INTERCONNECTED ENERGY FLOW ANALYSIS AND HEAT RECOVERY STRATEGY OF THE MICHELIN BRIDGEWATER MANUFACTURING FACILITY

by

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ABSTRACT

This study presents the analysis of the heating and cooling systems in the Michelin Bridgewater production facility and the investigation of the interconnected effects of the heating systems. The Michelin facility has been operational for over 30 years, and does not have an in-depth understanding of how production is affected by changes in steam production.

The steam production system has been modeled along with the cooling water systems. Each of the thermal energy sources and sinks has been represented in order to gain more understanding of what type of interconnection there are between processes. The amount of steam supplied to each process was calculated using simulations. Actual plant data for the total water usage and steam production were used in the model, along with measurements collected experimentally. In order to obtain simulated results that reflected the actual plant data, three individual models were created for the winter, summer and fall seasons.

The simulation offers a better understanding of how the individual production areas are connected and how changing individual operational parameters affects the other systems in the facility. The simulations could be used to test operational changes, and predict what effects there will be on the heating and cooling systems, without the risk of losing production during testing.

In addition to the overall plant simulation, an initial study was performed on the feasibility and potential cost savings of using the domestic hot water system as a potential heat sink. The results of this study suggest that there would be a saving of $16,513 per year of Bunker C fuel. This would be in addition to the reduced emissions from burning less fuel in order to heat the domestic hot water.

LIST OF ABBREVIATIONS AND SYMBOLS USED

Dimensional Variables

c_p	Heat capacity (J kg^{-1} K^{-1})
D	Diameter (m)
h	Convection coefficient (W m^{-2} K)
h	Enthalpy (kJ/kg)
k	Thermal conductivity (W m^{-1} K^{-1})
$\dot{m}$	Mass flow rate (kg h^{-1})
n	Exponential power (-)
P	Pressure (kPa)
Q	Volumetric flow rate (m^3 s^{-1})
q	Thermal power (kW)
q_x''	Heat flux (W m^{-2})
T	Temperature (°C)
u	Velocity (m s^{-1})

Greek Letters

Δh	Enthalpy change (kJ/kg)
$\Delta \dot{m}$	Mass flow difference (kg h^{-1})
Δq	Thermal power difference (kW)
ΔT	Temperature difference (K)
Δx	Thickness (m)
μ	Viscosity (N s m^{-2})
ν	Kinematic viscosity (m^2 s^{-1})
ρ	Density (kg m^{-3})

Subscripts

air	Air compressor system
c	Condensate
$cold$	Cold inlet of DHW

Cu	Copper
D	Diameter
f	Liquid
g	Gas
hot	Hot outlet of DHW
hw	Hot water
i	Inside wall temperature
in	Inlet stream from the compressor cooling system
inf	Infinity
m	Mean
o	Outer wall temperature
out	Outlet stream leaving the DHW pre-heating HX
s	Steam
steam1	Current steam in DHW heater
steam2	Modified steam for DHW with pre-heater
w	Water

Abbreviations

Prep	Preparation shop
S115	115lb steam line
S250	250lb steam line
WWTP	Waste Water Treatment Plant

Definition of non-dimensional variables

Nu_D	Nusselt number (hD / k)
Pr	Prandtl number ($C_p\mu / k$)
Re_D	Reynolds number ($\rho DV / \mu$)

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CHAPTER 1 INTRODUCTION

The industrial sector has increased their awareness of energy conservation and with that, how to increase their facilities functions. When facilities are purchasing and installing specialized equipment into their factories, it is often one piece at a time; the impact this machine has on the overall energy usage at the facility is generally unknown. Modifying a process in one area of a factory has the potential to disrupt the balance of the plant and shift the running conditions away from the original design parameters. The interdependence between processes is complex and not well understood. It is believed that many industrial facilities have potential for energy savings, if there was improved comprehension of the effects that each piece of equipment and process has on the factory's overall energy balance (Ong'iro et al., 1996). The following research project will investigate a manufacturing facility's industrial heating and cooling process systems and create a model to study the interconnectedness of those systems. This model will include the manufacturers' steam plant and water systems.

A reason for having a thermodynamic model created for a facility includes the ability to identify areas for capital investment in order to reduce operational expenditures (West et al., 2008; Arachchige et al., 2012). Studies like these are performed for a myriad of reasons, including but not limited to: system performance, design studies and to see the effect of system modifications without production downtime (Ong'iro et al., 1995; Ong'iro et al., 1996; Ordouei, 2009).

1.1 BACKGROUND

Manufacturing facilities are constantly evolving, upgrading equipment, central systems and increasing their physical footprints. With these changes, it can be difficult to keep all systems in check and running at ideal settings. This often results in restrictions being realized and available resources being reallocated in order to maintain production requirements.

Many older production facilities use municipal water as their source of cooling and do not use additional systems to increase the cooling capacity of the water. This can result in seasonal fluctuations in cooling capacity, as the municipal water temperature tends to change with the seasons.

The Michelin facility (Bridgewater, NS) being studied was originally constructed in the early 1970's to produce wire products for tire production. Since its original construction the plant has continued expanding to produce different types of wire products and light truck and passenger car tires. The total footprint of the plant is 92,903 m^2.

The plant has been asked if an increase in the amount of water used by production would be possible. The supply of the cooling water and the additional steam required will not be the limiting factor. The ability to cool and process the water in the wastewater treatment plant will be the bottleneck. The waste water treatment facility is currently operating near capacity and with the potential increase in demand for cooling water; the facility requires a study to determine the actual distribution of the raw materials so that projects and upgrades can be performed to allow for increases in cooling water usage.

1.2 PROBLEM DESCRIPTION

The interconnection of systems is an area of concern for Michelin because the interconnections between processes could have a large effect on how some processes perform depending on what other loads are present. If the plant has been set-up to perform best when all processes are running at 100% capacity, what happens when there is a new process added or an existing process is modified? Is there a detrimental effect when all processes are not running at 100% or when only some of the processes are running? With a better understanding of the interconnection of systems, it will be possible to predict how the facility will react to varying conditions.

1.3 RESEARCH OBJECTIVES

The objectives of this research project are to:

1) Create a thermal energy model of the heating, cooling and thermal processes in the plant.
2) Investigate the influence of the systems' interconnectivity.
3) Assess the domestic hot water system as a possible heat sink.

Objective 1: Create a thermal energy model of the heating and cooling process in the plant.

The model will be populated using actual plant data from the heating and cooling processes of Michelin's manufacturing facility. These processes include steam, domestic hot water, heating water, and cooling water. This model will show the interaction of each process on the overall system and the effect that each of the heating and cooling systems has on one another. The purpose of this model will be to simulate future plant modifications and weigh their impact on the system, as well as supply Michelin with a snapshot of how their facility currently performs.

Objective 2: Investigate the influence of the systems interconnectivity.

Upon completion of Objective 1, simulations will be performed using HYSYS to study the behaviour of the interconnected systems by modifying input parameters and determining their impact on the plant.

Objective 3: Assess the domestic hot water system as a possible heat sink.

Investigate using the central domestic hot water (DHW) system as a heat sink. This will include the evaluation of the current configuration and how much fuel would be saved if the domestic hot water were a heat sink.

1.4 DELIVERABLES

A HYSYS model showing the major sections of the facility and the analysis of the interconnectedness of the model will be performed. An assessment of the current domestic hot water system will be completed and a cost reduction analysis for using the domestic hot water as a heat sink will also be presented.

CHAPTER 2 LITERATURE REVIEW

The reduction in water and fuel is a vital step in order to reduce the environmental impact of industrial processes. In order to further reduce water and fuel usage, a more in depth knowledge is required of the interconnections of facilities processes and how those interactions cause the facility to react with changes to the operating conditions.

Re-designing systems to decrease water usage has been an area of focus in order to reduce the environmental impact of industrial facilities. There has been research done on new ways to recycle water, from one process to another, and what impact this recycling would have on the processes (Kuo and Smith, 1998). Other studies have investigated the opportunity for thermal energy recovery from effluent, as it often leaves a plant at a higher temperature than it entered (Picón-Núñez et al., 2007; Ponce-Ortega et al., 2010). Furthermore, the effluent temperature and composition needs to be monitored, on a regular basis, to ensure there are no detrimental environmental effects (Panjeshahi et al., 2009).

The available knowledge of individual components such as, pumps and heat exchangers is extensive. However, the study of a system including many components has only recently started to be investigated. The study of portions of systems such as, cooling towers and heat exchanger networks (Kim and Smith, 2001; Panjeshahi et al., 2009) has been studied more in the past two decades, along with the interaction between those components (Kim et al., 2001). There is little other published literature on the relationship between multiple thermal processes within a manufacturing facility. Most companies contract experts or consultants to study their manufacturing sites and propose solutions to reduce items such as electrical, fuel and/or water consumption levels.

In most systems, when a parameter is altered, there is a resulting effect on the overall system (Thomas et al., 2011; Thomas et al., 2012). The influence of each individual parameter can be studied by changing their values in the current plant configuration and monitoring the effects throughout the system (West et al., 2008). During equipment design and installation, there is little information about what the performance would be when running off of the original design specifications. To better understand how a system actually performs and what the effect of off-design parameters would be, simulations can be used (Queiroz et al., 2012). In manufacturing, there are many systems working in conjunction with one another making the overall system complex and difficult to model. Typically manufacturing simulations are used as decision making tools but, traditional simulation techniques are not capable of modeling such complex and distributed systems (Uygun et al., 2009).

Computer models and simulations have made it possible to understand and design processes more efficiently by not having to use the trial and error procedures (Lindgren et al., 2013). The model could also be used to predict change effects and evaluate the modifications on a process. Manufacturing facilities are often difficult to study as there is typically very little time allocated to experimental testing (Brammer and Hessami, 2008). This means that plant modifications could be assessed using simulations to prevent the facility from risks as discussed in Ordouei (2009). While models are usually created using the current configuration of the facility, they have the ability to be used for future design and optimization studies (Ordouei, 2009).

In the following four sections, two types of studies will be discussed (individual system components and multi-component systems) and two types of simulation software (Commercial software and personal codes)

2.1 INDIVIDUAL COMPONENT STUDIES

In general, individual components are a single piece of equipment, such as a pump whereas processes are thought to be a series of individual components assembled in such a way to create a product or complete a function. A plant or manufacturing facility is composed of several processes, including central heating and cooling systems and manufacturing processes.

When investigating facilities, there is often a desire to better understand how particular pieces of equipment are functioning. Whether the study is looking at the heat transfer in a heat exchanger (Khairul et al., 2013; Tan et al., 2013), the performance of a pump (Shojaeefard et al., 2012) or the performance of a plant condenser (Zhang et al., 1993), these investigations typically only include the specific component and not the equipment up or downstream of it.

Individual components are often replaced, upgraded and have fluctuating operating parameters. When a piece of equipment is being replaced or upgraded, there has typically been a study performed to support the modifications (Tanaka et al., 2000). Those studies typically state what the expected conditions, performance and load capacity are for that the piece of equipment. However, in the case of changing operating parameters, these changes can occur with modifications upstream from the piece of equipment and the effect not be realized (Ong'iro et al., 1996).

2.2 MULTI-COMPONENT SYSTEM STUDIES

Multi-component system models are created to study various aspects of an entire process. These models are usually not as focused on what each process does, as to what their influences are on other parts of the system. Examples of these types of studies are assessing the potential increase in the intake cooling water temperatures, if both the intake water an outfall cooling waters are trapped in the same narrow long channel (He, 2010) and investigating the overall flow and temperature field in a whole power plant (Liang et al., 2012). In both papers the authors look at several scenarios under various conditions. In each case the actual process was not of interest, however how the process would have been affected by the environmental conditions was. Whether it would be tides, currents, wind speeds or temperatures, these all have effects on the system performance.

Another study investigated the design and implementation of an adaptive predictive controller for a nonlinear dynamic industrial plant. This controller would be used to regulate a gaseous industrial plant to compensate for the pressure variations in topside output of the vessel in on-line form. The results of the simulation demonstrated the capability of the proposed approach to efficiently monitor and control an industrial gaseous plant in a real and practical manner (Ahmadgurabi, 2010). In this type of simulation the author was interested in creating a controller that can be used on-line and uses an updated model of the plant. There have also been investigations on the different steps in a process (Tersing et al., 2012) and the influence of the manufacturing chain.

In the cases mentioned above, the authors were creating models of multi-component systems and varying environmental conditions or control methods to see the effect on the system. The actual process that they were studying was not as important as what the outcome of changing non-process related parameters. Environmental conditions often play a role in the performance of how systems work, if not well understood the effects could reduce efficiency of the processes (Ong'iro et al., 1996).

If cooling water, used directly in a process, is supplied from a natural waterway, the temperature of that water will fluctuate seasonally. If those fluctuations are known and compensations are made to maintain consistent running conditions, then the effects can be managed. If the fluctuations go unmanaged, there could be the potential for cost reductions and process optimization.

2.3 SIMULATION TYPES

When looking to create a simulation, a clear understanding of what is trying to be accomplished is required. For instance, a simulation can be used to evaluate how an open source simulator compares to commercial simulators (Dias et al., 2010) when running the same model, or simulations could be created in order to optimize a system (Ponce-Ortega et al., 2010; Yi et al., 2012). The information used to create those simulations can be similar, but the results interpreted differently based on the purpose of the study. Thus, simulations can be used to study a wide variety of engineering problems, ranging from software effectiveness to energy usage, provided there is a clear understanding of what is trying to be accomplished.

Simulations can be of entire manufacturing facilities or one individual component on a piece of equipment and there are numerous types of simulators that can be used. Two of those methods to solve mathematical models are either using commercial software or a personal code. These methods have previously been used to study industrial processes (Zhang et al., 1993; Sokolov et al., 2001; Zhang et al., 2006; Wang et al., 2008; He, 2010). The applications of both commercial software and personal codes will be discussed in the succeeding sections.

2.3.1 Commercial Simulation Software

Commercial software programs have been developed for industry to simulate processes and to create designs. They use established assumptions, methodologies and techniques to perform the simulations (e.g. mass and energy balances). Commercial software packages often include generic items, such as pumps, compressors, heat exchangers, boilers, and cooling towers in an object oriented environment. This allows the user to easily create systems, without having to program the characteristics of individual components. The software performs mass and energy balances for the processes, based on user inputs. Commercial software typically solves processes as steady state, and will always produce a solution provided the user has supplied appropriate data. It is then up to the user to interpret the results as realistic and reasonable.

There are several areas where the use of commercial software is prevalent. One of those areas is the study of a chemical production process (Elkanzi, 2007; Doherty et al., 2009). Another area is the study of thermodynamic efficiencies of industrial facilities, by identifying the areas where energy is wasted (Abdollahi-Demneh et al., 2011). Another application, that West et al. (2008) was able to demonstrate, is that without the use of a commercial software package it is difficult to understand the interactions between all the different systems.

Commercial facilities are complex and have many systems that interact together. It is sometimes necessary to simplify processes to make modelling in commercial software easier (Nakashima and Junior, 2002). Such a simplification is made for the study of the flow and temperature of the air surrounding plants or processes. This type of simulation does not require the individual plant functions in order to create the model, only what the geometries and what their effects are on their surroundings. An example of such would be a computational fluid dynamics (CFD) simulation on a thermal power plant, which investigates the overall flow and temperature field of the whole power plant, focusing on the air-cooled heat exchanger (ACHE) in order to evaluate the feasibility of the thermal plant project (Wang et al., 2008). CFD techniques are used to predict the flow and temperature distribution in a large space. This model simulates the ACHE under different environmental loads, such as seasonal temperatures (Wang et al., 2008).

Commercial software has also been used to create thermal simulations of buildings (Fuller and Luther, 2002), in order to identify major influences of building design on thermal performance to decrease the environmental impact of the building. There have also been models of power plants to determine boiler thermodynamic calculations (Wang et al., 2011) and their circulating water waste heat recovery systems (Quinsheng et al., 2010).

Commercial software is widely available and some of the available software includes ASPEN HYSYS, ASPEN PLUS, PRO II, SIM42, TRNSYS (Transient System

Simulation Program), FLUENT, and CHEMCAD. With all of these programs having been used in various papers (Fuller and Luther, 2002; Elkanzi, 2007; Doherty et al., 2009; Dias et al., 2010; Quinsheng et al., 2010; Wang et al., 2011; Liang et al., 2012; Yi et al., 2012), it can be seen that the software has been adopted by both researchers and industry.

2.3.2 Personal Codes

In research, personal codes have been used to investigate problems using new methods or techniques that are still under development or not widely adopted (Zhang et al., 1993). In this paper the authors wanted a model that evaluates the performance of a power plant condenser, but that did not restrict the analysis due to using the common methods of a simplified two-dimensional representation. Zhang et al. (1993), uses three-dimensional flow modelling, that takes into account tube nesting, does not rely as heavily on experimental data, and knowing the flow patterns. This model proposes the first steps in order to predict and measure three-dimensional fluid flow and heat transfer in power plant condensers. With the increasing demands on efficiency and size, improved designs are required. This means a better understanding of the physical phenomena involved and enhancing the design tools to meet the demands.

These programs are also created when there are unusual boundary conditions, or material properties, that would not be well represented in commercial simulators (Sokolov et al., 2001; Zhang et al., 2006; He, 2010). In the case of Sokolov et al. (2001), the author is simulating the manufacturing of silica glass blocks by melting of powder batch. This process involves modeling the melting of a powder through radiant heating in a vacuum and the viscous flow of the glass into large cylindrical blocks at different instants of time. This simulation captures several material phases, volume and shape changes, all of which are time and temperature dependant. Zhang et al. (2006) also creates a model to represent the multiphase transient field during plasma deposition manufacturing. Both of the previously mentioned papers are focused on a specific manufacturing process, whereas, He (2010) creates a model to study the impact of a large sediment capping facility on local industrial cooling water temperature. This study uses a three-dimensional hydrodynamic model to investigate the water temperature structures in a channel where both the intake and cooling waters are trapped in a narrow long channel. These research works have studied specific processes, using personal codes in order to best represent boundary conditions and material properties.

There are also studies performed on larger systems that utilize personal codes (Kuo and Smith, 1998; Kim et al., 2001; Kim and Smith, 2001; Wang and Chen, 2008). These studies are interested in creating better designs of the systems in question, along with investigating the interaction between components.

Kuo and Smith (1998) address the interactions between the design of water-using operations and effluent treatment in the process industries. The study focuses on water use minimization and re-use of recycling, the interaction between water minimization, regeneration systems and effluent treatment systems and methods for how these interactions can be accounted for in the design. Likewise, Kim et al. (2001) introduce methods to design for reduced effluent temperatures using distributed effluent cooling systems.

A study looks at cooling water system design (Kim and Smith, 2001) and presents a model which examines the performance of the cooling tower to re-circulation flow rate and return temperature. The model also predicts the efficiency of cooling. This model uses the design method developed by Kim and Smith (2001) which accounts for the interactions and process constraints. This design method assumes fixed inlet and outlet conditions for the cooling water. Similarly, Wang et al. (2008) create a model which can give design suggestions to minimize unfavourable thermal flow and temperature fields surrounding equipment in thermal power plants.

2.4 SUMMARY

There have been many studies on how components of systems and entire systems function. Furthermore, there appears to be no published studies of modelling the interconnected effect of entire facilities in open literature. The only available information found were studies of cooling water systems, and their interactions with water-using operations. These studies are specifically focused on cooling water, with the interest to improve existing design methods. There appears to be a gap between creating models for improved design methods and models to examine existing facilities. Creating a model of an existing facility would allow for optimization of processes, studies of energy and water usage, all without risk to production. A model for an existing facility would also give a better understanding of how the plant functions and reacts to various scenarios. This information could allow for better control of process parameters, if there was better understanding of their effects on other plant processes.

It is clear that there are many different techniques used in modelling individual components and systems. In the case where new techniques are being applied, personal codes appear to be the best solution. In the case where an existing system is being modelled, and a better understanding of the interaction between components is desired, commercial software is the better option. In this study, ASPEN HYSYS has been selected to model the Michelin Bridgewater facility, in order to obtain a more in depth understanding of the interactions between system components and areas that require further investigation.

CHAPTER 3 MEASUREMENT

A significant amount of data was required in order to accurately model and predict how the Michelin Bridgwater facility functions, from a thermal energy point of view. Michelin supplied a wide range of data including: steam production by month, municipal water consumption and estimates on steam distribution to the different production areas. This data can be found in Appendix A, and was used to validate the HYSYS model. Although there was a large amount of data supplied, there was still a need to collect more detailed information in order to complete the model. The remaining data was collected experimentally and is presented in Appendix B.

