2, and N is the minimum required number of heat exchangers):

Total cost (Can$) = N (110000 + 5200 $(A/N)^{0.8}$)

For example, the cost determined by this equation is approximately halfway between the cost of a wide gap plate and frame heat exchanger and that of a spiral exchanger. This equation is only valid for a range of exchanger-areas, corresponding to the requirements of this example. The factor A/N represents the average heat transfer surface of each heat exchanger and allows us to make a preliminary cost evaluation for a network of N heat exchangers.

Target Values Obtained

With the help of Pinch Analysis software, we can draw curves showing the relationship between the desired targets and ΔT_{min}. We can then choose the value of ΔT_{min} that best matches the mill's objectives while satisfying its economic criteria. The targets thus obtained are the following:

- The annual steam savings (***Figure 4***),
- The purchase and installation costs (***Figure 5***),
- The payback periods (***Figure 6***).

Figure 4 Annual Steam Savings as a Function of ΔT_{min}

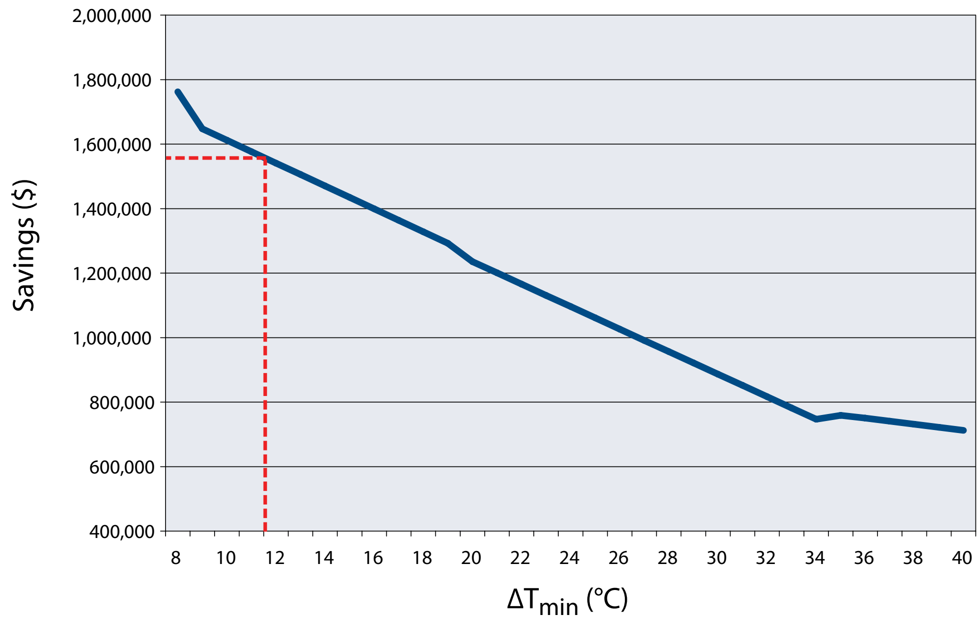


Figure 5 Purchase and Installation Costs as a Function of ΔT_{min}

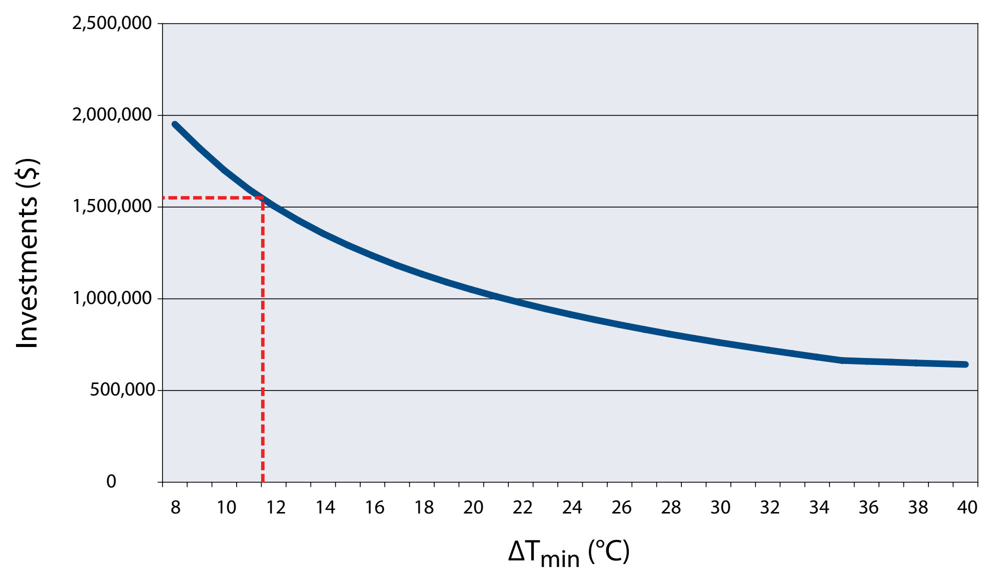


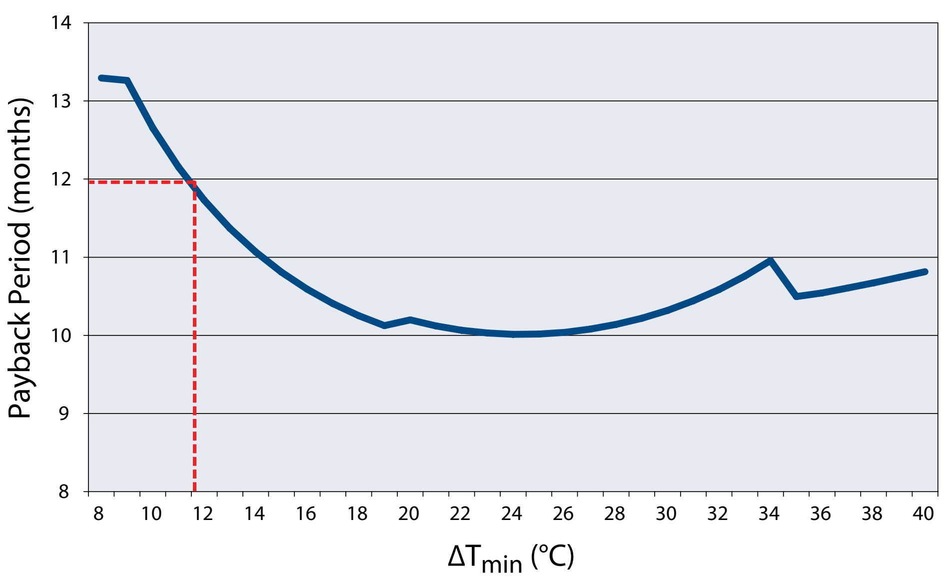
Figure 6 is a combination of the results shown in ***Figures 4*** and ***5*** (purchase and installation costs / annual steam savings). It should be noted that results obtained from various software packages that are available on the market could differ slightly from those shown here.

As well, we should observe that the heat recovery exchanger network that would meet the selected targets has not yet been designed. Nevertheless, the Pinch Analysis procedure allows us to determine, for a given ΔT_{min} value, the results that will be obtained once the design is completed. This is one of the most powerful features of Pinch Analysis. Another feature is its ability to identify, among all possible energy recovery projects, the ones that allow the designer to reach the minimum energy targets for the whole process (see *Project Design,* below).

