MODELING AND OPTIMAL SYNTHESIS OF COOLING WATER PUMPING AND DISTRIBUTION SYSTEMS

Preliminary Report
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INTRODUCTION

In a plant, several processes use of heat exchangers when cooling is required. The most used cooling fluid is water, since it has high values of density and specific heat, besides being an abundant fluid. Cooling water demands are considerably high, in the order of thousands of cubic meters per hour, resulting in the use of large diameter piping, and also pumps with high electrical energy consumption. Project engineers have the challenge of designing cooling water pumping and distribution systems that yield minimum capital and operating costs.

Cooling water is usually generated in a cooling tower that operates in a semi-closed circuit. The supply cooling water is stored in a cooling tower basin, from where it is pumped to the supply header that has branches to supply each cooling water consumer. Normally, the heated cooling water is collected by a return header so it can return to the cooling tower to reject the absorbed heat to the atmosphere.

Cooling water branches with high pressure drops or very distant from the pumping system cause the pumping system head to increase, yielding high consumption of electrical energy. Recently, some studies have focused in the minimization of cooling water system costs by the optimization of the cooling water distribution system. Sun et al. [1] and Ma et al. [2] considered the use of auxiliary pumps to reduce the costs of a distribution system with heat exchangers arranged in series. Although, in theory, serial arrangements reduce the cooling water consumption, plant engineers sometimes prefer heat exchangers arranged in parallel to avoid complicated challenges to the plant operation and control. Nevertheless, the use of auxiliary pumps can be still used by systems with a parallel arrangement to reduce the power consumption of the main pumping system and also to avoid high pressure drops through control valves.

OBJECTIVES

Given a study case with estimates for cooling water consumption, this study proposed different designs to supply multiple consumers with cooling water. The designs differed in the location or even presence of an auxiliary pumping system, as well as the use of more than one supply header.

For each different design, it was defined the following characteristics of the cooling water system:

- Number of pumps in the main and auxiliary pumping systems
- Pump models to be used according to the required total head
- Piping arrangement

The simulation of each design case calculated the electrical energy consumption by the pumps, defining the design that yielded the lowest overall energy consumption.

The pumps and control valves used in the simulation are based on models commercially available.

The AFT Fathom software was selected due to the sophisticated and user-friendly interface, and also due to the robust algorithm to solve piping design problems.

METHODOLOGY

Cooling Water System Designs

Four different designs cases for the cooling water system were simulated in this work and these are listed in Table 1.

Table 1 – Design Cases for Cooling Water System

Design Case	Characteristics
D1	One main pumping system Single circuit for distribution of cooling water
D2	One main pumping system One auxiliary pumping system after major consumer Single circuit for distribution of cooling water
D3	One main pumping system One auxiliary pumping system after largest pressure drop Single circuit for distribution of cooling water
D4	Two main pumping systems One circuit for distribution of cooling water to major consumer, another circuit to distribution to other consumers

Study Case

As case study, cooling water consumption data for the conceptual design of a paper mill in Brazil was used. This data is shown in Table 2.

Table 2 – Cooling water consumption forecast for a Brazilian paper mill

Consumer	Cooling Water consumption ($m^3.h^{-1}$)
J25	4100
J26	200
J28	1100
J29	2400
J30	1000
J31	1100
J32	32
J33	400
J34	800
J35	400
Total	11532

Models were built in AFT Fathom for a single cooling tower distributing water to these consumers. The following assumptions were made for the modeling:

- Cooling tower is built next to consumer J25
- Cooling tower height is 10 m
- Pipe-rack elevation is 10 m
- Cooling tower basin and pumps are installed on the ground (elevation 0 m)
- Distance between consecutive consumers is 100 m
- Distance from supply header to return header is always 30 m, which is the length of all branches
- Every cooling water consumer branch has a control valve and a single heat exchanger
- Density and viscosity of water are assumed constant for all cooling water system

Design Criteria

The control valves installed not only adjust the cooling water flow rate through individual branches, but also assure that the branch pressures equal the return header pressure at the junction points. Depending on the distance from the main pumping system and the pressure drop in heat exchangers, the pressure drop values differ for each control valve. Large pressure drops in control valves should be avoided, since it means that a large quantity of energy is lost and also that the valve might have to operate with a small opening, potentially causing operational instability and cavitation. The energy loss (*EL*) can be calculated by the following equation:

$$EL = dP \, . \, q$$

where dP is the pressure drop and q is the volumetric flow.