Steam usage by production area was of particular interest, as steam is used as a heat source in most processes. There are two primary delivery systems that are used by Michelin, the mixing of steam with fresh water and heat exchangers. In both cases the amount of steam being used is unknown as Michelin only measures the amount of steam produced, and does not have a breakdown of the individual steam lines. Therefore, it was necessary to measure the steam flow and the measured data can be seen in Appendix B. Unfortunately, it was not feasible to interrupt production to install in flow steam sensors during the time period that this study was performed. In place of measuring the flow of the individual steam lines, the amount of heat transferred from the steam to the working fluid was measured. This was achieved by measuring the surface temperatures of the cold in and hot out lines, calculating the midstream temperatures and determining the amount of energy required to achieve the temperature difference. This amount of energy was then converted to an amount of steam. These calculations can be seen in Appendix C. In order to determine whether the collected data was representative to actual usage, the steam output for the individual steam lines was compared to the steam usage estimates used by Michelin.

In the following sections the measurement tools used for data collection are presented. Each section discusses the application and reason for using each tool. This section also includes the method of how each tool was used in the field, the data collected and the problems encountered with each measurement type.

3.1 MEASUREMENT TOOLS

The measurements that were required were flow rates for relatively clean fluids, temperatures and heat flux. The clean fluids consisted of mostly water. There were a wide variety of pipe materials, with the majority being stainless steel, steel and copper. The temperatures needed to be measured from the surface of the pipes and was required for both steam and water pipes. The heat flux was needed for the hot water pipe out of the domestic hot water tank, in order to determine the amount of steam energy used to heat the fluid.

The following sections will discuss the tools used to collect the flow, heat flux and temperature data.

3.1.1 Liquid Measurement Tool – Handheld Ultrasonic Flow Meter (FDT-21)

To measure the flow of the liquid water, an ultrasonic flow meter was purchased. The FDT-21 (shown in Fig.3.1) is designed to measure fluid in a full and closed pipe. It can measure fluids with a temperature range of 0 to 160°C flowing at rates with a velocity between 0.01 to 30 m/s. Depending on the sensors used the device has the capability to be used on pipes ranging in size from 20 to 700 mm. The accuracy of the FDT-21 is ± 1% of the reading with flows greater than 0.2 m/s.

Figure 3.1 FDT-21 Handheld Ultrasonic Flow Meter

The device requires specific information about the pipes in order to calculate the distance between the transducers required for the flow measurement. The electroacoustic transducers emit and receive brief ultrasonic pulses through the pipe and fluid. The handheld device calculates how long the pulses should take to travel from one transducer to the other if the fluid was stagnant (based on the densities of the pipe and the fluid) and then calculates how long the signal actually took to travel from one transducer to the other and compares them. The difference in the values is related to the velocity at which the fluid is travelling.

In order for the ultrasonic flow meter to read the flow rate, the actual pipe diameter must first be entered, followed by the pipe thickness, material and fluid type. Once these parameters are specified, the handheld unit then needs to know the type of electroacoustic sensors being used and the mounting method. The type of sensor used depends on the diameter of the pipe and the temperature of the fluid/surface. In this study the FDT-21-S1 sensor was used in most cases. This transducer was acceptable for all pipe materials ranging in size from 20 to 100 mm and temperatures under 70°C. For the pipes over 100 mm the FDT-21-M2 sensor was used, which can be used on pipes ranging from 50 – 700 mm. For temperatures over 70°C, the FDT-21-S1H was used. It could be used on pipes ranging from 20 – 100 mm and for temperatures up to 160°C (See Appendix D for more Specifications). The V-method installation (also called the reflective method) places both sensors on the same side of the pipe, with both sensors in-line. This was the installation method used to mount the electroacoustic transducers, as it is the preferred method for pipe diameters under 76.2 mm. The majority of the pipes measured were in this range. The transducer spacing measurement was quite important; the closer to the calculated value that the handheld unit produces, the better the quality of the signal. The transducer spacing was measured using a measuring tape.

The sensors attach to the hand held unit using a pair of 5 m cables that connect to sockets on the device and on the transducers. The transducers come in two varieties: magnetic (FDT-21-S1, M2) and non-magnetic (FDT-21-S1H). There were also two types of acoustic gels, low temperature and high temperature. The use of a generous amount of gel, applied with an application stick, resulted in successful measurements.

The flow was measured at a minimum of 10 times the diameter of the pipe downstream from any fittings and at least 3 times the diameter of the pipe from any obstructions upstream (as recommended in the user manual). The measured section of pipe should be horizontal or vertical (providing the flow is going upwards). The manual also recommends not measuring the flow rate on vertical pipes with downward flow.

All pipes were assumed to be full, and not have a liner or build-up on the interior surface. The majority of the upgraded systems installed use stainless steel piping and fittings, whereas the older systems use either cast or carbon steel fittings and piping. As such, the newer pipes were the preferred measurement locations, as they were assumed to be less fouled and required less build-up to be removed from the surfaces to provide accurate measurements.

There were some problems encountered with the fluid flow measurements. With the corrosion that was observed on the outside of the pipes, it was assumed that the interior of the pipes had also deteriorated to some extent as well. The FDT-21 did not work well with surfaces that were not well cleaned. Rust and fouling was assumed to have caused several of the failed measurements, while the pipes not being full was assumed in other cases. The fouling on the interior of the pipes adds additional thickness to the pipe wall, which if not compensated for in the handheld device, the measurements would be inaccurate, if a flow can be measured.

The sensors that were used are magnetic and require an alternative attachment method with non-ferrous pipes. Clamps were first used, but installing them while maintaining the correct amount of ultrasonic gel between the sensor and the pipe was difficult. The clamps were often too tight, forcing the gel out from under the sensors. If the clamps were not tight enough the sensors would not remain attached to the pipe, due to the weight of the cables attached to the sensors. It also made getting the alignment and spacing of the sensors more difficult, as many minor adjustments were usually required. With the ferrous pipes, the magnets on the sensors worked very well, allowing for ease of alignment and minor adjustments. They provided enough force to hold the sensors in place, but not so much to squeeze the acoustic gel out from under the sensors.

There were only a few cases where it was not possible to collect any measurements. The cases that were not successful included a 203.2 mm pipe on the cooling network in the rubber preparation area. The pipes were heavily corroded on the exterior and the interior condition was unknown. There was also little room to measure the flow rates between the fittings. The pipes were assumed to be full, but verification was not possible. The combination of unknowns and the measurements being taken close to fittings resulted in no signal from the handheld device, and no measurements recorded. Another case was on a hot water line going to the wire production side of the plant, just after the Borax heat exchangers. The difficulty encountered here was that there was insulation on most of the piping, and the available sections that the transducers could be attached to were too close to fittings and valves. Due to the possibility of asbestos being found in the insulation, it was not feasible to remove any of the insulation, even temporarily, for measurements.

It was found that if the diameters or wall thicknesses specified were not accurate, the flow rates and velocities would be incorrect. The flow rates are calculated based on the cross sectional area of the pipe. Depending on the pipe material the actual pipe size varies, for instance a 76.2 mm schedule 40S stainless steel pipe has an OD of 88.9 mm and a wall thickness of 5.74 mm in comparison to a 76.2 mm schedule 40 steel pipe which has an OD of 88.9 mm and a wall thickness of 5.49 mm. With these small differences in wall thickness the overall area changes by approximately 60 mm^2 the resulting flow rates are then also skewed.

3.1.2 Flexible thin-film Heat Flux Sensor (HFS-3)

To measure the heat flux a flexible thin-film HFS-3 sensor was used (Fig. 3.2). This sensor is a self-generating thermopile transducer and the data was read using a digital multi-meter. The sensor outputs microvolts, which can be converted using the supplied sensitivity number associated with the sensor of 2.6 $\mu V/BTU/ft^2Hr$. The sensor has a response time of 0.20 seconds. The sensor can be attached to any surface type, provided that the adhesives used can bond to the materials. With the use of this sensor it was be possible to measure the heat flux through the pipe walls in order to determine the amount of heat that had been added to the fluid.

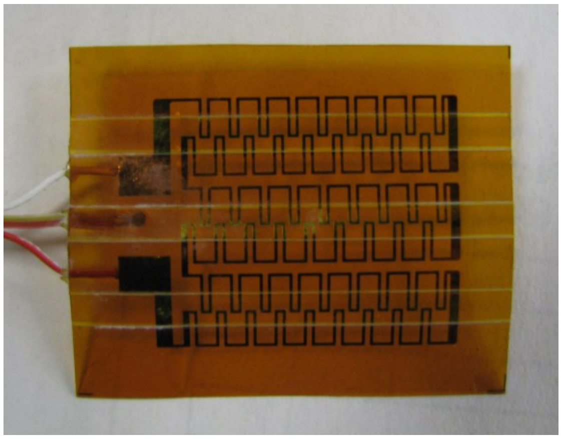

Figure 3.2 Thin Film Heat Flux Sensor (HFS-3)

The heat flux measurements were taken on most sections of pipe after heat addition. The heat flux sensors were attached to the sections of pipe using a combination of Omegatherm “201” paste (See Appendix D) and several polyimide film adhesive pads.

To collect the data a 2705B BK Precision multimeter was used (Fig. 3.3) and the values were recorded by hand off of the digital readout. The multimeter leads were modified in order to attach the bare wire ends of the Heat Flux sensor.

Figure 3.3 2705B BK Precision Multimeter

3.1.3 Thermocouples and data logger

Thermocouples and a thermocouple data logger (Figure 3.4) were used to measure temperatures of the steam, condensate and the heating and cooling water. The temperatures were measured on the surface of the pipe walls. These temperatures were used in conjunction with the heat flux values in order to determine the midstream temperature of the fluids. Type K thermocouples were used for the data collection. These thermocouples were used as the temperatures encountered throughout the plant were not expected to exceed -200 to 1250°C, and an accuracy of 2.2°C or 0.75% above 0°C was suitable for the application. The collected measurements can be found in Appendix B, along with a corresponding list of the locations measured.

Figure 3.4 Thermocouples and Portable Data Logger

3.2 METHODOLOGY FOR HEAT ADDITION TO FLUIDS

The amount of water used in the plant was divided into two groups; the first was the process hot water, domestic hot water, heating and steam production and the second group was cooling water.

The condensate lines contained only fluid, no mixed streams (steam/water). All of the process fluids were pure water. Any systems that capture heat from dirty condensate and steam vapour were treated as one system. All of the pressures for the water lines were set to a constant pressure. There were no pressure losses across any components (everything assumed to be ideal). Where there were streams that were mixing, the lowest pressure inlet stream was the pressure used for the outlet of the mixer.

The method that was used to measure the amount of energy transferred to the hot water systems, and ultimately estimate the amount of steam used, was to measure the temperature of the hot and cold water pipes, the flow rate, and the heat flux lost through the pipe. It was determined that the pipes had a constant heat flux, by taking several heat flux measurements along sections of pipe. With this information, along with the material and thickness of the piping, it was possible to calculate the midstream temperature of the water at both the inlets and outlets of the heating tanks. The amount of steam used to heat the water was then calculated using the midstream temperature.

The materials used for the water pipes in the hot water systems included plain carbon steel, stainless steel, copper and polyvinyl chloride (PVC). The thermal conductivities of these materials can be found in Table 3.1.

Table 3.1 Piping Thermal Conductivities

Material	**Thermal Conductivity ($Wm^{-1}K^{-1}$) @ 25°C**
Carbon Steel	43
Stainless Steel	16
Copper	401
PVC	0.19

The measured surface temperature of the pipes was used, along with the measured heat flux, to calculate the temperature of the inside wall of the pipe (T_i) using Eq. (3.1):

$$T_i = \left(\frac{q_x''\Delta x}{-k}\right) + T_0 \tag{3.1}$$

Where Δx is the thickness of the pipe wall, q_x'' is the heat flux through the pipe wall, T_0 is the measured outer wall temperature of the pipe and k is the thermal conductivity.

Once the flow rate and T_i are known, the midstream temperature of the fluid can be calculated. The following assumptions were made:

1. Steady state conditions;
2. Uniform heat flux;
3. Constant fluid properties (ρ, μ);
4. A radial continuity of outer pipe surface means in this case the heat flux through the pipe would be equal to the heat flux from the liquid;
5. Constant surface temperature;
6. Turbulent flow.

The Reynolds number for the flow is calculated using Eq. (3.2).

$$Re_D = \frac{\rho u_m D}{\mu} \tag{3.2}$$

The density of the fluid (ρ) and the viscosity (μ) are determined using the saturated water tables. The inside diameter of the pipe (D) is known and u_{m} is determined using the ultrasonic flow meter.

A constant surface temperature approach will be used because while measuring the surfaces of the pipes it was noted that the temperature was constant over the length of the pipes. There were most likely areas that did not have a constant surface temperature, but with the amount of insulation that was observed on most of the piping it was assumed to be the case throughout the plant. The fully developed turbulent flow assumption will be used, since typical Reynolds number are of 10^4 and the positions at which the flows will be measured are 10 times or greater than the diameter of the pipe from any fittings, where the flow should be fully developed. The constant surface temperature and turbulent flow allow for the use of Eq. (3.3).

$$Nu_D = \frac{hD}{k} = Re_D^{4/5} Pr^n \tag{3.3}$$

Where n is 0.4 for heating and 0.3 for cooling.

Once the local convection coefficients are calculated, it is possible to calculate the midstream temperature (T_m), of the streams using Newton's law of cooling Eq. (3.4), re-arranged as in Eq. (3.5).

$$q_x'' = h(T_s - T_m) \tag{3.4}$$

$$T_m = T_x - \left(\frac{q_x''}{h}\right) \tag{3.5}$$

These calculations were performed on all of the measured streams and the resultant temperatures, and it was found that in the cases measured, the surface temperature of the pipes was within a degree of the calculated midstream temperatures. The resulting stream temperatures were then entered into the ASPEN HYSYS model. An example calculation can be found in Appendix C.

3.3 SUMMARY

With all of the data collected and calculations performed, it was then possible to move on to creating a model that could be used to study the interconnected effects of the steam fed processes at the Michelin facility. The measurements supplied missing information in order to create a more complete model that can replicate the operating conditions of the facility. In the subsequent sections the data collected has been used as a starting point and a reference when troubleshooting and debugging the model.

CHAPTER 4 MODEL

The models that were created for this study represent the Michelin Bridgewater Tire Manufacturing facility. The components of the model represent individual thermal processes, and their associated energy and material streams. This section will present an overview of the model followed by the implementation of this model in HYSYS.

4.1 MODEL OVERVIEW

When the model was created, a top down approach was applied. Starting with a basic layout similar to the block diagrams in Fig. 4.1, more details were progressively added in order to obtain the final model used to run the four cases introduced in section 4.4. From the general layout in Fig. 4.1, the Other Systems, Boiler House sections were expanded to include the items in Figs. 4.2 and 4.3 respectively. Then the Process 7 section was expanded again using the components in Fig. 4.4.

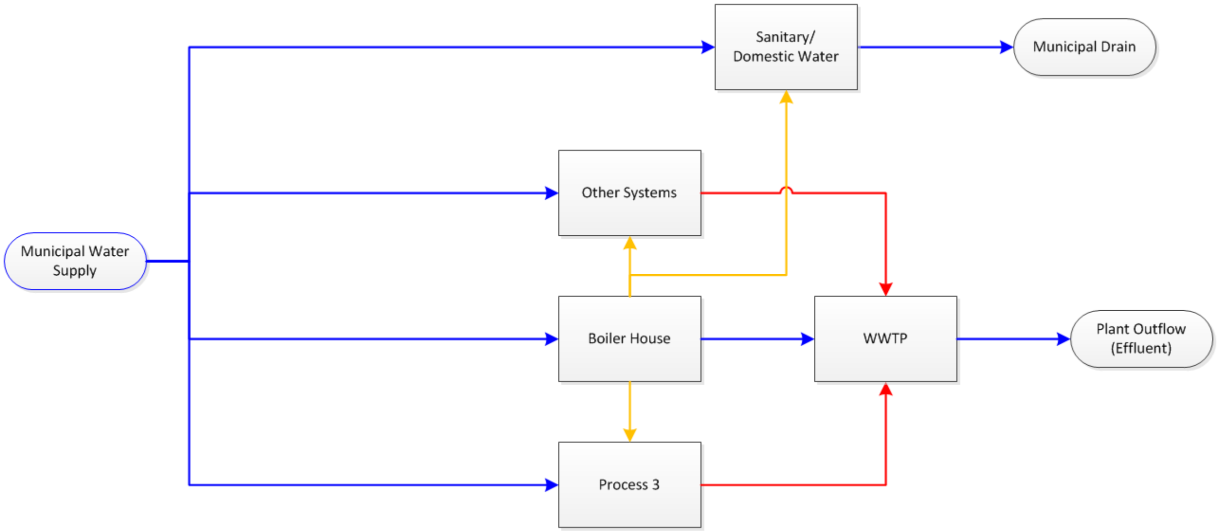

Figure 4.1 Michelin Overview

Figure 4.1 shows a general overview of the facility. The plant was split into five sections:

1. Boiler House;
2. Process 5;
3. Process 7;
4. Sanitary/Domestic Water;
5. Waste Water Treatment Plant (WWTP).

From this overview, the main material streams can be seen. The blue lines represent the Municipal Water, which has not been processed. The yellow lines represent the steam supply lines and the red lines represent the heated water leaving the processes.

This breakdown was chosen as it most closely represents the breakdown used within the facility as a method to divide up the Boiler House resources. There are many processes within each of the five sections represented here, however this was used as the starting point for the HYSYS model as the Municipal Water usage, and Plant Outflow are measured. Once this model was created and the streams were understood, each section was broken down into smaller components, as in Fig. 4.2.

Figure 4.2 represents the Other Systems, which includes both Process 5 and Process 7 components. Upon studying the facility, it was determine that the general overview in Fig. 4.1 did not represent the breakdown of the largest users of steam. In reality when the steam leaves the boilers, it is divided into two main streams. The 115lb steam line and the 250lb steam line. The 115lb steam line feeds all process in the facility, except Process 3, which is supplied by the 250lb line.

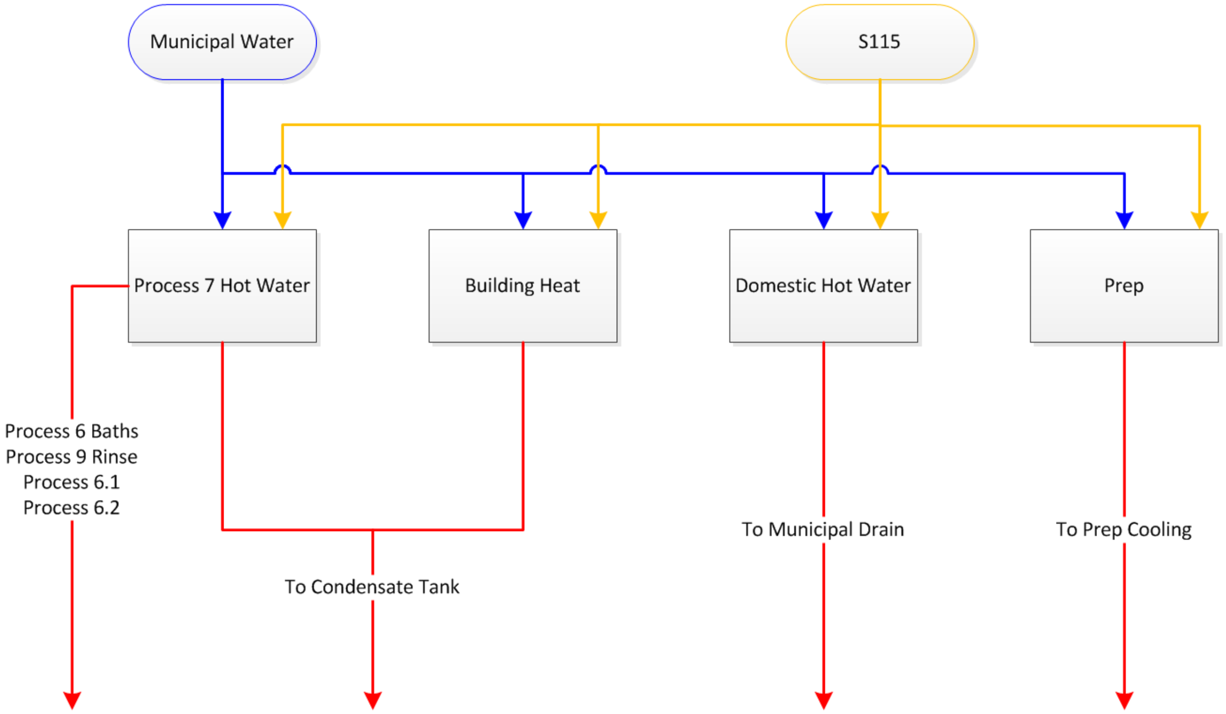

Figure 4.2 Layout of the Other Steam Systems

Figure 4.2 shows a breakdown of which sections are supplied municipal water and steam (blue and yellow lines, respectively, as well as the next destination of the heated fluids (red lines)). The Process 7 Hot Water block represents the hot water system for the wire production shop. In the case of the Process 7 section, the heated fluid is divided and flows to separate sections. The Process 7 stream furthest to the left, supplies specific pieces of machinery on that side of the plant, including Process 6 Baths, Process 9 Rinse, Process 6.1, and Process 6.2. This stream then flows to the Sludge Thickener before exiting the facility. The other stream flows to the condensate tank and then on to Process 8 Collection tank.