Selection of the Appropriate ΔT_{min}

We will now try to maximize the benefits of energy recovery, using management's profitability criterion, here an average payback period of less than 12 months for all projects together. ***Figure 6*** may be used to identify the payback period as a function of ΔT_{min}. Since a solution based on Pinch Analysis may be composed of many energy recovery projects (or heat exchangers), we will also need to verify that each individual project meets the profitability target (payback period of less than 24 months) imposed by plant management. This verification will be carried out later, during the design of the heat exchanger network.

Payback Period as a Function of ΔT_{min} **Figure 6**



In ***Figure 6***, we see that maximum energy savings are obtained at a ΔT_{min} value of 12°C, while also satisfying the maximum acceptable average payback period of 12 months. With the use of ***Figures 4*** and ***5***, we determine the following targets:

- Energy savings: $1,540,000/year
- Minimum capital costs: $1,506,00/year
- Global payback period: 11.7 months

The entire set of target values is presented in ***Table 2***. The procedure used above to select the value of ΔT_{min} can be automated with software. All available commercial software packages include an automatic algorithm that may be used for this calculation. The algorithm may, however, be slightly different than the procedure shown here. Some Pinch practitioners use their own experience to fix the value of ΔT_{min} instead of using a procedure similar to the one presented in this example. Such an approach is acceptable as long as the practitioner has solid experience applying Pinch Analysis to the type of process under study.