Therefore, the pump head was designed to minimize such pressure drops in valves. As design criteria, the lowest pressure drop in a control valve shall be 0.6 bar

The other design criteria used are:

- Water velocity is limited to 3.0 m/s
- Cooling water level in cooling tower basin is 1 m
- Cooling water pressure at cooling tower top is atmospheric

Pump and Control Valve Data

To model the pumps, this study used data available from Goulds Pump Selection System (PSS) software. The selected pump model is 3196, which is an ANSI horizontal pump with an overhung impeller [3]. The following design criteria were adopted for pump selection:

- Alternate current frequency of 60 Hz
- Maximum speed of 1800 rpm

For the control valve data, the Cv curve used was obtained from Sude 1750/1760 Series globe valves catalog [4].

Heat Exchangers Pressure Drop

During conceptual and basic design phases, the pressure drop values for heat exchangers are not known. Instead, a maximum allowable pressure drop to comply with is informed to heat exchanger manufacturers. As good engineering practice, a value of 0.5 bar is established for that purpose, however larger values (1.0-1.5 bar) can be established.

In AFT Fathom, the heat exchangers were modeled with a K Factor value of 10, yielding pressure drops near 0.5 bar. For the purpose of studying systems where one or more heat exchangers have a higher pressure drops, the heat exchangers for consumers J28 and J31 were simulated with a K Factor value of 40.

RESULTS

Figures 1 and 2 show results of the cooling water system for Case D1. Using the mentioned premises the cooling water distribution system was modeled and simulated with AFT Fathom. The supply header is composed by pipes P2 to P12, the return header is composed by pipes P46 to P55, the cooling water basin is represented by reservoir J1, the main pumping system is represented by pump J2, and the cooling tower top is represented by assigned pressure J47. Some of the most pertinent pressure drops (dP) and energy losses (EL) are also shown in Figure 1. The full results are shown in the Appendix.