The Building Heat block represents the building heating system. This system is comprised of several different types of heating (direct steam heating and indirect heating systems). For the purpose of this model, the individual systems are all treated as one large unit.

The Domestic Hot Water tank is the third block, and represents the tank used to produce the hot water for the changing rooms, kitchen, cafeteria and administration building washrooms and hot water needs for the quality assurance laboratories.

The final block in Fig. 4.2, Prep, represents an area on the tire production side of the plant that includes the rubber processing equipment.

Figure 4.3 shows the Waste Water Treatment plant along the top and the boiler house along the bottom of the figure. The first block represents the Process 8 collection tank, where certain processes from Process 7 and the leakage from Process 3 are collected. The Sludge Thickener tank is next, where streams with high levels of suspended particles are collected and processed. The Neutralization tank is where the remaining Process 7 streams and the water from Process 8 Collection, the Sludge Thickener are collected and neutralized. The Clarifier tank is where the water from the Neutralization tank is allowed time to clarify and the remaining particles to drop out of solution. The final block is the BFM Effluent, which is not a tank but represents all of the collected water that will be exiting the plant and released back into the environment.

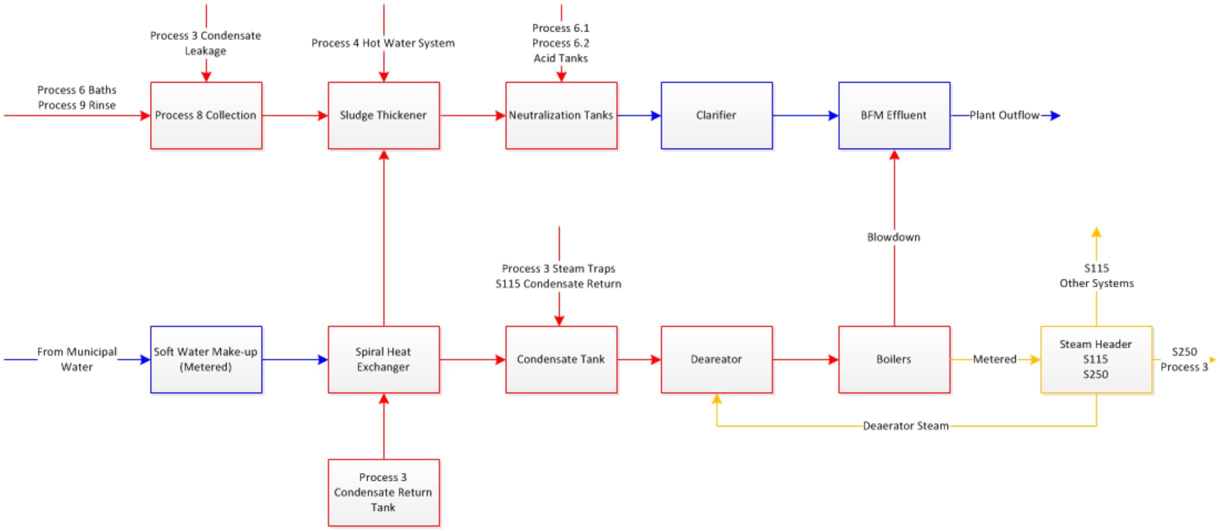

Figure 4.3 Layout of the Boiler House

The second string of blocks in Fig. 4.3 represents the boiler house. This strip of blocks is where the measured streams that Michelin supplied are located (Municipal Water, Soft Water Makeup, and Steam Produced). The first block from the left, Soft Water Makeup (Metered) represents the soft water destined for the Boilers. The Spiral Heat Exchanger represents one of the heat exchangers used to capture latent heat from the dirty condensate returning from the Process 3 Condensate Return Tank, which then goes to the Sludge Thickener. The following block, Condensate Tank, is the clean condensate tank where the condensate from the 115lb steam lines and the Process 3 steam traps are collected to be recycled back into steam. The Deaerator is where the clean condensate is reheated and the oxygen and other dissolved gasses are removed before entering the boilers. The second last block, Boilers, represents the steam generating boilers at Michelin. The last block, Steam Header S115 S250, is where the steam is divided into either 250lb steam for Process 3 or 115lb steam.

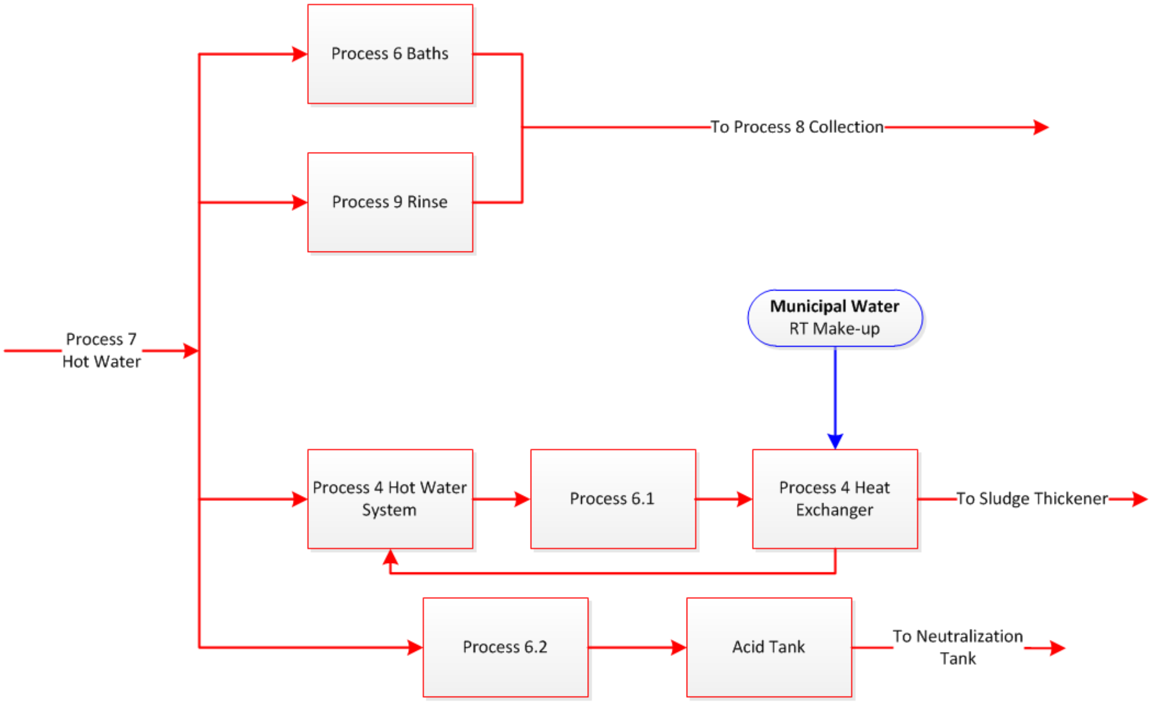

Figure 4.4 Process 7 Hot Water Layout

Figure 4.4 represents the Process 7 streams that were destined for specific process shown in Fig.4.2. The blocks represented in Fig. 4.4 are individual production areas comprised of different types of production equipment. The blocks at the top of the diagram, Process 6 Baths and Process 9 Rinse, are baths in which the product passes through before proceeding to the next production phase. The Process 4 Hot Water System block represents the tanks where the water treatments are performed for Process 6.1. The Process 4 Heat Exchanger block represents a heat exchanger used to pre-heat makeup water required for the Process 4 Hot Water System. All the process water from the Process 4 Hot Water System goes to the Sludge Thickener for further processes. Process 6.2 are water baths. The water from Process 6.2 then goes to the Acid Tank where the water is processed before heading to the Neutralization tank.

4.2 HYSYS MODEL

Aspen HYSYS was used for this model because of its strong thermodynamic foundation and built-in property packages (Aspen Technology, 2010). With the use of this software it was possible to model the different fluids that are present at the facility (steam and water), in one model, using the appropriate equations of state (EOS). The fluid package that was used for the steam and water streams was the ASME Steam package in HYSYS, which uses the 1967 ASME steam tables (Aspen Technology, 2010).

ASPEN HYSYS includes pumps, compressors, boilers, heat exchangers and many other products that required specific parameters be entered. This reduced the amount of time required in creating all of these items. The software also performed mass and energy balances and identified areas where there were problems in the calculations. ASPEN HSYS did have some limitations; such as it does not calculate losses due to pipe friction, or heat loss through the un-insulated pipes. The model does not account for suspended particles in the material streams (e.g. Borax solution) that would affect the heat transfer characteristics.

An overview of the model can be seen in Fig. 4.5, with the various sections of the plant highlighted. A general overview of the components used in the model can be found in the next section, and detailed descriptions of each component used in Appendix E.

The heaters were used to represent a process that adds heat to a material stream (e.g. boiler). The coolers were used to represent processes that extract heat. The heat exchangers were used to model the actual heat exchangers in the plant (e.g. Primary Soft Water (SW) Heat Exchanger). The mixers represent tanks that are found throughout the facility. Mixers were used in place of the tanks in HYSYS because the amount of steam leaving the tanks was not known. The mixers combine all of the flows, equalize the temperature at the output, and use the smallest pressure input as the output pressure. The amount of thermal energy that would have been lost through the open tanks was captured, as there was no drop in pressure entering the mixer. This would have been the worst-case scenario for temperatures leaving the mixers.

The material streams (which are the blue lines in Fig. 4.5) represent the fluid streams to and from each node. The actual path of each fluid stream was not known. Most of the steam lines were identified using schematics supplied by Michelin. The water streams were not all identifiable on the schematics provided, but several key streams were traced back inside of the facility. The streams with a known path are identified using names (e.g. From SW Water Pumps) where the streams with an uncertain path or very short runs between nodes were identified with numbers (e.g. 3). The energy streams are the amount of energy added or removed from a process. They are represented by the red lines, which can also be seen in Fig. 4.5. There were two adjustment streams used (represented as green lines in Fig. 4.5) to ensure that the ratios of those particular streams remain constant for the four case studied.

The material streams were defined as either pure liquid or steam. This was a realistic representation of the majority of the facility, as the majority of the water modeled would only have additives to reduce corrosion and build-up on the interior surfaces of the piping network. The additives would only slightly affect the boiling point and the heat transfer rates of the water. There were no mixed flow streams in the model. In order to ensure this condition, the steam lines were treated as constant pressure. The liquid and steam material streams cannot be visually distinguished on the HYSYS model other than by their labels.

The layout of the model flows generally left to right. The model starts with the municipal water flow, through to the boiler house and then to Process 7 and Process 5, with branches going to smaller processes, such as the domestic water system.

The seasonal distribution of steam was an unknown, therefore the yearly average for the flow ratios were used, as supplied by Michelin and not changed for the various case studies.

The model uses two steam loops, a 115lb loop and a 250lb loop. The 115lb loop returns as clean condensate to be processed into steam. The 250lb loop supplies Process 3 and returns as dirty condensate, and is used to pre-heat the soft water makeup for the boiler. Process 3 has many steam receptacles, most of which produce dirty condensate. The steam that does not get condensed in the processes is released into the building. The remaining heat is captured from the released steam using a rooftop glycol heat exchanger system. The glycol then preheats the soft water going to the boiler house. This entire 250lb system has been modeled as a cooler and all of the steam was assumed to be dirty condensate. With the simplifications, the amount of energy captured and the amount of condensate produced were still accurately depicted.

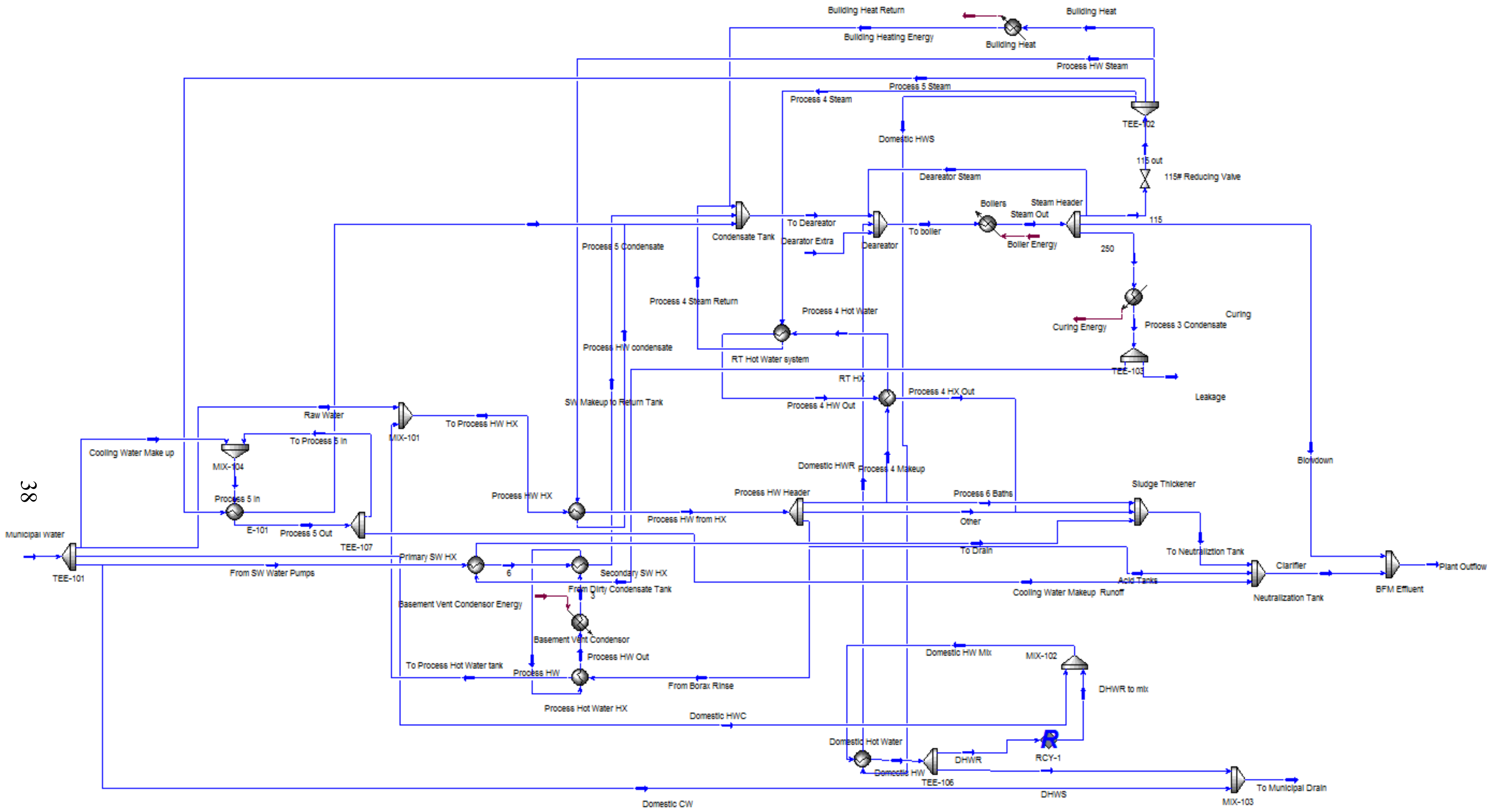

Figure 4.5 HYSYS Model

The production shops, both Process 5 and Process 7 were simplified by using heat exchangers to represent processes. Process 5 used one heat exchanger (E-101) in order to model the thermal loads whereas Process 7 uses two heat exchangers (Process 4 Hot Water system and Process 4 HX) to represent the thermal loads.

Steam production was the final area that was simplified. Rather than model the three boilers and estimate the production from each for the various seasons and conditions, one heater was used to show the total steam output. The actual steam production process was not of interest, only the interconnected effects of the individual systems, which was better represented using a heater.

It was found that the temperature and pressures supplied by Michelin did not correlate with the ASME Steam tables. The given temperature was higher than what would have been expected at the operating pressure. This was most likely due to the boilers producing superheated steam, in order to ensure the supply of dry steam. In order for the simulation to run properly the supplied pressure was used along with the corresponding temperature from the steam tables.

The tee's used specified flow ratios, where the ratios were known. In most instances the flow ratios were unknown and they were automatically populated, based on downstream demands of the system. Once the flow ratios were calculated for individual processes, the ratios would be fixed for the production streams, and unconstrained for the non-production related streams.

4.3 HYSYS Components – General Descriptions

In the following section the general components used in the HYSYS model are described. The individual components used in the HYSYS Model are described in more detail in Appendix E.

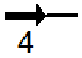

Figure 4.6 Example of a Material Stream in HYSYS

Figure 4.6 presents a material stream which requires the composition of the stream to be defined, in mole fractions. The mole fraction will populate some of the properties of the stream such as Molecular Weight. The conditions of the stream then need to be populated with temperature, pressure and flow or vapour/phase fraction, temperature and flow or other combinations of known parameters. Once the stream is fully defined HYSYS will populate the remaining parameters.

Figure 4.7 Example of an Energy Stream in HYSYS

An energy stream is used to add energy to heaters and coolers; it displays the amount of heat flow (kJ/h) used by the heater or cooler it is associated with. An example of an energy stream from HYSYS can be seen in Fig. 4.7.

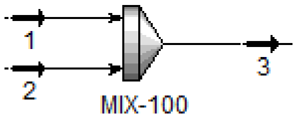

Figure 4.8 Example of a Mixer in HYSYS

In Fig. 4.8 the HYSYS representation of a mixer is shown. The mixers are used to combine two or more material streams into one new material stream. The outlet stream can either be an equalized pressure or set to the lowest inlet pressure. The mixers require two of the three streams to be fully defined (pressure, temperature, mass flow rate and composition) in order for HYSYS to calculate the unknown parameters of the third stream.

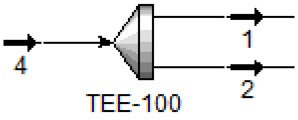

Figure 4.9 Example of a Tee in HYSYS

In Fig. 4.9 the HYSYS representation of a Tee is shown. The tees are used to split a material stream into two or more new material streams. The amount of flow to each stream does not need to be equal. The flow ratios can be specified or auto populated based on the downstream requirements. For instance, if stream 1 and 2 are fully defined (pressure, temperature, mass flow rate and composition), then stream 4 can be successfully calculated. In most cases the only inputs required were the stream 4 properties and the flow ratios for streams 1 and 2.

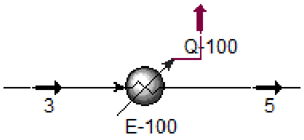

Figure 4.10 Example of a Cooler in HYSYS

In Fig. 4.10 the HYSYS representation of a cooler is shown. The cooler represents a cooling source in the material stream and requires and inlet and outlet material stream and an energy stream. The amount of cooling can be specified by a temperature difference, outlet stream temperature, or by stating the amount of cooling energy supplied by the energy stream. The coolers used in this model (Basement Vent Condenser, and Building Heat), used fully defined (temperature, pressure, mass flow rate and composition) entrance streams and a temperature differences across the coolers. The amount of thermal energy removed from the stream is calculated by HYSYS along with the properties for the cooler. In this model the cooler properties were not studied, only the material and energy stream values.

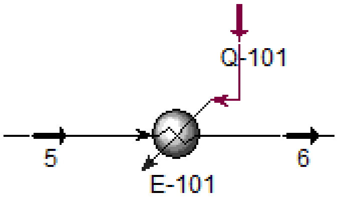

Figure 4.11 Example of a Heater in HYSYS

In Fig. 4.11 the HYSYS representation of a heater is shown. The heater represents a heat source in the material stream and requires and inlet and outlet material stream as well as an energy stream. The amount of heat can be specified with the energy stream or the outlet temperature can be specified and the energy stream will update with the amount of heat flow required for the specified change in temperature. The heater can also be used as a cooler, the only difference being that the energy stream would be negative, instead of positive. In the HYSYS model the material stream properties were defined for the heaters (Process 3 Heater and Boilers) allowing HYSYS to determine the required heater size and the amount of thermal energy required satisfy the defined properties.

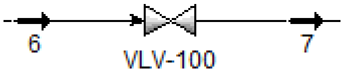

Figure 4.12 Example of a Valve in HYSYS

In Fig. 4.12 the HYSYS representation of a valve is shown. In the model a valve (115# reducing valve) was used to throttle the flow on the 115lb steam line leaving the steam header. The inlet stream was fully defined (pressure, temperature, mass flow rate, and composition) along with the desired outlet pressure of the stream. With these parameters HYSYS calculated the remaining outlet stream properties.