Finally, we observe that the composite curves in ***Figure 3***, drawn for a ΔT_{min} of 12°C, show the pinch point located at 60°C on the hot composite curve, and at 48°C on the cold composite curve. This information will be essential in the design phase.

Table 2: Targets Obtained for a ΔT_{min} of 12°C

Parameter	Existing Process	Target	Reduction
Steam demand (kW)	20,325	4,481	78%
Cooling tower load (kW)	15,945	1,433	91%
Effluent temperature (°C)	61	39.8	
Minimum exchange area (m²)		549	
Energy savings (kW)		15,844	
Energy savings ($/year)		1,426,000	78%
Investments ($)		1,506,000	
Payback period (months)		11.7	

Project Design

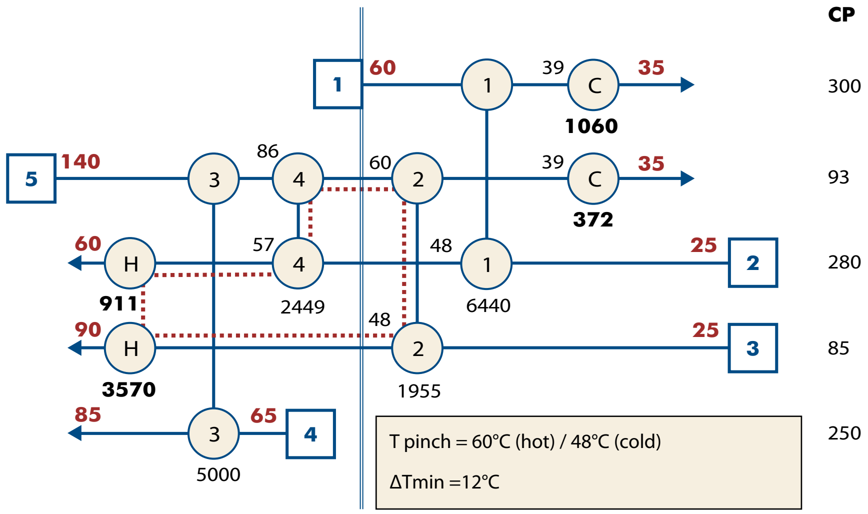
Pinch Analysis design rules allow the identification of solutions that meet certain study objectives, for example, minimum energy requirements. As discussed in **section 3.2** of the technical guide *Pinch Analysis for an Efficient Use of Energy, Water and Hydrogen* of Natural Resources Canada, these rules are a consequence of the constraints created by a temperature pinch point at the location of the ΔT_{min} on the composite curves.

There are three main rules that must be respected in order to reach the minimum energy consumption targets:

- Heat must not be transferred across the pinch (unless it is through a heat pump);
- There must be no cold utility (cooling water, air cooler, etc.) used above the pinch;
- There must be no hot utility (steam, hot gas) used below the pinch.

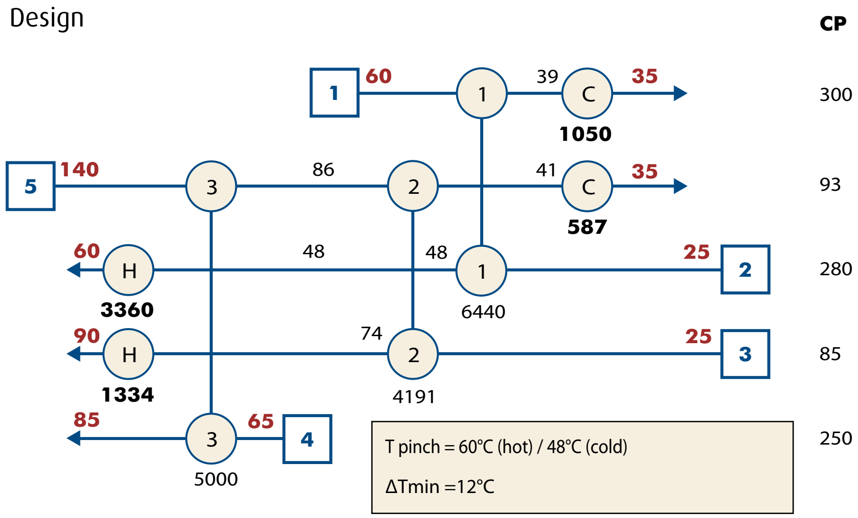
To efficiently design a heat exchanger network that will allow us to meet the targets presented in ***Table 2***, we use a design grid on which the pinch point location is clearly shown. By applying the above design rules, and by starting the design with the heat exchangers located around the pinch point, the heat exchanger network can be obtained, as presented on the grid diagram in ***Figure 7***. On this grid, the process streams are represented by horizontal lines. The circles connecting two lines correspond to the installation of a heat exchanger. The heat exchanger outlet and inlet temperatures are given, as well as the thermal load transferred from the hot stream to the cold stream through the heat exchanger (noted in kW under the lower circle). The utility loads of the network are represented by circles labelled H for heater (here steam), and C for cooler (here the cooling towers). ***Table 3*** summarizes the results obtained with the solution presented in ***Figure 7***.