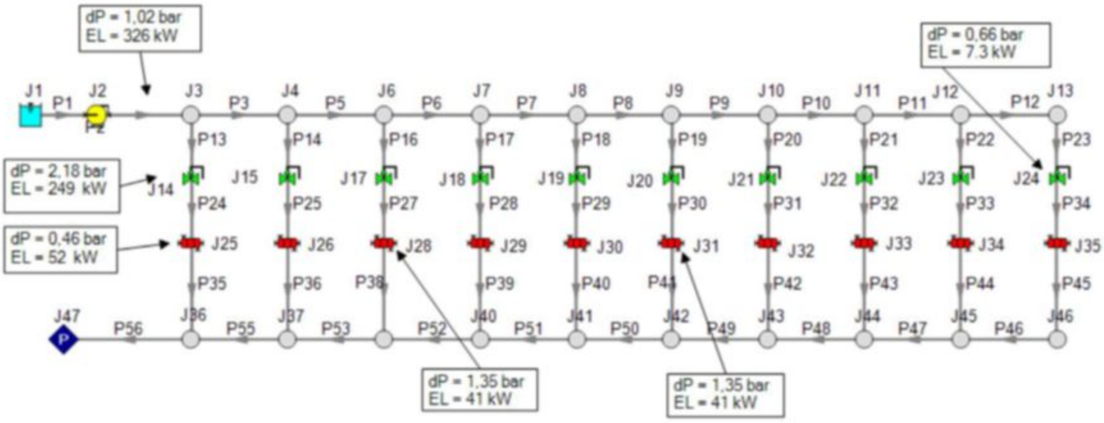

Figure 1 – Case D1 layout and results for the distribution system

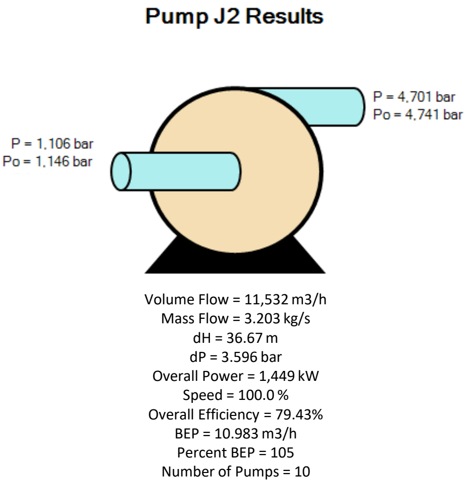

Figure 2 – Case D1 results for the pumping system

The largest pressure drop and energy loss is due to the pipe-rack and cooling tower top elevations, which is shown in the piping in the pump discharge, P2. This energy loss, cannot be minimized since the elevations are fixed project parameters. The next largest energy loss is in control valve J14 that is installed in the first consumer branch, J25, that is also the branch with the highest cooling water consumption. The pressure drop is significantly high, above 2.0 bar, but it cannot be minimized. To do so, the pump head (36.7 m) should be reduced, but that would reduce the pressure drops in all other valves causing the valves in the farthest branches from the main pumping system to operate with pressure drop in the control valves below 0.6, going against the design criteria. Hence the pump head cannot be reduced for this particular design of the cooling water system. The total power consumed for this design is 1449 kW.

In Case D2, an auxiliary pumping system (J48) is installed in the supply header, right after the Consumer J25 branch. Hence, the main pumping system head is reduced from 36.7 m to 22.2 m. Figures 3 to 5 show the results for the simulation of Case D2.

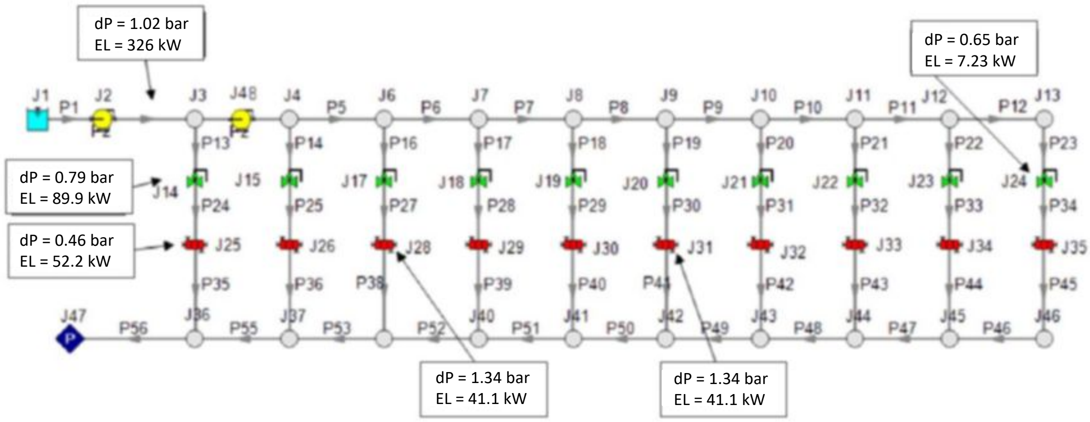

Figure 3 – Case D2 layout and results for the distribution system

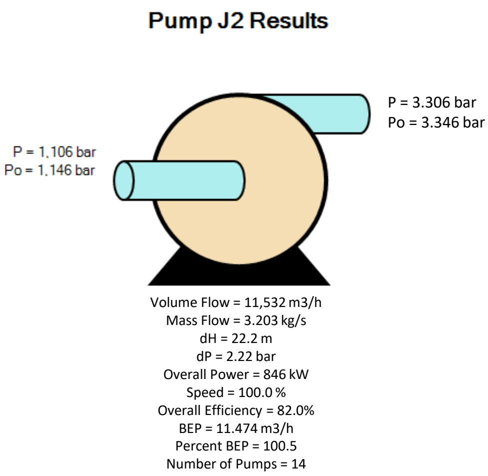

Figure 4 – Case D2 results for main pumping system

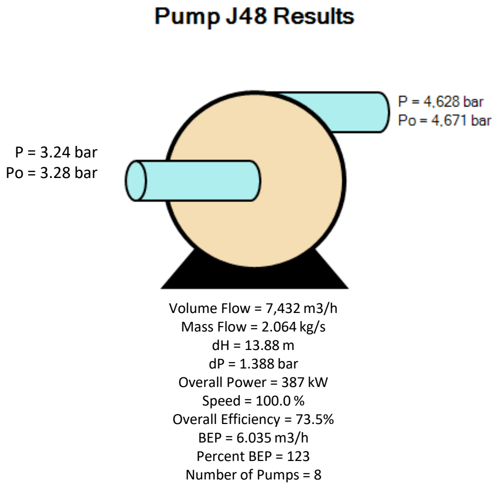

Figure 5 – Case D2 results for auxiliary pumping system

For Case D2, the energy loss in control valve J14 is reduced from 249 to 90 kW, contributing to a reduction in overall consumed energy from 1449 to 1233 kW.