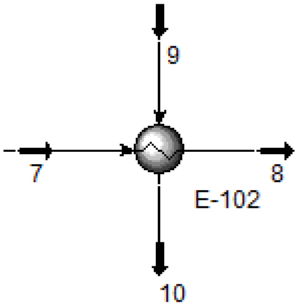

Figure 4.13 Example of a Heat Exchanger in HYSYS

A HYSYS representation of a heat exchanger can be seen in Fig. 4.13. The heat exchangers require four material streams, two inlets and two outlets. The inlet stream properties for the heat exchangers used in the model (Process 4 Hot Water system, Process 4 HX, Process Hot Water HX, Process HW HX, E-101(Process 5), Domestic Hot Water, Primary SW HX, and Secondary SW HX) were known, along with certain outlet stream properties. With the known inlet conditions (temperature, pressure, mass flow, and composition), the outlet temperatures were calculated (assuming no pressure drop across the heat exchanger) by estimating the maximum temperature difference possible across the heat exchanger, based on the inlet streams conditions. Typically, there would be a 10-15°C approach temperature to the heat exchangers. This would mean that the heated stream, could only come within 10-15°C of the heating stream.

4.4 CASE STUDIES

There were four case studies that were used in order to comprehend how the Michelin plant functions. The first case (Full Heat Model) was created to represent the plant during the winter season, specifically January 2012. This case represented the facility running at full building heat. The next case (No Heat Model) represents the facility during the summer months, when there would have been little to no building heat. In the second model, the building heat loop was turned off and the amount of steam produced reduced to the values provided by Michelin for the month of September 2012. All other parameters were left unchanged. The third case (Half Heat Model) represents the shoulder seasons; the model uses the data from April 2012. This case uses a setting of 50% for the building heat. The final case (Half Heat, Double Steam) uses the same setup as the Half Heat Model, but the amount of steam produced was doubled. The heating values used in the four configurations were based off of a heating energy estimate of 1 MW/m^2.

The first three cases were chosen, as the outputs from HYSYS could then be compared to the data supplied by Michelin, to confirm whether the model was in fact working correctly. The fourth case (Half Heat, Double Steam) was a scenario that would have produced results that could be compared to the other scenarios. This comparison would evaluate what process parameters changed and if those changes were caused do to an unforeseen interconnection between processes. These comparisons were done between all four cases; with the fourth case having the most dramatic changes to highlight the influence steam production has on the plant.

The first three case studies (Full Heat, No Heat, and Half Heat) used models configured to run with the corresponding Michelin monthly data. The initial intent was to use one model for all four case studies. After several attempts of creating one model with running parameters that would be sufficient for all cases, it was decided to create three separate models (with the third model being used for the fourth case study also).

With the supplied monthly data from Michelin, it was possible to create steady state models of the facility. The data collection performed, supplied supplementary values for critical systems that were not in the monthly reports from Michelin. The experimental measurements supplied instantaneous data for areas of interest, which were not supplied in the Michelin monthly data, in order to verify if the HYSYS model configurations were producing realistic results.

When building the individual models it was found that if the ratio of clean to dirty condensate were incorrect, than the amount of soft water makeup would also be incorrect. In order to find flow ratios that would allow the model to run, an iterative process was used gradually changing the steam ratios of the 115lb and 250lb streams. The blowdown ratio was a fixed value (8% of the steam production), which accounts for the actual blowdown of the boilers, which Michelin estimates to be 10% of the steam production. The deaerator ratio was the remaining steam after the 115lb, 250lb, and blowdown were all supplied. The constant ratio for steam distribution supplied by Michelin for the 115lb and 250lb streams was close to the correct values for the Full Heat Model only. The fluctuation in the ratios can be seen in the Steam Header flow ratios in Table 4.1.

Table 4.1 Steam Header Flow Ratios

	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Feed Molar Flow (kgmole/h)	1.08×10^3	6.72×10^2	8.49×10^2	1.67×10^3
Feed Temperature (°C)	204	204	204	204
Feed Pressure (MPa)	1.70	1.70	1.70	1.70
Flow Ratio(1) (115lb Steam)	0.45	0.32	0.45	0.23
Flow Ratio(2) (250lb Steam)	0.375	0.45	0.345	0.63
Flow Ratio(3) (Blow down)	0.08	0.08	0.08	0.08
Flow Ratio(4) (Deaerator)	0.1	0.165	0.13	0.06

The model used actual plant data for the mass flow rates of water and steam. The temperature of the municipal water fluctuates between 4.4°C to 21.1°C, with an average temperature of approximately 12.7°C. In early models the temperature was defined by the season, but it was determined from the model results, and experimental measurements, that the municipal water temperature does not have a large effect on the outputs studied. With the pre-heating of the soft water make-up, and other heat capturing processes, the temperature remains nearly constant at 10°C. A municipal water inlet temperature of 7°C was chosen for the model because, that was the temperature recorded when the experimental measurements were obtained (February 2013).

In order to create a model there were various streams that used defined variables. The Municipal Water mass flow was used as a controlling variable on the model and the values of the mass flow were 7.41×10^4, 7.09×10^4, 7.75×10^4, and 7.75×10^4 kg/h for the Full Heat, No Heat, Half Heat, and Half Heat Double steam cases, respectively.

Other streams that used defined parameters were:

- Stream 3 Temperature was not known and the temperature was estimated at 46°C. This stream feeds the secondary soft water Makeup Heat exchanger, on the hot side, from Process 3.
- Stream 6 Temperature was also not a known temperature as was estimated at 13°C. This stream feed the primary soft water makeup heat exchanger, as is the cold side of the heat exchanger, supplied from the Municipal Water header.
- From Dirty Condensate Tank was a measured temperature (44.8°C) at the dirty condensate tank. This stream was the hot side of the Primary Soft Water (SW) Heat Exchanger.
- SW Makeup to Return Tank was another stream that used an estimated temperature value (20°C) and remained constant for all of the four cases.
- To Process Hot Water Tank Temperature was an average of the temperatures from Process 1 and Process 2.
- Process HW temperature was defined at 40°C
- Process 3 Condensate temperature was defined as 44.8°C, based off of experimental measurements at the Michelin plant.
- Process 4 Makeup temperature was defined as 60°C, as it was fed from the Process HW material stream which was operating at 60°C.
- Process 4 Hot Water temperature was defined as 62°C.

- Municipal Water temperature 7°C, based off of experimental measurements taken at the facility.
- Process HW from HX temperature was defined as 60°C
- Process 5 Out temperature was defined as 40°C
- Domestic HW temperature was defined as 55.4°C, based off of experimental measurements taken from the domestic hot water system.
- DHWR to mix temperature was set as 55.4°C; this temperature at the facility was slightly lower, most likely due to heat losses through the piping networks.

4.5 COMPARISON OF CASE STUDIES TO SUPPLIED DATA

In order to simulate the various heating loads that were chosen, four case studies were created. An analysis of the four case study models was completed to determine if one model would be able to accurately demonstrate the expected changes, while still satisfying the defined inputs. To accomplish this analysis the relative errors between the defined amounts of steam used in HYSYS for each case and the provided amount of monthly steam produced by Michelin were calculated. The same calculations were performed for the amount of water used. The results are displayed in Figs. 4.14 and 4.15, respectively.

It can be seen in Fig. 4.14 that although there are relatively small differences in the amount of steam produced in the first three cases, the need for seasonal models was evident. The Full Heat model represents the colder months best, and would over supply steam in the warmer months. The No Heat model represent the warmer months best

(June, July, August and September), but would not be able to supply sufficient steam in the colder months. The Half Heat model matched the shoulder seasons (April and November), and could likely have been used to simulate the two other seasons, with minor adjustments to running conditions. The Half Heat Double Steam model was well above the other models, as the amount of steam produced was double any of the recorded Michelin values. The fourth case could be a representation of the Process 3 throughput being increased by 100%.

Similarly, Figure 4.15 shows the relative error between the defined Municipal Water values in HYSYS for each case study, to each of the monthly Michelin values. With the Municipal Water errors, it can be seen that differences between the case studies were not as large, as they were with the steam production. It should also be noted that the case studies do not represent the seasons as well and only match the specific input month. This was due to the Municipal Water supply varying slightly every month, with no two months having the same usage.

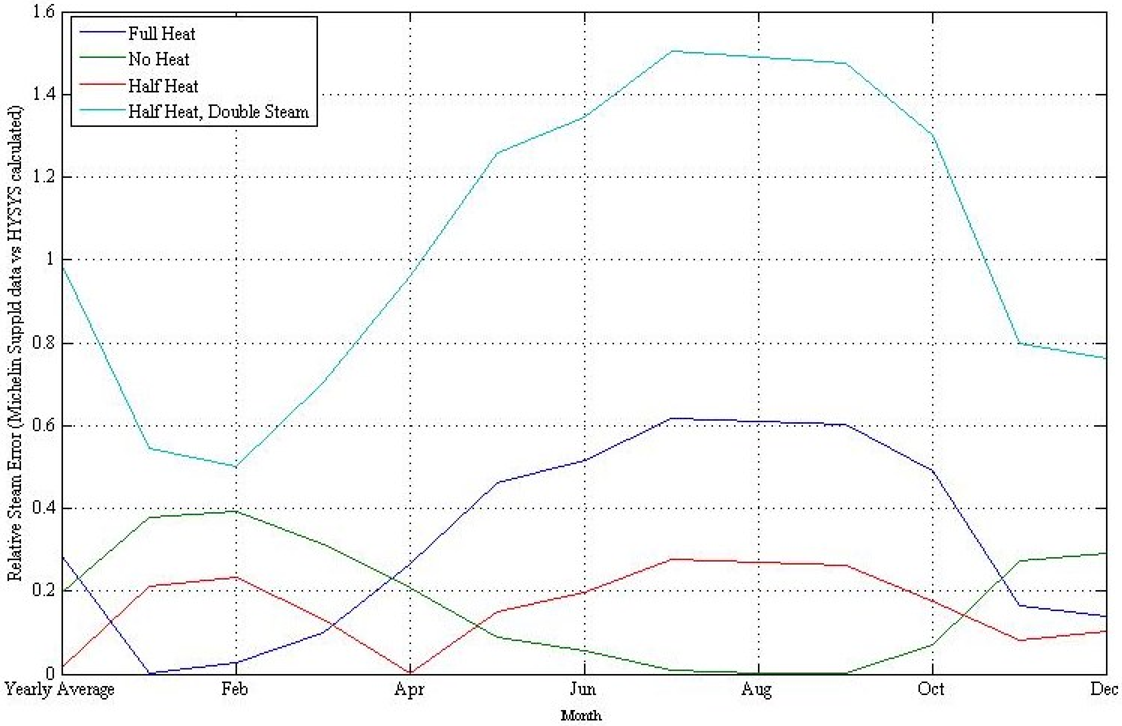

Figure 4.14 Relative Steam Error for the HYSYS Steam Values (Projected for a Month) Compared to the Michelin Monthly Steam Values.

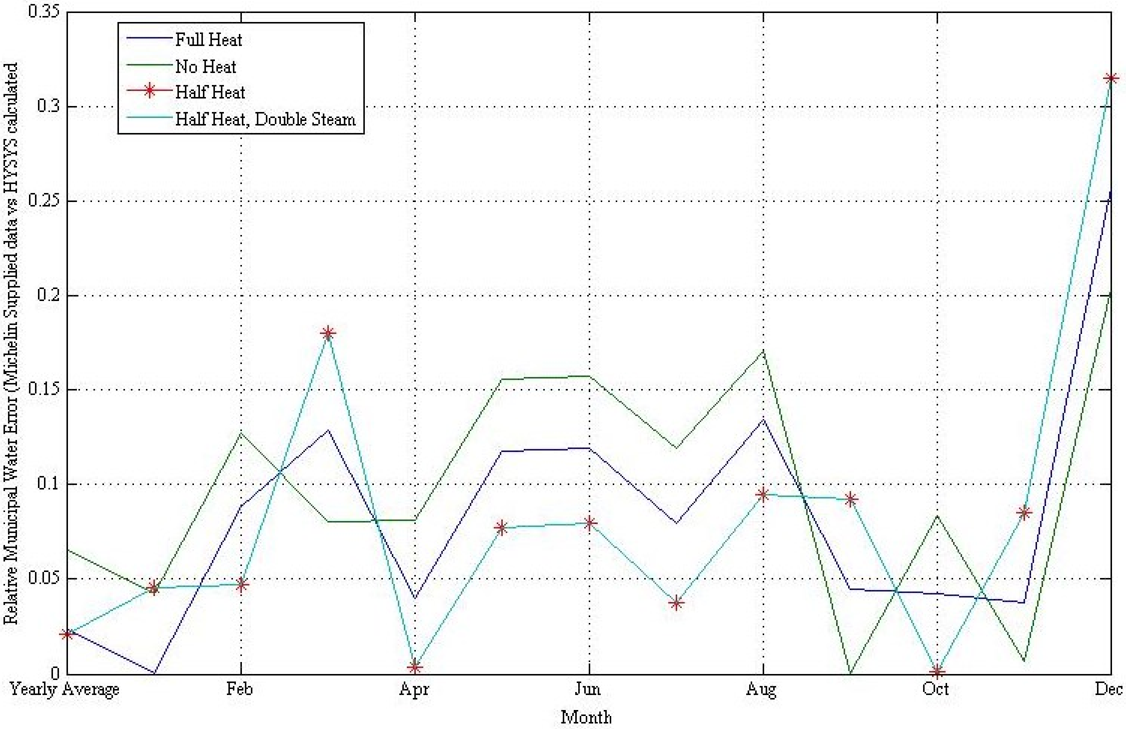

Figure 4.15 Relative Municipal Water Error for the HYSYS Municipal Water Values (Projected for a Month) to the Supplied Michelin Values

In the following sections the four case studies and their associated HYSYS models will be discussed.

4.5.1 Full Heat Model

This model, as mentioned earlier, used data from January 2012. The monthly total amount of municipal water (6.66×10^5 m^3) and steam produced (1.44×10^4 T) were two pieces of supplied data from Michelin. In order to use this data in HYSYS it was required to convert the monthly totals into flow rates, by dividing the monthly rate by the number of hours in the corresponding month. The municipal water flow rate (74.20 m^3/h) was entered into the model, along with the total amount of steam produced (1.94×10^4 kg/h) by the facility. The building heat was set to a value of 9.20×10^3 MJ/h. It was assumed that all other settings and parameters in the plant remained the same throughout the year, other than building heat.

4.5.2 No Heat Model

This model uses the monthly data from September 2012 to populate the municipal water (71.08 m^3/h) and steam (1.21×10^4 kg/h) values. The building heat loop was turned off by setting the Building Heat energy stream to 0 MJ/h. All of the other settings were unchanged.

4.5.3 Half Heat Model

This model uses data from April 2012 to populate the municipal water (77.40 m^3/h) and steam (1.53×10^4 kg/h) values. The building heat was set to half of the full heat model (4.60×10^3 MJ/h). This setting was estimated a good approximation for the two shoulder seasons (spring and fall), when heat would be required but, at a reduced amount.

4.5.4 Half Heat, Double Steam Model

This model again uses the April 2012, only the steam output was doubled (3.00×10^4 kg/h). This was done to see what the effect on the system would have been, both upstream and downstream from the boiler. There were no other parameters adjusted in this model. This case study was also used to investigate what interconnected effects there might be, in the steam or water systems, by dramatically changing the amount of steam produced, while keeping all of the other parameters unchanged.

4.6 SUMMARY

With a clear understanding of the components used by HYSYS, the information required, what each HYSYS component would represent (in relation to the Michelin plant) and the output supplied by each component, the data could now be interpreted to look for interconnected effects throughout the model.

With the information collected it was possible to verify the running conditions of the facility, as well as see what the effect of changing process parameters has on the other systems in the facility. With the data supplied by Michelin, the data collected experimentally and the data produced with the HYSYS models, it was possible to do side by side comparisons. The comparison suggests that the model was well constrained, producing results similar to the data supplied by Michelin.

In the above case studies, it was found that one single model would not be sufficient. Three models were created for specific seasons (winter, summer and spring/fall). With the three models completed, the fourth model was created, based off of the Spring/Fall (Half Heat) model and doubling the amount of steam produced. This change in steam production was used to investigate what changes were caused by a dramatic increase in steam production but no change in downstream flow ratios. This model was use to investigate the interconnectedness of the processes to steam production. The following section presents the results obtained with these models and discussed the implications of these results

CHAPTER 5 SYSTEM INTERCONNECTION: RESULTS AND DISCUSSION

The simulations that were performed in this study supplied large amounts of data. With the numerous material streams and components, there were many parameters that used averaged monthly data, instantaneous experimental data, and estimates. The model also used a simplified configuration that influenced the manner in which the plant responded to changes in running conditions. The models successfully show that it was possible to model the Michelin facility using HYSYS and to study the interconnected effects of the steam system.

The four case studies provided a more in depth understanding of the thermal energy usage at the plant. The first three case studies suggested that there were operating conditions that would dramatically affect the rest of the facility when they are changed (Steam Out, Municipal Water, Steam Header ratios, Building Heat). These pieces of information were critical pieces of data that influenced how the plant functioned, from the hot water temperature of processes, to the amount of energy used in Process 3. In the following sections the results from the studies will be presented and discussed.

5.1 STEAM MATERIAL STREAM RESULTS

In Table 5.1 (Full Heat and No Heat) and Table 5.2 (Half Heat and Half Heat Double Steam) the steam material streams are presented. The parameters that changed between the four case studies can be identified by the yellow highlights, whereas the defined parameters are identified using blue text.

The material streams were divided into two sections, unaffected material streams, material streams with expected changes.

5.1.1 Unaffected Material Streams

This section covers the streams that used defined values (Steam Out, Deaerator Steam, Process 4 Steam and Building Heat).

Table 5.1 HYSYS Output Comparison – Steam Material Streams for the Full Heat and No Heat Case Studies

	Full Heat			No Heat		
	Temperature (°C)	**Pressure (MPa)**	**Mass Flow (kg/h)**	**Temperature (°C)**	**Pressure (MPa)**	**Mass Flow (kg/h)**
Steam Out	204.3	1.70	1.94×10^{4}	204.3	1.70	1.21×10^{4}
115	204.3	1.70	8.72×10^{3}	204.3	1.70	3.85×10^{3}
250	204.3	1.70	7.18×10^{3}	204.3	1.70	5.34×10^{3}
Blowdown	204.3	1.70	1.55×10^{3}	204.3	1.70	9.68×10^{2}
115 out	186.6	1.00	8.72×10^{3}	186.6	1.00	3.85×10^{3}
Process HW Steam	186.6	1.00	2.19×10^{3}	186.6	1.00	1.84×10^{3}
Process 5 Steam	186.6	1.00	1.81×10^{3}	186.6	1.00	1.81×10^{3}
Deaerator Steam	204.3	1.70	1.94×10^{3}	204.3	1.70	1.94×10^{3}
Domestic HWS	186.6	1.00	9.96×10^{1}	186.6	1.00	9.96×10^{1}
Process 4 Steam	186.6	1.00	1.00×10^{2}	186.6	1.00	1.00×10^{2}
Building Heat	186.6	1.00	4.53×10^{3}	186.6	1.00	0.0

Table 5.2 HYSYS Output Comparison – Steam Material Streams for the Half Heat and Half Heat Double Steam Case Studies

	Half Heat			Half Heat Double Steam		
	Temperature (°C)	**Pressure (MPa)**	**Mass Flow (kg/h)**	**Temperature (°C)**	**Pressure (MPa)**	**Mass Flow (kg/h)**
Steam Out	204.3	1.70	1.53×10^{4}	204.3	1.70	3.00×10^{4}
115	204.3	1.70	6.83×10^{3}	204.3	1.70	6.83×10^{3}
250	204.3	1.70	5.31×10^{3}	204.3	1.70	1.88×10^{4}
Blowdown	204.3	1.70	1.22×10^{3}	204.3	1.70	2.40×10^{3}
115 out	186.6	1.00	6.83×10^{3}	186.6	1.00	6.83×10^{3}
Process HW Steam	186.6	1.00	2.56×10^{3}	186.6	1.00	2.56×10^{3}
Process 5 Steam	186.6	1.00	1.81×10^{3}	186.6	1.00	1.81×10^{3}
Deaerator Steam	204.3	1.70	1.94×10^{3}	204.3	1.70	1.94×10^{3}
Domestic HWS	186.6	1.00	9.96×10^{1}	186.6	1.00	9.96×10^{1}
Process 4 Steam	186.6	1.00	1.00×10^{2}	186.6	1.00	1.00×10^{2}
Building Heat	186.6	1.00	2.27×10^{3}	186.6	1.00	2.27×10^{3}

There were two streams (Process 5 Steam, Domestic HWS) which were not defined amounts of steam, but did not vary throughout the case studies. These two streams were process specific and had defined values in order to ensure a constant flow of steam.

5.1.2 Material Streams with Expected Changes

The material stream 115 represents the steam from the steam header to be used in the 115lb steam lines, before having the pressure reduced to 1.0MPa from 1.70MPa. The mass flow rates (8.72×10^3, 3.85×10^3, 6.83×10^3, 6.83×10^3 kg/h) [1] of this material stream varied for the first three case studies, and remained constant in the fourth case study because the 115lb steam line used a fixed flow ratio at the steam header as previously mentioned in Table 4.1. The material stream 115 Out represents the reduced pressure and temperature steam for the 115lb steam lines. The mass flow for this stream remained the same as the 115 material stream, as there were no losses of flow through the reducing valve.