Figure 7 Design Allowing to Reach the Minimum Energy Consumption Targets



In a second step, a final optimization process allows the evolution of the design towards a simpler, more flexible, and more profitable network. Here, it is possible to eliminate a heat exchanger using the loop and path concept. (For more details on this concept, see references at the end of the document). A loop consists of a group of heat exchangers connecting several streams into a closed circuit. The presence of a loop means there is one exchanger more than the minimum number required to satisfy process needs. This concept allows the identification of exchangers that may be discarded in order to simplify the design and reduce capital costs.

Figure 8 Final Design



However, simplifying the design will cause a penalty in the energy consumption that will be larger than the minimum required.

Figure 7 highlights a loop on which these concepts have been applied to eliminate exchanger #4. The final design is shown in ***Figure 8***.

Figure 9 presents the process diagram obtained from the design in ***Figure 8***. The new design includes three heat exchangers. The reject from the chip wash water cleaners is used to heat the paper machine showers. At the same time, the reboiler's contaminated condensate first heats the pulp washers' showers, and then, the steam plant make-up water.

Table 3: Comparison of Design Results, Identified Targets, and Current Energy Consumption

Parameter	Final Design	Target	Current Values
Steam usage (kW)	4,694	4,481	20,325
Energy savings (kW)	15,631	15,844	-
Total exchange area (m^2)	590	549	0
Number of exchangers	3	4	0
Effluent temperature (°C)	40.3	39.8	61
Energy savings ($/year)	1,407,000	1,540,000	-
Capital costs ($)	1,397,000	1,506,000	-
Payback period (months)	11.8	11.7	-

Table 4: Results for Each Exchanger in the Final Design

Parameter	Exch. 1	Exch. 2	Exch. 3	Total
Thermal load (kW)	6,440	4,191	5,000	15,631
Exchange area (m^2)	312	184	94	590
ΔT_{ln} (°C)	12.8	14.0	35.5	-
Energy savings ($/year)	580,000	377,000	450,000	1,407,000
Capital costs ($)	624,000	447,000	307,000	1,378,000
Payback period (months)	12.9	14.2	8.2	11.8

A summary of the results obtained from the final solution (as shown in ***Figure 8***), appears in ***Table 3***. The results are compared to the targeted values predicted for the ΔT_{min} of 12°C, and to current energy consumption.