In Case D3, the auxiliary pumping system is moved further downstream from the main pumping system. The main pumping system head is increased from 22.2 to 32.1 m in comparison with Case D2. In the other hand, the auxiliary pumping system head is reduced from 13.9 to 4.1 m. Figures 6 to 8 show the simulation results for Case D3.

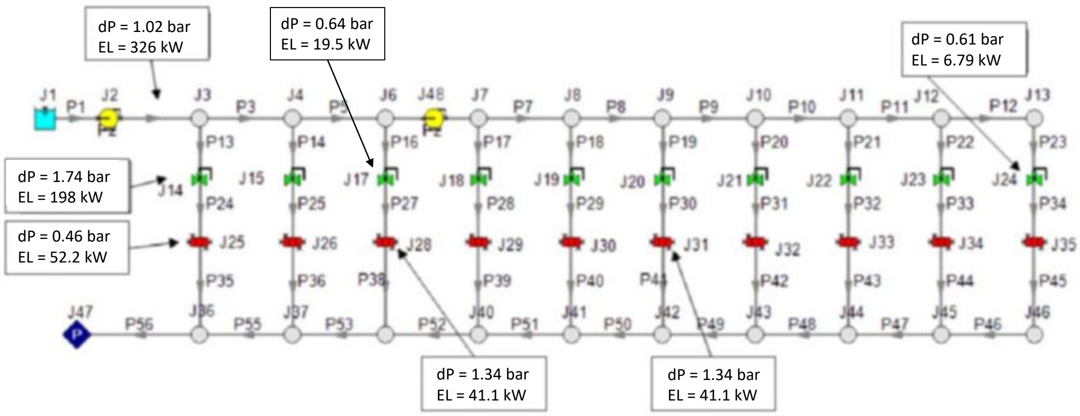

Figure 6 – Case D3 layout and results for the distribution system

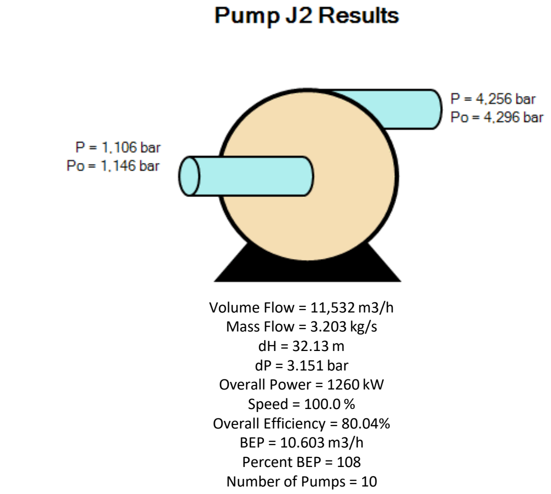

Figure 7 – Case D3 results for the main pumping system

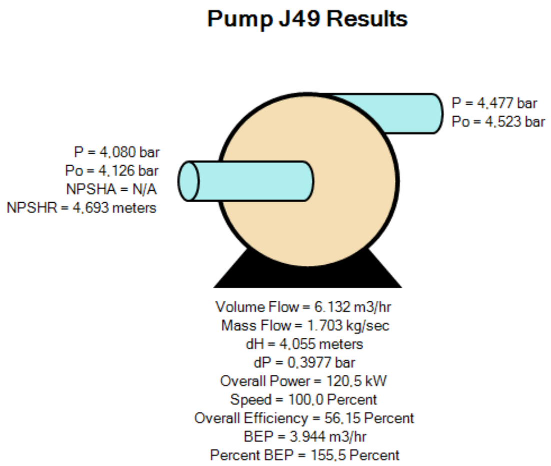

Figure 8 – Case D3 results for the auxiliary pumping system

The main pumping system in Case D3 consumes 1260 kW, while the auxiliary pumping system consumes 121 kW. The energy loss in control valve J14 is 198 kW, lower than the energy loss in Case D1, but larger than the one in Case D2. This happens due to the fact that the pressure drop in control valve J17 is 0.64 bar, therefore limiting the main pumping system head to a minimum of 32 m, and the pressure drop in control valve J14 to 1.7 bar. The auxiliary pumping system head is relatively low, causing this particular pump selection to have a low efficiency. The overall energy consumption is 1381 kW, yielding a reduction of 68 kW.