Material stream 250 represented the 250lb steam lines that supply Process 3. The mass flow rate of steam supplied to this shop varied with total steam production (7.18×10^3, 5.34×10^3, 5.31×10^3, 1.88×10^4 kg/h). The ratio of steam between material stream 115 Out and 250 changed depending on the case study. The steam ratio, for material stream 250, was unconstrained and would fluctuate depending on the amount of steam required for the other processes. Without data to support or verify the ratios, it was not possible to determine if these fluctuations were realistic.

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[1] In the parentheses, the values presented are in order of Full Heat, No Heat, Half Heat and Half Heat Double Steam simulations.

The Blowdown material stream used a constant flow ratio of 8% (Table 4.1), which resulted in a mass flow rate that changed for each case study (1.55×10^3, 9.68×10^2, 1.22×10^3, 2.40×10^3 kg/h). Michelin supplied a value of approximately 10% of steam produced was lost to parasitic loads and blowdown. The Blowdown was routed to the WWTP in this model resulting in higher Plant Outflow temperatures and an idea of how much thermal energy could be captured from the blowdown.

The material stream Process HW Steam represents the steam used to heat the water used in various production processes. The mass flow rates (2.19×10^3, 1.84×10^3, 2.56×10^3, 2.56×10^3 kg/h) changed for each of the first three case studies, while remaining the same in the fourth case study. The changes in mass flow rates were attributed to the fact that this material stream supplied the thermal energy to heat the process hot water, using the Process HW HX. This heat exchanger had a defined temperature change, for the stream being heated, and the model determined the amount of steam required to satisfy that change in temperature.

The model successfully showed the steam usage and distribution, but with no data to compare these values to, it was not possible to say whether or not the results were realistic. The model did show which streams were affected by changes in steam production (e.g. Blowdown). The steam production system used several defined values that were based off of assumptions (e.g. that process streams do not fluctuate seasonally). If the amount of steam supplied to specific lines was known, the model could use defined ratios and then be used to look at what interconnections are present in the steam lines. Those interconnections could be used to perform a sensitivity analysis which could predict how much of a change would be expected in the plant when a process experiences a change in running conditions. The current configuration showed that when the amount of defined steam changed, the downstream lines also varied as expected.

The following section looks at the water material stream results.

5.2 WATER MATERIAL STREAM RESULTS

In Table 5.3 (Full Heat and No Heat) and Table 5.4 (Half Heat and Half Heat Double Steam), all of the water streams used in the HYSYS model for the Michelin simulation are presented. The stream parameters that changed between the four case studies are highlighted in yellow and the defined values are identified with blue text.

The simulation results were divided into three sections, for each of the material streams. The first were the streams that were unaffected by the changes in steam production and municipal water supply. Theses streams are defined, and stay as constants throughout the four case studies. The second section, were the streams that had expected changes. This set of streams shows that there were interconnected effects with the variation of steam production and municipal water supply. The third section, were the streams that changed due to an interconnectedness of the system but changed in an unexpected manner.

5.2.1 Unaffected Material Streams

The four case studies yielded numerous streams that were unaffected by the changes in Municipal water, Steam Production and varying building heat. The values in Table 5.3 and 5.4 in black text, represent the streams that did not change.

The streams that did not change used defined mass flow rates that were independent of other loads in the facility. These streams would represent constant loads within the facility that do not fluctuate monthly, or even seasonally.

Table 5.3 HYSYS Output Comparison – Liquid Material Streams for the Full Heat and No Heat Case Studies

	Full Heat			No Heat		
	Temperature (°C)	**Pressure (MPa)**	**Mass Flow (kg/h)**	**Temperature (°C)**	**Pressure (MPa)**	**Mass Flow (kg/h)**
3	46.0	0.20	2.27×10^4	46.0	0.20	2.27×10^4
4	40.0	0.20	2.27×10^4	40.0	0.20	2.27×10^4
From SW Water Pumps	7.0	0.20	1.94×10^4	7.0	0.20	1.94×10^4
6	13.0	0.20	1.94×10^4	13.0	0.20	1.94×10^4
From Dirty Condensate Tank	44.8	1.70	6.81×10^3	44.8	1.70	6.81×10^3
To Drain	27.6	1.70	6.81×10^3	27.6	1.70	6.81×10^3
From Borax Rinse	60.0	0.20	1.02×10^4	60.0	0.20	1.02×10^4
To Process Hot Water tank	50.0	0.20	1.02×10^4	50.0	0.20	1.02×10^4
SW Makeup to Return Tank	20.0	0.20	1.94×10^4	20.0	0.20	1.94×10^4
9	44.5	0.20	2.27×10^4	44.5	0.20	2.27×10^4
Bypass	40.0	0.20	0.0	40.0	0.20	0.0
Process HW	40.0	0.20	2.27×10^4	40.0	0.20	2.27×10^4
Process HW Out	44.5	0.20	2.27×10^4	44.5	0.20	2.27×10^4
To Deaerator	69.9	0.20	2.80×10^4	46.3	0.20	2.32×10^4
To boiler	120.2	0.20	1.94×10^4	120.2	0.20	1.21×10^4
Process 3 Condensate	44.8	1.70	7.18×10^3	44.8	1.70	5.34×10^3
Leakage	44.8	1.70	3.77×10^2	44.8	1.70	-1.46×10^3
To Neutralization Tank	52.9	0.20	2.38×10^4	52.3	0.20	2.19×10^4
Plant Outflow	64.6	0.18	5.30×10^4	57.7	0.18	4.93×10^4
Process 6 Baths	60.0	0.20	2.55×10^3	60.0	0.20	2.27×10^3
Process 4 HX Out	63.4	0.20	1.42×10^3	63.9	0.20	1.26×10^4
Process 4 Makeup	60.0	0.20	1.42×10^3	60.0	0.20	1.26×10^4
Process 4 Hot Water	62.0	0.20	1.42×10^3	62.0	0.20	1.26×10^4
Process 4 HW out	65.4	0.20	1.42×10^4	65.9	0.20	1.26×10^4
Acid Tanks	60.0	0.20	1.12×10^3	60.0	0.20	-1.37×10^2
Clarifier	46.4	0.20	5.15×10^4	45.5	0.20	4.84×10^4
Raw Water	7.0	0.20	1.81×10^4	7.0	0.20	1.50×10^4
Municipal Water	7.0	0.20	7.41×10^4	7.0	0.20	7.09×10^4
Process HW from HX	60.0	0.20	2.83×10^4	60.0	0.20	2.52×10^4

Process HW condensate	179.9	1.00	2.19×10^{3}	179.9	1.00	1.84×10^{3}
To Process HW HX	22.5	0.20	2.83×10^{4}	24.4	0.20	2.52×10^{4}
Other	60.0	0.20	2.83×10^{2}	60.0	0.20	2.52×10^{2}
Cooling Water Make up	7.0	0.20	2.66×10^{4}	7.0	0.20	2.66×10^{4}
Process 5 Out	40.0	0.20	5.61×10^{4}	40.0	0.20	5.61×10^{4}
Process 5 Condensate	179.9	1.00	1.81×10^{3}	179.9	1.00	1.81×10^{3}
Process 5 In	24.3	0.20	5.61×10^{4}	24.3	0.20	5.61×10^{4}
Domestic HWC	7.0	0.20	9.99×10^{2}	7.0	0.20	9.99×10^{2}
Domestic HW	55.4	0.20	2.80×10^{3}	55.4	0.20	2.80×10^{3}
Domestic HWR	179.9	1.00	9.96×10^{1}	179.9	1.00	9.96×10^{1}
Domestic CW	7.0	0.20	8.97×10^{3}	7.0	0.20	8.97×10^{3}
Domestic HW Mix	38.1	0.20	2.80×10^{3}	38.1	0.20	2.80×10^{3}
DHWR	55.4	0.20	1.80×10^{3}	55.4	0.20	1.80×10^{3}
DHWS	55.4	0.20	9.99×10^{2}	55.4	0.20	9.99×10^{2}
DHWR to mix	55.4	0.20	1.80×10^{3}	55.4	0.20	1.80×10^{3}
To Municipal Drain	11.8	0.20	9.97×10^{3}	11.8	0.20	9.97×10^{3}
Process 4 Steam Return	179.9	1.00	1.00×10^{2}	179.9	1.00	1.00×10^{2}
Building Heat Return	179.9	0.10	4.53×10^{3}	179.9	1.00	0.0
Cooling Water Makeup Runoff	40.0	0.20	2.66×10^{4}	40.0	0.20	2.66×10^{4}
To Process 5 in	40.0	0.20	2.95×10^{4}	40.0	0.20	2.95×10^{4}
Deaerator Extra	87.4	0.20	-1.07×10^{4}	70.7	0.20	-1.31×10^{4}

Table 5.4 HYSYS Output Comparison – Liquid Material Streams for the Half Heat and Half Heat Double Steam Case Studies

	Half Heat			**Half Heat Double Steam**		
	Temperature (°C)	**Pressure (MPa)**	**Mass Flow (kg/h)**	**Temperature (°C)**	**Pressure (MPa)**	**Mass Flow (kg/h)**
3	46.0	0.20	2.27×10^{4}	46.0	0.20	2.27×10^{4}
4	40.0	0.20	2.27×10^{4}	40.0	0.20	2.27×10^{4}
From SW Water Pumps	7.0	0.20	1.94×10^{4}	7.0	0.20	1.94×10^{4}
6	13.0	0.20	1.94×10^{4}	13.0	0.20	1.94×10^{4}
From Dirty Condensate Tank	44.8	1.70	6.81×10^{3}	44.8	1.70	6.81×10^{3}
To Drain	27.6	1.70	6.81×10^{3}	27.6	1.70	6.81×10^{3}
From Borax Rinse	60.0	0.20	1.02×10^{4}	60.0	0.20	1.02×10^{4}
To Process Hot Water tank	50.0	0.20	1.02×10^{4}	50.0	0.20	1.02×10^{4}
SW Makeup to Return Tank	20.0	0.20	1.94×10^{4}	20.0	0.20	1.94×10^{4}
9	44.5	0.20	2.27×10^{4}	44.5	0.20	2.27×10^{4}
Bypass	40.0	0.20	0.0	40.0	0.20	0.0

Process HW	40.0	0.20	2.27×10^{4}	40.0	0.20	2.27×10^{4}
Process HW Out	44.5	0.20	2.27×10^{4}	44.5	0.20	2.27×10^{4}
To Deaerator	61.8	0.20	2.62×10^{4}	61.8	0.20	2.62×10^{4}
To boiler	120.2	0.20	1.53×10^{4}	120.2	0.20	3.00×10^{4}
Process 3 Condensate	44.8	1.70	5.31×10^{3}	44.8	1.70	1.88×10^{4}
Leakage	44.8	1.70	-1.50×10^{3}	44.8	1.70	1.20×10^{4}
To Neutralization Tank	53.4	0.20	2.58×10^{4}	53.4	0.20	2.58×10^{4}
Plant Outflow	60.8	0.18	5.61×10^{4}	73.2	0.18	5.73×10^{4}
Process 6 Baths	60.0	0.20	2.85×10^{3}	60.0	0.20	2.85×10^{3}
Process 4 HX Out	63.1	0.20	1.59×10^{4}	63.1	0.20	1.59×10^{4}
Process 4 Makeup	60.0	0.20	1.59×10^{4}	60.0	0.20	1.59×10^{4}
Process 4 Hot Water	62.0	0.20	1.59×10^{4}	62.0	0.20	1.59×10^{4}
Process 4 HW out	65.1	0.20	1.59×10^{4}	65.1	0.20	1.59×10^{4}
Acid Tanks	60.0	0.20	2.48×10^{3}	60.0	0.20	2.48×10^{3}
Clarifier	47.2	0.20	5.49×10^{4}	47.2	0.20	5.49×10^{4}
Raw Water	28.3	0.18	0.0	28.3	0.18	0.0
Municipal Water	7.0	0.20	2.15×10^{4}	7.0	0.20	2.15×10^{4}
Process HW from HX	7.0	0.20	7.75×10^{4}	7.0	0.20	7.75×10^{4}
Process HW condensate	60.0	0.20	3.17×10^{4}	60.0	0.20	3.17×10^{4}
To Process HW HX	179.9	1.00	2.56×10^{3}	179.9	1.00	2.56×10^{3}
Other	20.8	0.20	3.17×10^{4}	20.8	0.20	3.17×10^{4}
Cooling Water Make up	60.0	0.20	3.17×10^{2}	60.0	0.20	3.17×10^{2}
Process 5 Out	7.0	0.20	2.66×10^{4}	7.0	0.20	2.66×10^{4}
Process 5 Condensate	40.0	0.20	5.61×10^{4}	40.0	0.20	5.61×10^{4}
Process 5 In	179.9	1.00	1.81×10^{3}	179.9	1.00	1.81×10^{3}
Domestic HWC	24.3	0.20	5.61×10^{4}	24.3	0.20	5.61×10^{4}
Domestic HW	7.0	0.20	9.99×10^{2}	7.0	0.20	9.99×10^{2}
Domestic HWR	55.4	0.20	2.80×10^{3}	55.4	0.20	2.80×10^{3}
Domestic CW	179.9	1.00	9.96×10^{1}	179.9	1.00	9.96×10^{1}
Domestic HW Mix	7.0	0.20	8.97×10^{3}	7.0	0.20	8.97×10^{3}
DHWR	38.1	0.20	2.80×10^{3}	38.1	0.20	2.80×10^{3}
DHWS	55.4	0.20	1.80×10^{3}	55.4	0.20	1.80×10^{3}
DHWR to mix	55.4	0.20	9.99×10^{2}	55.4	0.20	9.99×10^{2}
To Municipal Drain	55.4	0.20	1.80×10^{3}	55.4	0.20	1.80×10^{3}
Process 4 Steam Return	11.8	0.20	9.97×10^{3}	11.8	0.20	9.97×10^{3}
Building Heat Return	179.9	1.00	1.00×10^{2}	179.9	1.00	1.00×10^{2}
Cooling Water Makeup Runoff	179.9	1.00	2.27×10^{3}	179.9	1.00	2.27×10^{3}
To Process 5 in	40.0	0.20	2.66×10^{4}	40.0	0.20	2.66×10^{4}
Deaerator Extra	40.0	0.20	2.95×10^{4}	40.0	0.20	2.95×10^{4}
3	84.0	0.20	-1.29×10^{4}	120.2	0.20	1.81×10^{3}

5.2.2 Material Streams with Expected Changes

The following streams were expected to have changes in either mass flow or temperature due to the direct relationship to the Steam Out and Municipal Water streams:

- The To Boiler mass flow rates (1.94×10^4, 1.21×10^4, 1.53×10^4, 3.00×10^4 kg/h) varied for the four cases. This stream supplied the boiler and, due to conservation of mass, the same amount of water was required to supply the boiler as there was steam produced by the boiler. The To Boiler mass flow was essentially a defined value, controlled by the defined value set for Boiler Out. The changes in flow were expected and reflect the total amount of steam produced.
- The Process 3 Condensate mass flow rates (7.18×10^3, 5.34×10^3, 5.31×10^3, 1.88×10^4 kg/h) varied across all four cases. This stream represents the condensed 250lb steam line returning from Process 3. The steam header, which supplied the 250lb steam line, used defined flow ratios for all of the streams, except for the 250lb line. The simulations were setup as driven systems, with any excess steam going to the 250lb steam line. The changes in mass flow rate were expected for this stream.
- The To Neutralization Tank material stream had varying temperatures (52.9, 52.3, 53.4, 53.4°C) and mass flow rates (2.38×10^4, 2.19×10^4, 2.58×10^4, 2.58×10^4 kg/h) for the first three cases, but was unaffected by the increase in steam production in the fourth case. The change in temperatures was relatively small, which was to be expected. The water streams that supply the To Neutralization Tank are process streams which have constant temperatures. The To Neutralization Tank was the output of the Sludge Thickener, which mixed the To

Drain, Process 4 HX Out, Other, and Process 6 Bath's material streams. The changes witnessed in the mass flow rates were expected, as they were all fixed ratios of the Municipal Water supply.

- The Process 6 Bath's / Process 8 had mass flow rates of 2.55×10^3, 2.25×10^3, 2.85×10^3 and 2.85×10^3 kg/h, for the four case studies. This stream was identified with two variables names, and was only shown on the HYSYS Model with the Process 6 Bath's label because the Process 6 Baths stream was the only supply for the Process 8. The mass flow rates changed in the first three cases, while remaining constant in the fourth case. This was expected, and was due to the amount of municipal water not changing between the third and fourth case. The Process 6 Baths were supplied from the Raw Water material stream, which was a fixed flow ratio (TEE-101) from the Municipal Water stream. The changes in mass flow rates were also expected, due to the defined flow ratios of the upstream tees supplied by the Municipal Water stream.
- The Process 4 HX Out material stream temperatures (63.4, 63.9, 63.1, 63.1°C) and mass flow rates (1.42×10^3, 1.26×10^4, 1.59×10^4, 1.59×10^4 kg/h) varied across the four case studies. The variation in temperature was small, as it used to preheat the constant temperature Process 4 Makeup water. The slight temperature variations were a result of the varying supply of steam to the process. This stream represented a process which was assumed to use constant temperature water. The mass flow rates show that with the change in Municipal Water, there was a direct effect seen on the Process 4 Heat Exchanger. These changes were all expected, as the source for this material stream was the Municipal Water.

- The Process 4 HW Out material stream temperatures (65.4, 65.9, 65.1, 65.1°C) fluctuated to some extent leaving Process 4. This was expected, as it was a manufacturing process, and the temperature should have remained constant throughout the various scenarios. This stream was directly heated with 115lb steam, from the 115lb steam header. Although there were fluctuations in steam supplied to the Process 4 Hot Water system, there was always adequate thermal energy to maintain a relatively constant temperature.
- The Process HW from HX mass flow rate fluctuated (2.83×10^4, 2.52×10^4, 3.17×10^4, 3.17×10^4 kg/h) across the first three case studies, and remained constant for the final case study. This material stream was the outlet stream for the Process HW HX and has To Process HW HX as a source stream. With no mass flow losses across the heat exchanger, this result shows that the amount of process HW is not influenced by increased volumes of steam production.
- The To Process HW HX temperatures fluctuated in the first three case studies (22.5, 24.4, 20.8, 20.8°C) suggesting that the process hot water temperature was influenced directly by the total amount of steam produced. The mass flow rates were the same as the Process HW from HX, and experienced the same changes (2.83×10^4, 2.52×10^4, 3.17×10^4, 3.17×10^4 kg/h). These were expected changes, as the Municipal Water was the source for this material stream.
- The To Deaerator stream represents the fluid from the Clean Condensate Tank, which has Process 5 Condensate, Building Heat Return, Process HW condensate, SW Makeup to Return Tank, and Process 4 Steam Return as feeding material streams. The To Deaerator temperatures (69.9, 46.3, 61.8, 61.8°C) and mass flow

rates (2.8×10^4, 2.32×10^4, 2.62×10^4, 2.62×10^4 kg/h) varied for the first three cases. The fourth case (Half Heat Double Steam) remained the same as the third case (Half Heat). These results show that although the parameters, of the To Deaerator stream, fluctuated through the first three models the changes were related to the amount of 115lb steam. In the fourth case, the total amount of steam produced doubled, but the 115lb steam value remained the same, which resulted in the amount of clean condensate remaining constant.

- The material stream, Other, had mass flow rates which varied across the four case studies (2.83×10^2, 2.52×10^2, 3.17×10^2, 3.17×10^2 kg/h). The To Process HW HX was the source for this material stream, and used a fixed flow ratio, at the Process HW Header, to control the mass flow rate for the material stream, Other. These changes in mass flow rates were expected.
- The RAW Water material stream mass flow rates fluctuated in the four case studies (1.81×10^4, 1.50×10^4, 2.15×10^4, 2.15×10^4 kg/h). This result was anticipated, as the Raw Water stream was supplied from the Municipal Water header (Tee-101), which used fixed flow ratios.
- The Clarifier stream mass flow rates (5.15×10^4, 4.84×10^4, 5.49×10^4, 5.49×10^4) changed only slightly across the four case studies. The mass flow rate was expected to change based on the amount of Process 3 Condensate, RAW Water, and Cooling Water Makeup Runoff used in the facility. The amount of condensate, from Process 3, was directly related to the amount of 250lb steam being produced. Most of the 250lb steam would be lost to the atmosphere, with only a small portion being converted to dirty condensate. The remaining steam

would leave the facility as leakage. The model used a fixed flow rate for the Process 3 condensate returning to the sludge thickener. This would enable the model to simulate the approximate amount of heat captured from the condensate and used in the Primary SW HX. The fixed amount of condensate was the minimum amount of condensate required to pre-heat the SW Makeup. The Municipal Water stream supplied the RAW Water and Cooling Water Makeup Runoff. The variations in these streams were expected.