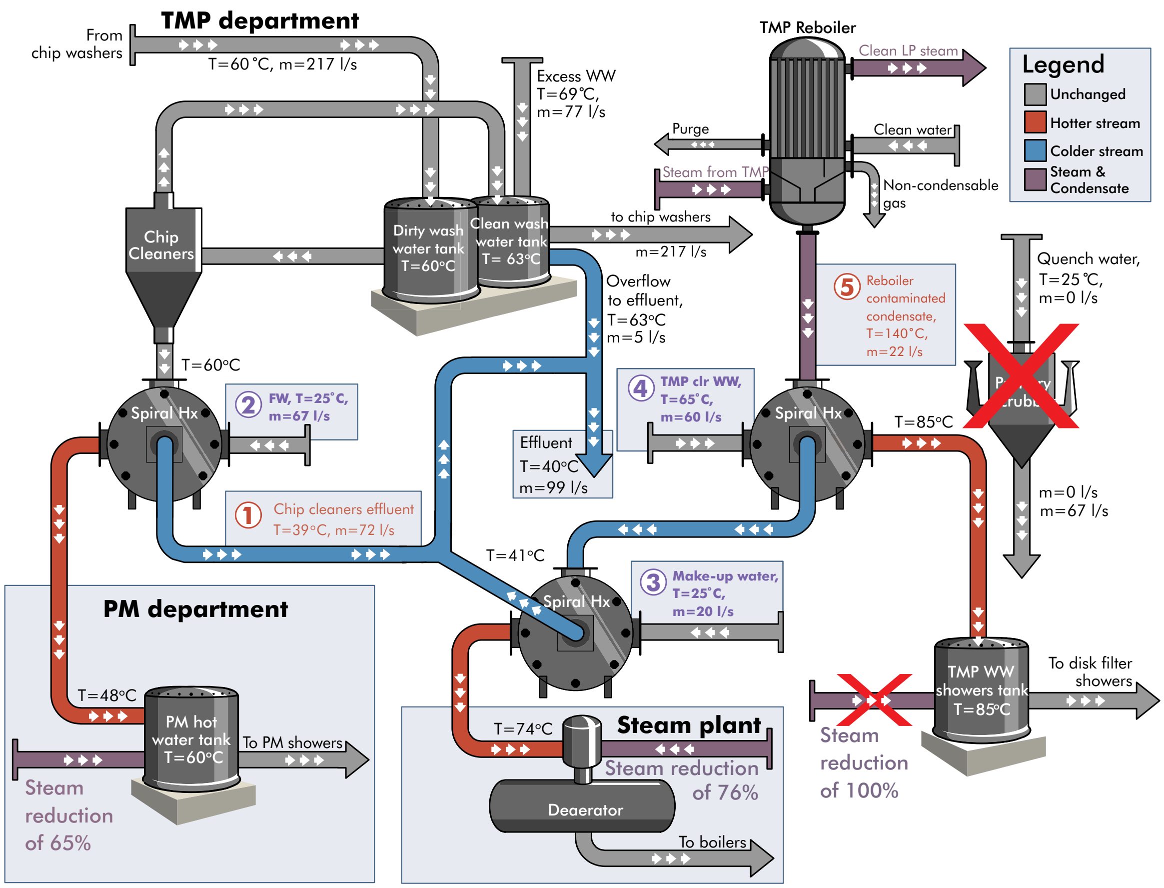
Table 4 presents detailed results for each heat exchanger. The purchase and installation costs of each heat exchanger are evaluated in the same way as the overall cost for all heat exchangers together, that is, with the following formula:

Individual cost (CAN$) = 110,000 + 5,200 $(A)^{0.8}$

A is the surface of each individual heat exchanger. In ***Table 4***, the total cost of all exchangers differs slightly from the one presented in ***Table 3*** because we evaluate each heat exchanger individually, rather than evaluating them as a function of the total heat transfer area of all heat exchangers together. We observe that, on an individual basis, all exchangers meet the specified criterion of a payback period shorter than 24 months.

The new design also generates fresh water savings by eliminating the reboiler condensate dilution, originally encountered in the scrubber. This contributes to a reduction of the effluent volume by 31%. Furthermore, it is important to emphasize that, in addition to reducing energy costs related to steam production, these projects also eliminate the capital costs that would have been associated with increasing boiler and cooling tower capacity.

Simplified Process Diagram Showing the Proposed Changes **Figure 9**



CONCLUSIONS

Pinch Analysis is a powerful technique for identifying minimum energy consumption targets for heating and cooling. At the same time, it facilitates the design of heat exchanger networks that enable us to reach, or get very close to, these targets while respecting the technical and economic constraints of a given plant.

To facilitate calculations, complex heat exchanger networks are usually designed with the help of Pinch Analysis software. Regardless of the software's performance and features, applying Pinch design rules combined with good judgement is essential to obtain the final solution.

Applying Pinch Analysis to an entire mill would obviously be more lengthy and complex, but this simplified example correctly illustrates the components of a Pinch Analysis study, and the powerful capabilities of this approach. In fact, the more complex the plant, the more important it is to use a systematic approach such as Pinch Analysis.

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The CanmetENERGY research centre in Varennes is one of three research and innovation centres of Natural Resources Canada (NRCan). CanmetENERGY in Varennes designs and implements technological solutions, and disseminates knowledge in order to produce and use energy in ways that are more efficient and sustainable, to reduce greenhouse gas (GHG) and other air emissions, and to improve innovation capabilities of targeted sectors of the Canadian economy.

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