For Case D4, two cooling water distribution systems and two distinct main pumping systems (J2 and J262) are used. Since consumer J25 has the largest cooling water demand, a dedicated distribution system is designed for this consumer, as shown in Figures 9 and 10. For the remaining consumers, a second distribution system is designed, as shown in Figures 11 and 12.

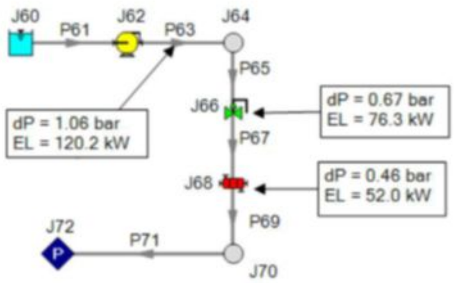

Figure 9 – Case D4 layout and results for first distribution system

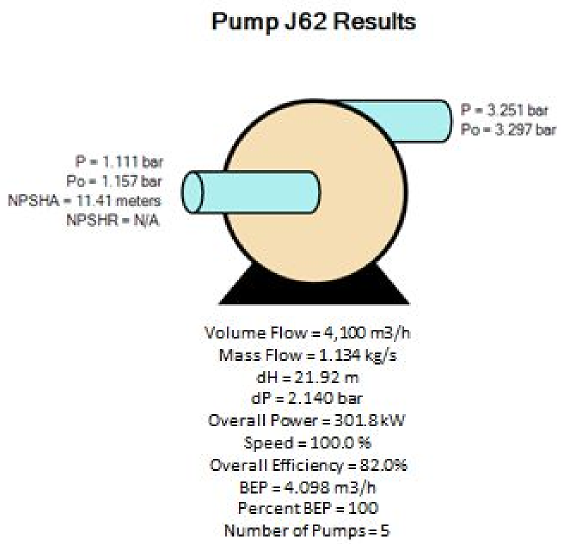

Figure 10 – Case D4 results for first pumping system

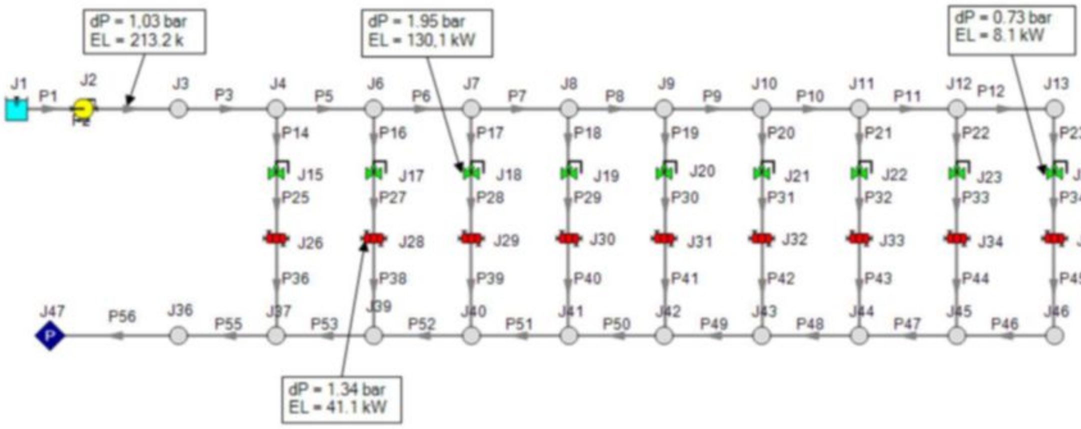

Figure 11 – Case D4 layout and results for second distribution system

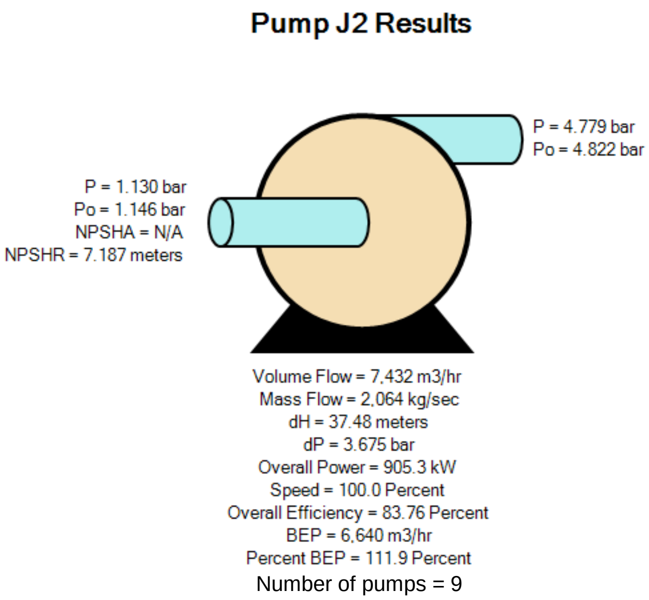

Figure 12 – Case D4 results for second pumping system

The overall consumed electrical power in Case D4 is 1207 kW, which represents a reduction of 240 kW (about 17%) from the value presented in Case D1. The difference in energy losses in control valve J15 from Case D4 to D1 accounts for 173 kW of that reduction.

Table 3 presents a comparison for the results of Cases D1 to D4.

Table 3 – Simulation results for Cases D1 to D4

Case	Energy Loss for Valve J14 (kW)	Main Pumping System Power (kW)	Auxiliary Pumping System Power (kW)	Overall Energy Consumption (kW)
D1	249	1449	0	1449
D2	135	846	387	1233
D3	198	1260	121	1381
D4	76	302 + 905	0	1207

Pressure drop values in piping due to friction are low compared to the values found for control valves and heat exchangers in all four design cases. The piping diameters could be theoretically reduced, but that would cause the water to flow at high velocities, increasing the possibility of damage from water hammer.

For a pipe length of 100 m, the pressure drop value is about 0.1 bar, hence for very lengthy headers (1000 m or more) the cumulative pressure drop due to friction in the piping has a more significant impact in the pump head. This can be noted by the relatively low pressure drop values for control valve J24, installed on the farthest branch from the main pumping system.

CONCLUSIONS

The initial focus of this study was on the elaboration of different designs for the cooling water system and the impact of these designs on the operating costs of the pumping system. Case D1 represents a relatively simple and straightforward design for the cooling water system, but also one that has the highest electrical energy consumption. The energy loss in the control valve (J15) of the largest consumer is high and impacts considerably on pump heads and, therefore, on the pump power. This happens since the pump has to pressurize the cooling water sufficiently for it to reach the consumer farthest from the pumping system, despite the fact that the energy loss in this consumer is relatively low.