The results of the water material streams demonstrated that with a change in the amount of Municipal Water, Steam Out, or Domestic Heating there were downstream effects. This result was expected, as when the supply to a process varies, there would be an anticipated change in the process as well. With the above material streams the source of water, for these streams, were either defined flow ratios or mass flow rates. In either case, it shows that the systems were interconnected, in the sense that a change in supply would also change the downstream systems.

5.2.3 Material Streams with Unexpected Changes

The following streams were expected to change, but did so with unexpected results.

The temperatures for the Plant Outflow are higher than expected at 64.6°C, 57.7°C, 60.8°C, and 73.2°C. This was most likely due to the fact that the Waste Water Treatment Plant (WWTP) was modelled as a series of mixers, where in reality the WWTP was a series of open tanks. The tanks would lose energy to the atmosphere, thereby reducing the water temperature leaving the plant. By modeling the WWTP as a series of mixers it was possible to see the amount of residual heat left in the process streams that was not being captured and re-used. The higher temperatures of this stream also indicated that there were still process streams with a high amount of energy, such as the blowdown stream. This energy could be reused in other energy saving systems.

There were two material streams that had negative values for flow rates. The first stream was the Deaerator Extra material stream, and was expected to have a negative flow, as it was added in order to balance the model. The Deaerator Extra temperatures (87.4, 70.7, 84.0, 120.2°C) and mass flow rates (-1.07×10^4, -1.31×10^4, -1.29×10^4, 1.81×10^3 kg/h) suggested that the amount of clean condensate, returned to the deaerator, was higher than required. In the final case the mass flow rate showed that in order to produce double the amount of steam, there was insufficient supply of clean condensate and Municipal Water.

The second stream with negative flow was the leakage stream, which was a stream off of the Process 3 Condensate line at TEE-103. This material stream was used to represent the condensate that may not have been captured by either the steam traps or the roof top condenser. In the simulation it ended up acting as a make-up stream for the dirty condensate, in two of the four case studies (Half Heat and No Heat). These two cases both have a reduced amount of steam being supplied to Process 3, resulting in a negative flow of the leakage stream that was not expected. The simulation required a minimum amount of condensate supplied to the Primary SW HX, to ensure that it functioned properly. In the two cases where the leakage flow was negative, there was insufficient condensate from Process 3 to maintain the Primary SW HX. The simulated values for the Leakage material stream were mass flow (3.77×10^2, -1.46×10^3, -1.50×10^3, 1.2×10^4 kg/h) varied for the four cases. In the first case and last case, the flow was positive re-affirming that this flow was in fact a loss of fluid in the system. In the No Heat and Half

Heat models the flow was negative. This result showed that there were interconnected effects in the system by reversing the flow rate of a material stream, in order to ensure that the defined parameters were satisfied. In order to ensure that this stream would always have a positive flow (liquid leaving the plant), the defined temperatures on the Primary SW HX would need to be removed (which may result in the SW HX not being used for certain seasons), and a minimum amount of steam being supplied to Process 3 would be required in order to ensure adequate heat transfer in the SW HX (or the SW HX could be removed for season with lower steam production). The Leakage stream should also be a defined percentage of the Process 3 Condensate, rather than having the Process 3 Condensate flow rate defined.

The streams with the negative flow rates flow rates suggest that there are interconnected effects that need to be further investigated. For instance the Deaerator Extra stream was required in order to ensure there was the correct amount of water being supplied to the boilers. The requirement of this stream showed that there was an interconnection between the amount of Municipal Water being supplied to the boiler house, and the ratio of clean condensate to dirty condensate. There was a percentage of the Municipal water allocated for steam production but, the majority of the steam was produced from clean condensate returning from the processes. If there were too much dirty condensate being produced, there was no direct link to the Municipal water to increase supply. This meant that there would have been insufficient water to create the specified amount of steam. The opposite was also true, if there was an excess of Municipal Water or clean condensate being supplied to the boiler house there would be too much steam produced. In order to ensure that this stream would always be positive (liquid leaving the plant), the Softwater flow ratio and the Municipal Water flow rate would need to be increased. This would result in higher calculated Municipal Water flow rates than Michelin has recorded. The reduction in water consumption by the other processes in the facility would not be adequate in order to always ensure a positive flow rate from the Deaerator Extra stream.

Without more detailed information about more processes, it was not possible to determine specifically which flows were not representative of the actual flows. The outputs show that it was possible to create a model of the water material streams from the Michelin plant, and obtain results of how the plant would react to various loads. With detailed data, it would be possible to create a more realistic model.

5.3 ENERGY STREAM RESULTS

The amount of energy used for building heat, process 3, the boilers and the basement vent condensers can be seen in Table 5.5.

Table 5.5 HYSYS Energy Stream Outputs

	Full Heat (*GJ/h*)	**No Heat (*GJ/h*)**	**Half Heat (*GJ/h*)**	**Half Heat Double Steam (GJ/h)**
Boiler Energy	44.41	27.70	35.03	68.67
Basement Vent Condenser Energy	0.142	0.142	0.142	0.142
Process 3 Energy	18.71	13.92	13.83	49.06
Building Heating Energy	9.20	0	4.60	4.60

The Boiler Energy (44.41, 27.70, 35.03, 68.67 GJ/h) varied in each of the four cases, because the steam produced changed for each case. The Basement Vent Condenser Energy (0.142, 0.142, 0.142, 0.142 GJ/h) was also a defined value, but used temperatures to control the amount of energy extracted. The Process 3 Energy varied across the four case studies, as the excess steam not required in the 115lb Steam lines was sent to the 250lb steam system. This result was expected, as the 115lb steam line used a fixed amount, and the excess steam would flow to the unrestricted 250lb steam line. In reality the amount of steam used in the 250lb system would be a constant, as it was the thermal energy source for Process 3. The amount of steam that Process 3 would use would be dependent on tire production. With the use of fixed steam ratios, the amount of steam supplied to processes was not dependant on the demand. The Building Heating Energy (9.20, 0, 4.60, 4.60 GJ/h) were defined values for all four case studies.

5.4 SUMMARY

The models demonstrated that with the current configurations, there were no unexpected interconnected effects between the processes. Although there were several material streams that yielded unexpected results, the streams were expected to vary with the changing input parameters.

The interconnected effects, discussed in the results, demonstrated that there were certain material streams that are more susceptible to variations within the facilities running conditions. These sensitivities were typically addressed by defining parameters that would force the system to continue to function.

The first three case studies use a variation in the amount of domestic heating as their differentiator (Full Heat, No Heat, and Half Heat). With the change in domestic heat, it can be said that the supply of thermal energy to other processes must be adjusted in order to accommodate for the change in thermal loads or steam production would need to be adjusted.

The water material streams demonstrated that only unconstrained streams reacted to the changes in the input parameters. The only stream that displayed higher temperatures than expected was the Plant Outflow. The increased temperature in the plant outflow can be attributed to the condensate lines not having a pressure drop from the steam (resulting in higher temperature condensate), along with their being no ambient heat loss in the model.

The models used defined mass flow rates and flow ratios in order to produce results that were representative of the Michelin facility. These defined values were the reason that predicting which streams were going to react to the changes in Municipal Water, and Steam Out possible.

The simulations used fixed steam ratios in order to force the model to produce more steam than would be normally required by the system. In doing so, it was possible to see which streams were affected. The resulting models show that there are certain streams that require a minimum amount of water or steam in order to maintain constant running parameters. When these minimums are not met, streams such as leakage, will reverse their flow in order to compensate for the lack of fluid. The interconnectedness in these simulations suggested that there were many aspects of the facility that were affected by changes within the system. Although most of the changes were expected, there are many smaller processes that were not represented in the simulations that may react unexpectedly due to their configurations into the steam and water systems.

CHAPTER 6 DOMESTIC HOT WATER PRE-HEATING

6.1 INTRODUCTION

At the Michelin Bridgewater plant, there are certain auxiliary systems that use a small portion of thermal energy annually but are not related to the production processes. In the case discussed here the auxiliary system in question is the domestic hot water system. This system uses a small amount of steam annually, in comparison to the production process, in order to heat water. The domestic hot water is used in the kitchen, labs, and in the three locker rooms (includes the showers and the hand washing stations). The domestic water, also referred to as sanitary water (including both the hot and cold water used in the system), has no heat recapture on the water leaving the facility and is discharged into the municipal waste water system.

There is one central domestic hot water system in the facility, which is heated by the 115lb steam line. With no energy capture on the domestic hot water leaving the facility, and with a shortage of heat sinks with available yearly capacity the Michelin plant has asked what the possibility would be of pre-heating the central domestic hot water using the cooling water leaving the air compressors. This reduction in energy would result in less fuel burned to produce the steam required to heat the hot water (Liu et al., 2010). The advantage of using the domestic hot water as both a heat sink and reduce the steam usage would be a reduction in effluent temperatures and reduced fuel costs to generate steam required to heat the water.

There are currently systems in place at the Michelin facility to control the temperature of the effluent leaving the plant. Once the effluent has reached this point, there have been many streams of higher and lower temperatures mixed. This results in a reduction in the amount of energy that can be captured from the effluent. If the hottest streams can be identified before they are mixed into the effluent, and smaller heat capturing systems implemented such as the domestic hot water pre-heating, the greater the amount of energy that could be extracted from the stream. This would result in cooler temperatures of streams being mixed into the effluent thereby lowering the overall temperature.

The following sections discuss the required measurements, the methods used to obtain the measured values, calculations used, as well as the results and discussion.

6.2 SYSTEM DESCRIPTION

The domestic hot water system is comprised of a large insulated water tank, heated with steam. A graphical representation of the model can be seen in Fig. 6.1. The heating method is indirect with the use of a closed loop steam line, entering the tank as saturated steam and exiting the tank as clean condensate. As the steam condenses and drains out of the steam loop, it is collected in a condensate tank. Once the condensate tank has reached a certain volume of liquid, the tank is emptied with the use of two small pumps and more steam is added to the heating loop. The hot water system uses a hot water recirculation loop in order to maintain the temperature in the system. This recirculating loop is used to pre-heat the make-up water entering the hot water tank.

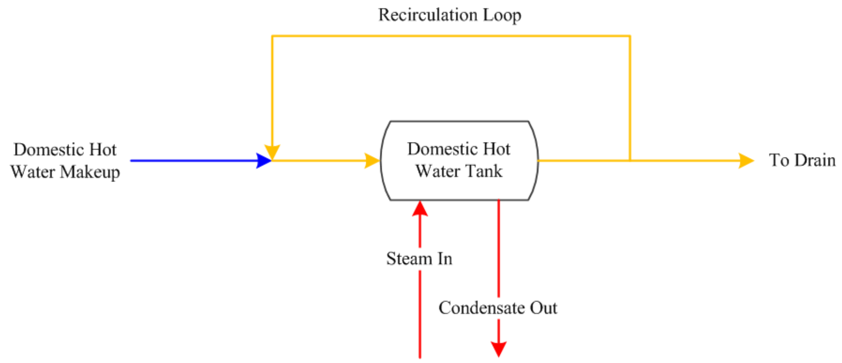

Figure 6.1 Domestic Hot Water System Representation

The other system of interest would be the air compressor cooling system. The air compressors were chosen as the best candidate to pre-heat the domestic hot water system, as they are located nearby. The air compressors appeared to all be cooled with the use of domestic cold water, which makes a single pass through the air compressors and then discharge to the WWTP. There are several different types of air compressors use at the Michelin plant and for the purpose of this study, the temperatures recorded off all of the compressors were averaged and treated as one unit.

In order to determine how much heat the domestic hot water system currently uses the flow rates of the water were required at the entrance and exit of the tank. The flow rate of the hot water out of the domestic hot water tank was similar to that of the air compressor cooling water, at 2.2 m^3/h. The cold water was delivered at a third of the rate of the hot water leaving the tank, at 0.8 m^3/h. The cold water is mixed with the water from the recirculation loop, yielding a stream with a temperature of 41°C, which then enters the hot water tank.

The hot water is diluted, using mixers, before entering taps or areas where skin could be exposed to the high temperature water. With the hot water storage temperature measurement of 54.7°C and the air compressor cooling water being at 41°C, an additional 12.70 kW of energy will still be required. In reality slightly more energy would be required as the make-up water temperature will only approach the air compressor cooling water temperature to within 10-15°C.

With the temperature of the cold water being added to the recirculation loop varying throughout the seasons, an average temperature of 10.5°C was used to determine the amount of energy that could be added to the cold water from the hot side of the air compressors.

In order to determine the amount of steam used, a constant mass flow rate of steam was assumed to be continuously heating the cold water makeup being supplied to the hot water tank.

6.3 MEASUREMENTS

In order to determine the amount of steam used to heat the domestic hot water, there were several pieces of information that were first required. The domestic hot water system required the water temperatures at the inlets and outlets of the tank. The make-up water and recirculation temperatures were also required. Once the temperatures were obtained, the flow rate of the inlet and outlet water streams were required, along with the makeup and recirculation water flow rates. In addition to the domestic hot water system measurements the air compressor cooling water systems also required measurements. The temperatures at the inlet and outlet of the cooling water system and the flow rates were required for all of the compressors.

The amount of steam required to heat the domestic how water tank was one value that was not able to be measured directly. The steam was delivered intermittently, as it condensed inside of the tank and also depended on the demand for domestic hot water. In order to determine how much steam was used, the amount of thermal energy extracted from the steam was required. To do this the temperature of the condensate leaving the domestic hot water tank was required.

6.3.1 Flow rate

In order to calculate the flow rate of the water, the FDT-21 handheld ultrasonic flow meter, shown in Fig. 3.1, was used. The pipes used in the domestic hot water system were painted copper pipes.

The flow rate of the steam was also required, however, direct measurement was not feasible. The amount of energy added to the hot water system was calculated by using the inlet and outlet temperatures and specific heat of the water. The mass flow rate of steam was estimated by using the change in enthalpy (from a gas to a liquid) and the amount of energy required to heat the water.

6.3.2 Temperature

In order to obtain the temperature measurements, type K thermocouples where attached to the various water pipes using thermocouple adhesive pads. The data was recorded using the handheld thermocouple data logger shown in Fig. 3.4. As previously mentioned, the difference between the surface temperatures and the midstream temperatures were minimal. Therefore the surface temperatures were assumed to be the same as the midstream temperatures.

The temperature for the steam entering the tank was assumed to be at saturation temperature for steam at 0.80 MPa, which was 180°C. The condensate temperature was measured using the same methods as the water pipes.

6.4 DOMESTIC HOT WATER: RESULTS AND DISCUSSION

The calculations used in order to determine the amount of potential cost savings will be covered in this section, as well as a discussion of those results.

The measured data for the temperatures for the inlet (T_{cold}) and outlet (T_{hot}) temperatures of the hot water tank are presented in Table 6.1. This table also presents the measured volumetric flow rate (Q) of the make-up water, the density (ρ_w) of water (at 10.5°C), the heat capacity of water (C_{pw}), and the calculated mass flow rate ($\dot{m}$).

Table 6.1 Measured Data and Water Data from Tables

Name	Value
T_{hot} (°C)	54.7
T_{cold} (°C)	10.5
$\Delta T = T_{hot} - T_{cold}$	44.2
Q (m^3/h)	0.8
ρ_w (kg/m^3)	999.9
Cp_w (kJ/kg-K)	4.18
$\dot{m}_{hw}$ (kg/h)	799.9

To calculate the mass flow rate of the make-up water stream Eq. (7.1) was used.

$$\dot{m}_{hw} = \rho_w \times Q \tag{7.1}$$

With the calculated domestic hot water make-up mass flow rate, it was then possible to determine the amount of thermal energy required to heat the make-up water using Eq. (7.2).

$$q = Cp_w \times \dot{m_{hw}} \times \Delta T = 41.1 \text{ kW} \tag{7.2}$$

Using the amount of energy required to heat the make-up water entering the domestic hot water tank (q), the mass flow rate of the steam was estimated ($\dot{m}_{\text{steam1}}$) using Eqs. (7.3) and (7.4).

$$\Delta h = h_g - h_f \tag{7.3}$$

$$\dot{m}_{steam1} = \frac{q}{\Delta h} \tag{7.4}$$

In order to calculate the change in enthalpy (Δh), both the enthalpy of steam and the resulting condensate were required, which can be found in Table 6.2. The temperature of the steam (T_s) was slightly less than that of the 115lb steam lines, as the steam passes through another reduction valve, reducing the pressure to 80 kPa gauge (180 kPa) and also reducing the temperature to 116.9°C. The measured condensate temperature (T_c) can also be found in Table 6.2.

Table 6.2 Steam in and Condensate Out of Domestic Hot Water Tank Data

Name	**Value**
T_s (°C)	116.9
T_c (°C)	93.5
p (kPa)	80
h_g (kJ/kg)	2701.5
h_f (kJ/kg)	490.5
Δh	2211

$$\dot{m}_{steam1} = \frac{q}{\Delta h} = 66.84 \text{ kg/h} \tag{7.4}$$

The amount of steam required to heat the makeup water for the domestic hot water tank was found to be 66.84 kg/h. This mass flow rate assumed that there was a constant load on the domestic hot water system, which required a constant amount of steam. The loads actually fluctuated, with the calculated value being an average.

The next step was to determine the amount of potential energy in the air compressor cooling water.

In Table 6.3 the inlet (T_{in}), outlet (T_{out}) and temperature difference (ΔT) for the air compressor cooling water streams are shown. T_{in} represented the measured exit temperature of the cooling water leaving the compressors. The mass flow rate of the air compressor cooling water ($\dot{m}_{air}$) was the average of the experimental measurements. The mass flow rate of the air compressor cooling water was 2.75 times higher than the amount of domestic hot water make-up. This large difference in flow rates would have resulted in more energy being available, in the air compressor stream, than was required for the pre-heating system when T_{out} was set to 10.5°C. The total amount of energy that could be extracted from the air compressors would be 77.90 kW, with a temperature difference of 30.5°C. This amount of energy would heat the make-up water to above 41°C, which is not possible. Therefore the amount of energy required to heat the domestic hot water make-up, from 10.5°C (inlet water temperature) to 41°C (the temperature of the water exiting the air compressor cooling system), was calculated to be 28.35 kW. T_{out} was then determined using equation 7.5.

$$T_{out} = T_{in} - \frac{q_{air}}{Cp_w \dot{m}_{air}} = 29.9°\text{C} \tag{7.5}$$

Table 6.3 Air Compressor Energy Contribution Data

Air Compressor Energy Contribution	
T_{in} **(°C)**	41
$\Delta T = T_{in} - T_{out}$	11.1
$\dot{m}$ **(kg/h)**	2199.78
q_{air} **(kW)**	28.35

The difference in power required to heat the domestic hot water make-up water was calculated using Eq. (7.6). This difference would represent the amount of power required to heat the makeup water for the domestic hot water tank, with the use of the air compressor cooling water as pre-heating.

$$\Delta q = q - q_{air} = 12.70 \text{ kW} \tag{7.6}$$

The reduction in required power to heat the makeup water, would result in a reduced amount of steam required. This mass flow was calculataed using Eq. (7.7), with $\dot{m}_{steam2}$ representing the reduced steam mass flow rate.

$$\dot{m}_{steam2} = \frac{\Delta q}{\Delta h} = 20.11 \text{ kg/h} \tag{7.7}$$

The resulting savings from this reduction in steam usage was calculated using equation 7.8.

$$Savings = \frac{\Delta\dot{m} \times 24\frac{h}{day} \times 365\frac{day}{year} \times Bunker\ C\ Cost}{1000} \tag{7.8}$$

The steam production for domestic hot water would be reduced by 69% (46.15 kg/h) and would result in fuel savings of $16,984 per year (based on a Bunker C cost of $42.00/Tonne of Steam). Although this would be a small reduction in overall steam production, the amount of savings in Bunker C could make for a feasible project.

With the excess amount of thermal energy in the air compressor cooling system, it may be of interest to store the energy using thermal energy storage system for when there is an increase in thermal loads. This may also increase the amount of possible savings.

6.5 SUMMARY

The pre-heating of the domestic hot water appeared to be a feasible project, based on the initial study performed. In order to determine the full potential of this project as a cost savings and as an additional heat sink, a more in depth study would be required. Actual steam and water usage would be required for both the domestic hot water usage, and the air compressor cooling water systems. A suitable heat exchanger could be selected for use in the system with a more detailed study.

With the excess amount of thermal energy available in the air-compressor cooling system, the possibility of thermal energy storage may be of interest to investigate. The energy could be stored for when there is an increase in domestic hot water usage, or it could be used in other processes.

There are some concerns with this setup, such as the domestic hot water system is a cyclical load (not as constant as the compressor cooling water). This would mean that there would still be potential for energy to be extracted from the compressor cooling water for the periods that the domestic hot water usage is low and store the energy using thermal energy storage devices.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The study of the Michelin Bridgewater facility has presented several findings that are of value, such as the requirement of seasonal running conditions (steam header flow ratios). It was possible to create a model of an existing facility using Aspen HYSYS, provided an adequate supply of relevant information and a complete system outline. The model predicts the outcomes of changes in process parameters and demonstrates that there are interconnections present in the model, and that the sensitivity of the plant could be determined using a more refined HYSYS model.

The model demonstrated that by varying the amount of Building heat, the plant configuration must also adapt in order to compensate for the change in thermal load. This was evident by requiring different case studies to represent the various seasons. Although this did not directly show that there were interconnected effects, it did show that the plant was affected by the amount of building heat. This suggests that when other processes change there would be a measureable effect expected in other systems throughout the facility, unless there were appropriate adjustments made to the running conditions of the plant.

There were indications that there were interconnected effects throughout the facility. For instance there were two streams that experienced negative flows, in order to satisfy defined parameters. The material streams themselves, Deaerator Extra and Leakage, were added in order to create a model that could have losses. The Deaerator Extra stream showed that there was an interconnection between the amount of water returning to the deaerator and the total amount of steam produced. In itself that was not unexpected, however the fact that there was a negative flow showed that even though all of other process conditions were satisfied, there was an inadequate amount of water returning to the deaerator. The Leakage stream represented the steam that was lost to the atmosphere in Process 3. The condensate from Process 3 was used to pre-heat the soft water make-up going to the boiler house. The soft water had a constant ΔT and thereby required a constant amount of thermal energy. This meant that there had to be a constant amount of dirty condensate from Process 3, which was a defined value. In two of the cases, there was insufficient condensate resulting in the Leakage stream having a negative mass flow rate. This negative flow rate suggests that there must have also been an interconnection between in soft water temperature and the amount of Process 3 condensate.

With more data collection on key material streams, it would be possible to create a model that better predicts if there are interconnected effects, and show the sensitivity of the plant to those interconnections. Further investigation into the actual material stream configuration at the facility would also provide further insight into how processes are connected. The case studies presented used a simplified material stream configuration, as the actual configuration was not known for all aspects of the facility.

During the compilation of the models there were several pieces of information that were realised to be inaccurate or the use of an averaged value not feasible. The estimates that were used to divide up the steam usage by production area were only reasonable for certain periods of the year, and only under certain operating conditions. The water usage estimates supplied by HYSYS appear to underestimate the amount of water being used.

Enhanced data collection would be required in order for a more accurate model. Up to date drawings of the flow of fluids would also be an asset in order to see more specific interactions between processes. Steam measurements are required. Knowing only the total amount of steam produced was not enough to accurately determine which areas are the largest users. The amount of heat extracted from the steam merely gives an indication of how much steam may be used. Process 3 appears to be the largest user but the amount of steam used by that shop is an estimate.

To better model the facility, permanent measurement or long term measurement devices would be required, in order to collect year round information at various production levels. The temperature measurements at specific locations could be used to better monitor the effect of upstream modifications. Effluent water temperature from the plant and the temperature of the Waste Water Treatment Plant outlet would be two recommendations of places that should be monitored.

The domestic hot water pre-heating system appeared to be a feasible project, based on cost saving from Bunker C fuel alone. With the amount of potential thermal energy in the air compressor cooling water being in excess of what was required to pre-heat the domestic hot water system, there was still the potential to pre-heat other systems or store the thermal energy for future use or when there was an increase in domestic hot water demand.

7.2 RECOMMENDATIONS

It would be beneficial to know the actual amount of steam that Process 3 uses. The Process 3 load should be fairly consistent across the different seasons. With that defined amount it would help in determining the distribution of the steam. It could be possible to estimate the amount of steam used in Process 3 by using the production values (for a given time period), the approximate change in temperature of the product (from ambient to the final temperature), and the change in temperature of the supplied steam to condensate. With this information the amount of steam required could then be calculated, and extrapolated to estimate the total amount of steam required for all of Process 3. The only missing piece of information in order to calculate this would be the final temperature of the products. This information is proprietary and was therefore not available to be used in this project.

Throttling of the certain process flow rates may be an area of interest, as the inlet water temperatures fluctuate during the seasons and a reduction in the amount of water used could reduce costs. It may also yield a more stable performance of some of the systems if the cooling rates are constant year round.

Improved instrumentation and measurement systems, performing continuous data collection on-site, would vastly improve the model. The use of more data in the model would reduce the number of assumptions used, and thereby increase the accuracy of the model.

Extension of the model with this added information could be used to study the impact of specific changes in processes. The current model uses more of a global process configuration because of a lack of specific process information. Results from the refined model could lead to better understanding of thermal energy usage, losses and recuperation within the plant.

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APPENDIX A: MICHELIN DATA

Michelin Data

Table A.1 Selected Data supplied by Michelin

2012	STEAM (T)	MUNICIPAL WATER (m^3)	DECANTER DISCHARGE (m^3)	EFFLUENT (°C)	SOFT WATER (m^3)	SOFT WATER (Make-up sheet) (m^3)	Bunker C (L)
Total	132077.58	666039.00	450158.00	14.36	86257.48		8278357.22
JAN	14441.54	55237.00	49663.00	11.61	7320.67	7315.90	912720.86
FEB	13423.52	54730.00	44791.00	11.11	7283.73	7278.98	826707.79
MAR	13108.99	48952.00	47042.00	11.61	7775.75	7770.68	827799.31
APR	11018.47	55701.00	38600.00	12.39	7116.01	7111.37	699725.37
MAY	9887.61	62603.00	52108.00	14.11	7470.02	7465.15	638221.47
JUN	9214.52	60706.00	30852.00	16.22	7106.18	7101.55	569430.77
JUL	8919.82	60013.00	32749.00	19.67	7218.97	7214.26	547384.10
AUG	8971.58	63794.00	34075.00	21.44	7509.82	7504.92	545144.62
SEP	8721.48	51178.00	29123.00	17.44	6981.61	6977.06	534201.27
OCT	9693.17	57684.00	32272.00	14.00	7062.73	7058.13	591910.28
NOV	12004.46	51505.00	31316.00	11.44	7410.22	7405.39	741560.41
DEC	12672.42	43936.00	27567.00	11.33	6001.76	5997.85	843550.96

Table A.2 Michelin data in time based units

2012	Time (Hrs/Month)	STEAM (kg/h)	MUNICIPAL WATER (m^3/h)	DECANTER DISCHARGE (m^3/h)	SOFT WATER (m^3/h)	Bunker C (L/h)
Total	8760	15077.35	76.03	51.39	9.85	945.01
JAN	744	19410.68	74.24	66.75	9.84	1226.78
FEB	672	19975.47	81.44	66.65	10.84	1230.22
MAR	744	17619.61	65.80	63.23	10.45	1112.63
APR	720	15303.43	77.36	53.61	9.88	971.84
MAY	744	13289.80	84.14	70.04	10.04	857.82
JUN	720	12797.94	84.31	42.85	9.87	790.88
JUL	744	11989.01	80.66	44.02	9.70	735.73
AUG	744	12058.58	85.74	45.80	10.09	732.72
SEP	720	12113.17	71.08	40.45	9.70	741.95
OCT	744	13028.46	77.53	43.38	9.49	795.58
NOV	720	16672.87	71.53	43.49	10.29	1029.95
DEC	744	17032.82	59.05	37.05	8.07	1133.81

Table A.3 Bunker C Energy Data

Property Tables (GJ/L)	High	4.22×10^{-2}
	Low	4.35×10^{-2}
Michelin Supplied Value (GJ/L)	High	4.11×10^{-2}
	Low	4.11×10^{-2}
Difference	High	3%
	Low	5%

The amount of Energy per Litre used by Michelin was between 3-5% lower than published values.

APPENDIX B: MEASURED DATA

Table B.1 Domestic Hot Water Measured Data

	Top (ºC)	Bottom (°C)	OD (mm)	ID (mm)	Material	Measured Flow Rate (m^3/s)	Velocity (m/s)	Q (υV)
Cold In	10.6	10.3	79.4	74.8	Copper	2.22×10^{-4}	0.057	
Hot In	55.4	55.3	22.2	19.9	Copper			
Mixed In	51.4	49.3	79.4	74.8	Copper	5.00×10^{-4}	0.095	
Condensate Out	91	61	22.2	19.9				
Hot Out	54.7	54.7	79.4	74.8	Copper	6.11×10^{-4}	0.33	0.4

Table B.2 Process 1 Measured Data

	Temperature (°C)	Measured Flow Rate (m^3/s)	Velocity (m/s)
Cold In	17.2	8.53×10^{-4}	1.68
Condensate Return	35.3		
Return Water Header	28	8.83×10^{-4}	1.71
Cold to Elevator	18.6		
Hot Supply	39	6.30×10^{-4}	
Component 1	48.3	1.17×10^{-3}	
Component 2	24.1	6.30×10^{-4}	
Component 3	24.1	6.30×10^{-4}	
Component 4	68.5	6.93×10^{-4}	
Component 5	47	0.00	
Component 6	40.1	1.39×10^{-3}	
Component 7	49	1.13×10^{-3}	

Table B.3 Process 2 Data Measured

	Temperature (°C)	Measured Flow Rate (m^3/s)	Velocity (m/s)
Cold In	17.2	6.22×10^{-4}	1.28
Condesate Return	44.9	1.75×10^{-4}	0.57
Component 1	25.5	6.93×10^{-4}	
Component 2	25.8	7.56×10^{-4}	
Component 3	26.5	9.45×10^{-4}	
Return Water Header	28	2.40	0.3
Component 4	38.5	8.82×10^{-4}	
Component 5	67.1	1.01×10^{-3}	
Component 6	23.2	8.82×10^{-4}	
Component 7	26.3	6.30×10^{-4}	
Component 8	67.9	3.15×10^{-4}	
Component 9	48.3	1.51×10^{-3}	
Component 10	55.1	1.51×10^{-3}	

Table B.4 Process 3 Data

	Temperature (°C)	Material	Flow (m^3/s)
Condensate Return	44.8	Carbon Steel	2.78×10^{-4}

Table B.5 Process 3 Information

	Density (kg/m^3)	Dynamic Viscosity (Ns/m^2)
Condensate Return	990.5	6.00×10^{-4}

Table B.6 Borax Heat Exchanger A

	Temperature (°C)	Material	Flow (m^3/s)
Town In	10.2	Carbon Steel	5.36×10^{-3}
Town Out	31.5	Carbon Steel	
Borax In	70	Carbon Steel	4.49×10^{-3}
Borax Out	37.6	Carbon Steel	

Table B.7 Borax Heat Exchanger A

	Density (kg/m^3)	Dynamic Viscosity (Ns/m^2)
Town In	999.7	1.31×10^{-3}
Town Out	995.7	7.98×10^{-4}
Borax In	977.8*	4.04×10^{-4}*
Borax Out	992.2*	6.53×10^{-4}*

*Values are estimated, based on a relatively low mixture ratio of borax to water. Actual values may vary.

Table B.8 Borax Heat Exchanger B

	Temperature (°C)	Material	Flow (m^3/s)
Town In	10.6	Carbon Steel	5.42×10^{-3}
Town Out	33.6	Carbon Steel	
Borax In	74.2	Carbon Steel	4.08×10^{-3}
Borax Out	36.8	Carbon Steel	

Table B.9 Borax Heat Exchanger B

	Density (kg/m^3)	Dynamic Viscosity (Ns/m^2)
Town In	999.7	1.31×10^{-3}
Town Out	993.75	7.25×10^{-4}
Borax In	974.8	3.79×10^{-4}
Borax Out	992.2	6.53×10^{-4}

Table B.10 Process 1 Calculated Data

	Calculated Flow Rate (m^3/s)	Density (kg/m^3)	Dynamic Viscosity (Ns/m^2)	Re_D
Cold In	1.02×10^{-3}	998.95	1.15×10^{-3}	4.03×10^{4}
Condensate Return		993.95	7.25×10^{-4}	
Return Water Header	1.65×10^{-3}	995.7	7.98×10^{-4}	7.50×10^{4}
Cold to Elevator		998.2	1.00×10^{-3}	
Hot Supply		992.2	6.53×10^{-4}	
Component 1		988.1	5.47×10^{-4}	
Component 2		996.95	9.00×10^{-4}	
Component 3		996.95	9.00×10^{-4}	
Component 4		977.8	4.04×10^{-4}	
Component 5		988.1	5.47×10^{-4}	
Component 6		992.2	6.53×10^{-4}	
Component 7		988.1	5.47×10^{-4}	

Table B.11 Process 2 Calculated Data

	Calculated Flow Rate (m^3/s)	Density (kg/m^3)	Dynamic Viscosity (Ns/m^2)
Cold In		998.95	1.15×10^{-3}
Condesate Return	1.78×10^{-4}	990.15	6.00×10^{-4}
Component 1		996.95	9.00×10^{-4}
Component 2		996.95	9.00×10^{-4}
Component 3		996.95	9.00×10^{-4}
Return Water Header	2.41×10^{-4}	995.7	7.98×10^{-4}
Component 4		992.2	6.53×10^{-4}
Component 5		977.8	4.04×10^{-4}
Component 6		998.2	1.00×10^{-3}
Component 7		996.95	9.00×10^{-4}
Component 8		977.8	4.04×10^{-4}
Component 9		988.1	5.47×10^{-4}
Component 10		985.65	5.07×10^{-4}

The pipe diameters were measured for only the Cold In and Return Water Header, because all of the other lines are fed from or return to those two lines. The streams with no diameter or material were only measured to obtain an average temperature to use in the HYSYS model.

Table B.12 Domestic Hot Water Calculated Data

	Calculated Flow Rate (m^3/s)	Density (kg/m^3)	Dynamic Viscosity (Ns/m^2)	Re_D	q'' (W/m^2)
Cold In	2.50×10^{-4}	999.7	1.31×10^{-3}	3.26×10^{3}	
Hot In		985.7	5.07×10^{-4}		
Mixed In	4.17×10^{-4}	988.1	5.47×10^{-4}	1.28×10^{4}	
Condensate Out		965.3	3.15×10^{-4}		
Hot Out	1.45×10^{-3}	985.7	5.07×10^{-4}	4.80×10^{4}	4.85

APPENDIX C: MID-STREAM FLUID TEMPERATURE CALCULATIONS

In order to calculate the temperature on the interior surface of the pipe, the below equation was used.

$$T_i = \frac{q''_x D_x}{-k} + T_0 \tag{C.1}$$

The following equiation was used to solve for the Nusselt number.

$$Nu_D = \frac{hD}{k} = 0.023 Re_D^{4/5} Pr^n \tag{C.2}$$

Once the Nusselt number was calculated the equation below was re-arranged to determine the convection coefficient, *h*.

$$Nu_D = \frac{hD}{k} \tag{C.3}$$

Re-arranging this equation to find *h*.

$$h = Nu_D \frac{k_w}{D} \tag{C.4}$$

$$q''_x = h(T_i - T_m) \tag{C.5}$$

Re-arranging this equation to solve for the mid-stream temperature, T_m.

$$T_m = T_i - \left(\frac{q''_x}{h}\right) \tag{C.6}$$

The calculations performed below are example calculations. The data used for the calculations has been taken from the Domestic Hot Water Tank.

Table C.1 Constants and Values to Calculate the Mid-Stream Fluid Temperatures

n*	0.3
***k_{cu}* (W/m-K)**	401
***k_w* (W/m-K)**	6.48×10^{-1}
***T_0* (K)**	327.7
Δx *(m)*	4.57×10^{-3}
Re_D	4.80×10^{4}
Pr_f	3.285
D (m)	7.4803×10^{-2}

Table C.2 Measured Temperatures

***T_{inf}*(°C)**	23
***T_0* (°C)**	54.7
Δ*T* (°C)	31.7

Table C.3 Calculated Values

q_x'' (W/m^2)	-4.85
T_i (K)	327.7
Nu_D	182.75
h (W/m^2-K)	1.58×10^3
T_m (K)	327.70

It can be seen in Table C.3, that the midstream temperature is 327.70 K (54.3°C), and the measured surface temperature was 328.1 K (54.7°C). This small difference in temperature resulted in the surface temperatures being used for the fluid temperatures.

The temperature inside the smaller diameter pipes seems to be quite uniform. A pipe with a much smaller Reynolds number would expect to see a larger temperature difference across the pipe.

APPENDIX D: SPECIFICATION SHEETS

FDT – 21 Specifications

Accuracy: ±1% of reading > 0.2m/s (0.6 ft/s)
Repeatability: 0.2%
Linearity: 0.5%
Response Time: 0 to 999 seconds (user configured)
Velocity: ±0.01 to 30 m/s (±0.03 to 105 ft/s) bi-directional
Temperature Range:
Standard: 0 to 70°C (32 to 158°F)
With High Temp Transducers: 0 to 160°C (32 to 320°F)
Pipe Size: DN 20 to 100 mm (0.75 to 4") standard[up to DN 6000 mm (236") with optional transducers] **Transducer Frequency:** 1 MHz
Rate Units (User Configured): Meter, feet, cubic meter, cubic feet, USA gallon, oil barrel, USA liquid barrel, imperial liquid barrel, million USA gallons
Totalizer: 7-digit totals for positive, negative and net flow Liquid Types: Most liquids including clean water, sea water, waste water, chemical liquids, oil, crude oil, alcohol, beer, and more
Suspension Concentration: ≤20,000 ppm (may contain very small amounts of air bubbles)
Pipe Material: All metals, most plastics and fiberglass
Security: Programmable lock-out code
Display: 4 × 16 english letters
Communications: RS232C (baud rate from 75 to 115,200 bps)
Transducer Cable Length: 5 m (15')
Power: 3 “AAA” Ni-H built-in batteries (included) with 90 to 230 Vac charger, fully charged lasts over 12 hrs.
Data Logger: Built-in, stores over 2000 lines of data Totalizer/Calibration: 7-digit press-to-go for calibration
Housing: ABS plastic with aluminum alloy protective carrying case
Case: NEMA-4 (IP65)
Dimensions: 100 H × 66 W × 20 mm D (3.9 × 2.6 × 0.8")
Weight: 514 g (1.2 lb)

HFS – 3 Specifications

Upper Temperature Limit: 150°C (300°F)
Number of Junctions:
HFS-3: 54
HFS-4: 112
Carrier: Polyimide film (Kapton®)
Nominal Sensor Resistance:
HFS-3: 140 Ω
HFS-4: 175 Ω
Lead Wires: #30 AWG solid copper, PFA insulated color coded, 3.1 m (10' long)
Weight: 28 g (1.0 oz)

Nonimal[t] Sensitivity (µV/Btu/Ft^2-Hr): 3.0
*Max Rec'd Heat Flux (Btu/Ft^{2}Hr): 30,000
Built-in T/C Type K: Yes
Resp. Time (sec): 0.60
Thermal Capacitance (Btu per Ft^2 °F): 0.02
Thermal Resistance (°F per Btu/Ft^2 Hr): 0.01
Nonimal Thickness mm (inches): 0.18 (0.007)

*Exceeding the maximum recommended heat flux can result in a large enough temperature rise to cause delamination of the Kapton® bonding material. The given maximum values assume a 38°C (100°F) ambient.

[t] Nominal Sensitivity is ±10%. Sensitivity is supplied with unit.

OMEGATHERM® 201

OMEGATHERM® 201—is a very high thermally conductive filled silicone paste, ideally suited for many temperature measurement applications. This thick, grey, smooth paste wets most surfaces and will not harden on long exposure to elevated temperatures. It is rated for continuous use between -40 and 200°C (-40 and 392°F).
OMEGATHERM® 201 provides an excellent means of conducting heat and expanding the heat-path area from a surface to a temperature measurement sensor, thus increasing the speed of response and improving accuracy. Some applications are:
a) **Surface Measurement Probes—**dab a small amount on the surface and push the sensor into this area.
b) **Temporary bonding and encapsulating of temperature sensors—**simply dab OMEGATHERM® 201 onto the surface or in the cavity, plant the sensor in the paste, and tape to hold in place.

Typical Properties
Material: Silicone grease
Continuous Temperature: 200°C (392°F)
Cure: Not required
Adheres to Most*: Wets most surfaces
Thermal conductivity (k) (BTU) (in)/(hr) (ft ^{2}) (°F): Extremely high 16
Electrical Insulation Volume Resistivity ohm–cm: Very high 10^{14}

*M = Metal
PA = Paper products
C = Ceramic
W = Wood
PL = Plastic

APPENDIX E: HYSYS COMPONENTS - SPECIFIC

Individual Component Descriptions – Specific

This appendix includes detailed information for the tees, mixers, heaters, coolers, heat exchangers, energy streams and material streams used in the HYSYS model. The texts highlighted in blue, in all of the tables, are defined values (based off of experimental or supplied data).

Tees

This section covers the specific tees used in the HYSYS model. The flow ratios associated with each of the tees is presented below each figure, along with the feed flow, temperature and pressure.