Case D4 considered separate headers in order to distribute cooling water to the highest consumer, reducing the energy loss found in control valve J15 to a minimum value.

The result for Case D4 yielded the highest reduction of energy consumption from Case D1, about 17%, but the impact on the capital costs of the use of more pumps (14 against 10) and more piping has to be accounted.

Cases D2 and D3 presented designs of single supply and return headers, but with an auxiliary pumping system, where additional pumps are installed in the headers to boost the cooling water pressure. For Case D2, the auxiliary pumping system is installed after the first and largest consumer, while for Case D3 it is installed after the third consumer. The energy loss in control valve J15 calculated for Case D2 is reduced to similar values found in Case D4; hence the energy reduction is significant, about 15%. For Case D3, the energy loss in control valve J15 increases and the energy consumption reduction is lowered to 5%.

The partial results of this study show that it is necessary to identify through simulation not only the highest energy losses of the cooling water system but also the bottlenecks that limit the required pump head. Different designs reduce these constraints, but at the likely expense of an increase of capital costs.

RESEARCH CONTINUATION

For the second part of this study, the focus will be on the evaluation of the capital costs for the different design cases described in this report. A research on market prices for pumps, piping and control valves will be conducted to evaluate the capital costs, besides a research on electrical energy costs. Different project scenarios will be simulated, where parameters such as interest rates and plant operation horizons will be varied to assess the effect on these parameters on the optimal design solutions.

The primary objective of the study is to develop a methodology to attain the optimal design for cooling water systems considering operating and capital costs. The AFT Fathom use is necessary to evaluate these overall costs. As the methodology is developed, better design solutions are elaborated and there will be need to simulate these solutions.

The schedule for the second part of the research is the following:

Activity	February	March	April	May	June	July
1 – Equipment cost research	x	x				
2 – Capital costs calculation	x	x	x			
3 – Optimal design methodology			x	x	x	
4 – Technical paper first draft for journal submission					x	x

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