Table E.1 Domestic HW Tee Flow Ratios

TEE-106	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Feed Molar Flow (kgmole/h)	155.26	155.26	155.26	155.26
Feed Temperature (°C)	55.4	55.4	55.4	55.4
Feed Pressure (kPa)	200	200	200	200
Flow Ratio(1)	0.64	0.64	0.64	0.64
Flow Ratio(2)	0.36	0.36	0.36	0.36

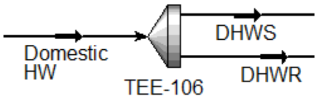

Figure E.1 Domestic Hot Water Tee

The domestic hot water tee (TEE-106) parameters are shown above in Table E.1. The parameters remain the same across all four of the case studies. This tee is used to divide the domestic hot water into the domestic hot water supply (DHWS) and the domestic hot water return (DHWR). The DHWS represents the domestic hot water being used in the plant, whereas the DHWR represents the hot water that is recycled through the system. The HYSYS representation of this tee can be seen in Figure E.1.

Table E.2 Tee-101 Flow Ratios

TEE-101	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Feed Molar Flow (*kgmole/h*)	4112.69	3937.63	4300.48	4300.48
Feed Temperature (°C)	7	7	7	7
Feed Pressure (kPa)	200	200	200	200
Flow Ratio(1)	0.24	0.21	0.28	0.28
Flow Ratio(2)	0.26	0.27	0.25	0.25
Flow Ratio(3)	0.01	0.01	0.01	0.01
Flow Ratio(4)	0.12	0.13	0.12	0.12

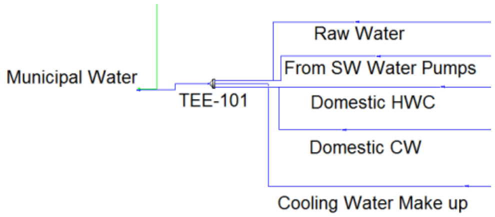

Figure E.2 Tee-101 Municipal Water Header

This is the municipal water header where the Municipal Water Material stream is split into the outgoing material streams. The feed flow varies through this tee, along with the flow ratios, for each of the four case studies. The last two case studies have the same conditions, as the municipal water values were not changed for this case. These parameters can be seen in Table E.2. Figure E.2 shows the feeder stream name, Tee name, and the outgoing material stream names.

Table E.3 Steam Header Flow Ratios

Steam Header	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Feed Molar Flow (*kgmole/h*)	1076.87	671.66	849.29	1665.27
Feed Temperature (°C)	204.31	204.31	204.31	204.31
Feed Pressure (kPa)	1700	1700	1700	1700
Flow Ratio(1)	0.45	0.32	0.45	0.23
Flow Ratio(2)	0.37	0.44	0.35	0.63
Flow Ratio(3)	0.08	0.08	0.08	0.08

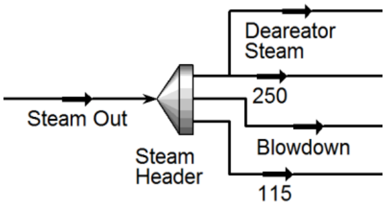

Figure E.3 Steam Header and Associated Material Streams

Table E.3 shows the parameters associated with Steam Header across the four case studies. The flow ratios remain unchanged across the four cases, even though the feed flow varies. There is a visualization of this tee in Figure E.3.

Table E.4 Tee-102 Flow Ratios

TEE-102	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Feed Molar Flow (kgmole/h)	484.26	213.70	379.03	379.03
Feed Temperature (°C)	186.60	186.60	186.60	186.60
Feed Pressure (kPa)	1000	1000	1000	1000
Flow Ratio(1)	0.25	0.48	0.37	0.37
Flow Ratio(2)	0.21	0.47	0.26	0.26
Flow Ratio(3)	0.01	0.03	0.01	0.01
Flow Ratio(4)	0.01	0.03	0.01	0.01
Flow Ratio(5)	0.52	0	0.33	0.33

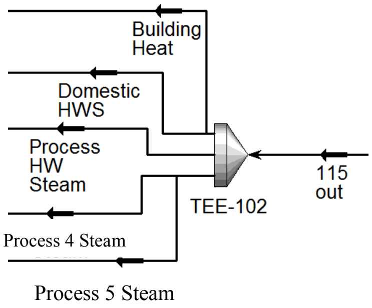

Figure E.4 Tee-102 and Associated Material Streams

The 115lb steam header, depicted in Figure E.4, is used to distribute the steam to all of the steam processes other than Process 3. The specific parameters can be seen in Table E.4.

Table E.5 Tee-107 Flow Ratios

TEE-107	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Feed Molar Flow (kgmole/h)	3111.87	3111.87	3111.87	3111.87
Feed Temperature (°C)	40	40	40	40
Feed Pressure (kPa)	200	200	200	200
Flow Ratio(1)	0.47	0.47	0.47	0.47
Flow Ratio(2)	0.53	0.53	0.53	0.53

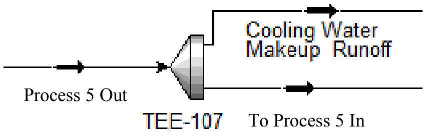

Figure E.5 Tee-107 and Associated Material Streams

In Figure E.5, TEE-107 is shown with the associated feed and supply lines. This tee is used to split the Process 5 water into two streams. To Process 5 In represents the flow going to heat exchanger E-101, which represents the tire building processes which consume steam energy. The Cooling Water Makeup Runoff stream represents the excess water which goes to the Neutralization Tank. The specific feed flows, temperatures, pressure and flow ratios can be found in Table E.5, for TEE-107.

Table E.6 Process Hot Water Header Flow Ratios

Process HW Header	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Feed Molar Flow (kgmole/h)	1572.93	1397.88	1760.73	1760.73
Feed Temperature (°C)	60	60	60	60
Feed Pressure (kPa)	200	200	200	200
Flow Ratio(1)	0.01	0.01	0.01	0.01
Flow Ratio(2)	0.36	0.41	0.32	0.32
Flow Ratio(3)	0.09	0.09	0.09	0.09
Flow Ratio(4)	0.04	-0.01	0.08	0.08
Flow Ratio(5)	0.5	0.5	0.5	0.5

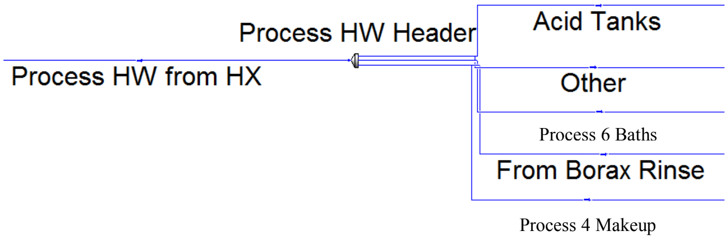

Figure E.6 Process Hot Water Header and Associated Streams

In Table E.6, the process parameters for the Process Hot Water Header are shown. The table shows the changes seen in the flow ratios between the four case studies. A visual depiction of the tee can be seen in Figure E.6.

Mixers

In the HYSYS model mixers were used as a representation for tanks. The parameters used for the mixers were to set the outgoing material stream pressure to equal the lowest incoming stream pressure. The product temperatures shown are a weighted average (dependant on the flow) of the incoming material streams.

Table E.7 Condensate Tank Mixer Data

Condensate Tank	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Product Molar Flow (kgmole/h)	1556.86	1286.3	1451.63	1451.63
Product Mass Flow (kg/h)	28047.01	23172.8	26151.24	26151.24
Product Volume Flow (m^3/h)	28.10	23.22	26.20	26.20
Product Temperature (°C)	69.90	46.28	61.77	61.77
Product Pressure (kPa)	200	200	200	200

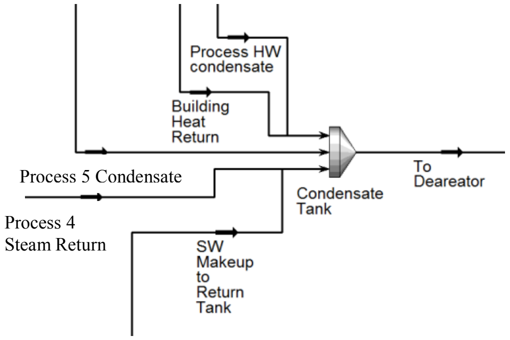

Figure E.7 Condensate Tank and Associated Material Streams

The Condensate Tank Mixer is shown in Figure E.7, along with the associated material streams. The specifications for this mixer can be seen in Table E.7.

Table E.8 Deaerator Mixer Data

Deaerator	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Product Molar Flow (kgmole/h)	1076.87	671.66	849.29	1665.27
Product Mass Flow (kg/h)	19400	12100	15300	30000
Product Volume Flow (m^3/h)	19.44	12.12	15.33	30.06
Product Temperature (°C)	120.23	120.23	120.23	120.23
Product Pressure (kPa)	200	200	200	200

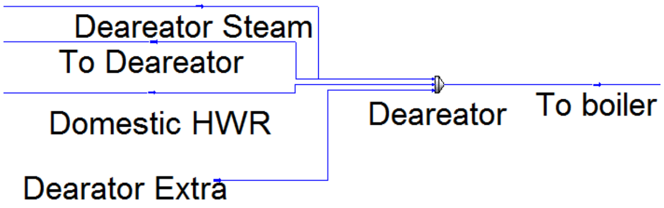

Figure E.8 Deaerator and Associated Material Streams

The deaerator and the associated material streams can be seen in Figure E.8. The specific information about the mixer used to represent the deaerator can be seen in Table E.8.

Table E.9 Sludge Thickener Mixer Stream Data

Sludge Thickener	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Product Molar Flow (kgmole/h)	1321.58	1216.55	1434.26	1434.26
Product Mass Flow (kg/h)	23808.44	21916.3	25838.35	25838.35
Product Volume Flow (m^3/h)	23.86	21.96	25.89	25.89
Product Temperature (°C)	52.88	52.26	53.44	53.44
Product Pressure (kPa)	200	200	200	200

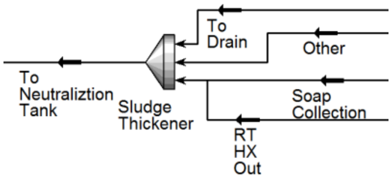

Figure E.9 Sludge Thickener Mixer and Associated Streams

The Sludge Thickener used in the HYSYS model can be seen in Figure E.9, with the associated material streams. The specifications for the mixer, used to represent the Sludge Thickener, can be seen in Table E.9.

Table E.10 To Neutralization Tank Material Stream Data

Neutralization Tank	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Product Molar Flow (kgmole/h)	2858.99	2683.94	3046.79	3046.79
Product Mass Flow (kg/h)	51505.08	48351.40	54888.25	54888.25
Product Volume Flow (m^3/h)	51.61	48.45	55.00	55.00
Product Temperature (°C)	46.39	45.50	47.23	47.23
Product Pressure (kPa)	200	200	200	200

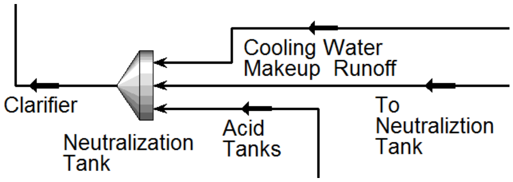

Figure E.10 Neutralization Tank and Associated Streams

In Table E.10, the specifications for the Neutralization Tank from the four case studies are shown. The HYSYS representation of the Neutralization Tank can be seen in Figure E.10.

Table E.11 BFM Effluent Material Stream Data

BFM Effluent	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Product Molar Flow (kgmole/h)	2945.14	2737.67	3114.73	3180.01
Product Mass Flow (kg/h)	53057.08	49319.4	56112.25	57288.25
Product Volume Flow (m^3/h)	53.16	49.42	56.23	57.40
Product Temperature (°C)	64.57	57.73	60.77	73.22
Product Pressure (kPa)	177	177	177	177

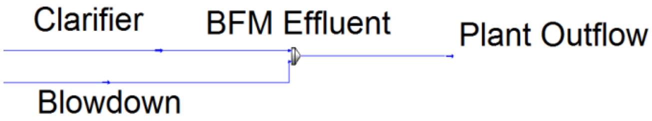

Figure E.11 BFM Effluent Mixer and Associated Material Streams

The BFM Effluent mixer can be seen in Figure E.11, along with the associated material streams. The associated properties of the mixer can be seen in Table E.11.

Table E.12 Process 8 Stream Data

Process 8	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Product Molar Flow (kgmole/h)	141.56	125.81	158.47	158.47
Product Mass Flow (kg/h)	2550.29	2266.46	2854.77	2854.77
Product Volume Flow (m^3/h)	2.56	2.27	2.86	2.86
Product Temperature (°C)	60	60	60	60
Product Pressure (kPa)	200	200	200	200

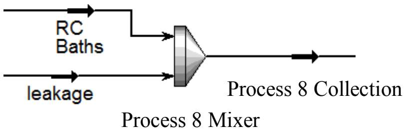

Figure E.12 Process 8 Mixer and Associated Material Streams

In Figure E.12, the Process 8 mixer is shown, with the associated material streams. The specific data for the mixer can be found in Table E.12.

Table E.13 Mix-101 Stream Data

MIX-101	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Product Molar Flow (kgmole/h)	1572.93	1397.88	1760.73	1760.73
Product Mass Flow (kg/h)	28336.50	25182.9	31719.67	31719.67
Product Volume Flow (m^3/h)	28.39	25.23	31.78	31.78
Product Temperature (°C)	22.47	24.42	20.82	20.82
Product Pressure (kPa)	200	200	200	200

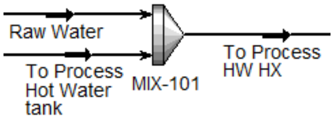

Figure E.13 Mix-101 and Associated Material Streams

The mixer shown in Figure E.13 is used to combine Raw Water and the Process Hot Water, before heading to the process hot water heat exchanger. The outgoing stream information from Mix-101 can be found in Table E.13.

Table E.14 Mix-102 Data

MIX-102	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Product Molar Flow (kgmole/h)	155.26	155.26	155.26	155.26
Product Mass Flow (kg/h)	2797.04	2797.04	2797.04	2797.04
Product Volume Flow (m^3/h)	2.80	2.80	2.80	2.80
Product Temperature (°C)	38.11	38.11	38.11	38.11
Product Pressure (kPa)	200	200	200	200

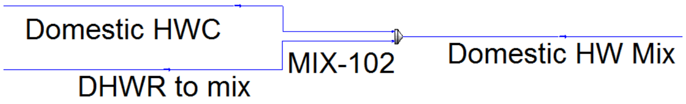

Figure E.14 Mix-102 and Associated Material Streams

The domestic hot water mixer shown in Figure E.14 represents the cold water addition to the domestic hot water return loop, before entering the domestic hot water mixer. The mixer data can be seen in Table E.14.

Table E.15 Domestic Water Collector Data (MIX-103)

MIX-103	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Product Molar Flow (kgmole/h)	553.39	553.39	553.39	553.39
Product Mass Flow (kg/h)	9969.44	9969.44	9969.44	9969.44
Product Volume Flow (m^3/h)	9.99	9.99	9.99	9.99
Product Temperature (°C)	11.84	11.84	11.84	11.84
Product Pressure (kPa)	200	200	200	200

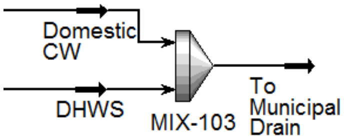

Figure E.15 MIX-103, Domestic Water Collector

The Domestic Water Collector (MIX-103) specifications are shown in Table E.15. The specifications for this mixer were set to be a constant rate in the four case studies. An image of the mixer and the associated material streams can be seen in Figure E.15.

Table E.16 Mix-104 Stream Data

MIX-104	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Product Molar Flow (kgmole/h)	3111.87	3111.87	3111.87	3111.87
Product Mass Flow (kg/h)	56060.61	56060.6	56060.61	56060.61
Product Volume Flow (m^3/h)	56.17	56.17	56.17	56.17
Product Temperature (°C)	24.34	24.34	24.34	24.34
Product Pressure (kPa)	200	200	200	200

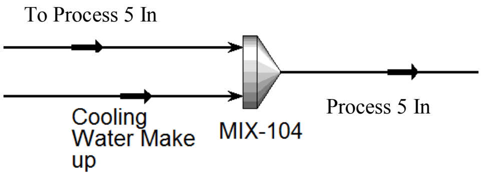

Figure E.16 Mix-104 and Associated Material Streams

The mixer shown in Figure E.16 represents the makeup water addition to the Process 5 water system. The mixer parameters for the four case studies can be seen in Table E.16.

Heaters

Table E.17 Basement Vent Condenser Parameters

Basement Vent Condenser	**Full Heat**	**No Heat**	**Half Heat**	**Half Heat Double Steam**
DUTY (MJ/h)	141.90	141.90	141.90	141.90
Feed Temperature (°C)	44.50	44.50	44.50	44.50
Product Temperature (°C)	46	46	46	46

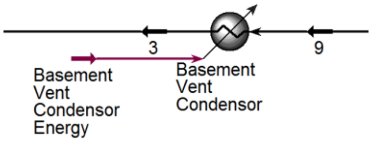

Figure E.17 Basement Vent Condenser

The energy used to condense the steam in stream 9 is represented as the Basement Vent Condenser Energy, as shown in Figure E.17. This value is the same as the Duty values shown in Table E.17, for the Basement Vent Condenser heater.

Table E.18 Boiler Data

Boilers	**Full Heat**	**No Heat**	**Half Heat**	**Half Heat Double Steam**
DUTY (GJ/h)	44.41	27.70	35.03	68.68
Feed Temperature (°C)	120.23	120.23	120.23	120.23
Product Temperature (°C)	204.31	204.31	204.31	204.31

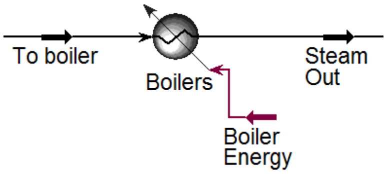

Figure E.18 Boiler and Associated Streams

In Table E.18 the parameters for the boilers can be seen. The values in Table E.18 for the duty change across the four case studies, as expected. The feed temperatures and product temperature were set values to ensure saturated steam at the exit of the boiler. Figure E.18 shows the HYSYS representation of the boiler, along with the associated streams.

Coolers

Table E.19 Building Heat Cooler Data

Building Heat	**Full Heat**	**No Heat**	**Half Heat**	**Half Heat Double Steam**
Duty (GJ/h)	9.2	0	4.6	4.6
Feed Temperature (°C)	186.6	186.6	186.6	186.6
Product Temperature (°C)	179.88	179.88	179.88	179.88

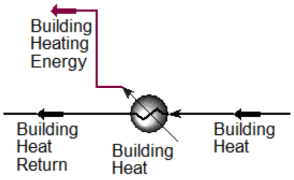

Figure E.19 Building Heat and Associated Streams

The amount of energy extracted in Process 3 (duty) can be seen in Table E.19. The HYSYS representation of this cooler can be seen in Figure E.19, with the associated energy and material streams. The energy stream, Building Heating Energy, is the same value as the duty of the Building Heat cooler.

Table E.20 Process 3 Cooler Data

Process 3	**Full Heat**	**No Heat**	**Half Heat**	**Half Heat Double Steam**
Duty (GJ/h)	18.71	13.92	13.83	49.06
Feed Temperature (°C)	204.31	204.31	204.31	204.31
Product Temperature (°C)	44.8	44.8	44.8	44.8

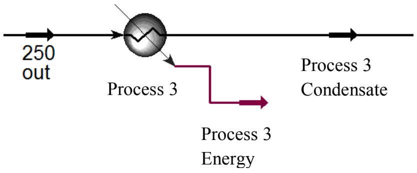

Figure E.20 Process 3 Heater and Associated Streams

The amount of energy used by Process 3, calculated by HYSYS, is shown in Table E.20. The HYSYS representation of this cooler can be seen in Figure E.20, along with the associated energy and material streams. The value of the energy stream, Process 3 Energy, is the same value as the duty of the Process 3 cooler.

Valves

Table E.21 115lb Steam Line Reducing Valve

115# Reducing Valve	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Molar Flow (kgmole/h)	484.26	213.7	379.03	379.03
Pressure Drop (MPa)	0.7	0.7	0.7	0.7
Feed Pressure (MPa)	1.7	1.7	1.7	1.7
Percentage open (%)	100	100	100	100

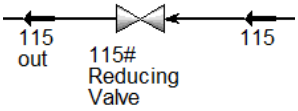

Figure E.21 115lb Reducing Valve

The specific parameters relating to the 115lb steam line reducing valve can be seen in Table E.21. In Figure E.21, the HYSYS representation of the reducing valve, with the associated material streams can be seen.

Heat Exchangers

In the HYSYS the heat exchangers were used to depict both heat exchangers found in the Michelin facility, as well as certain processes that were best represented as heat exchangers (E-101 (Process 5), Process HW HX, Process 4 Hot Water System).

Table E.22 Process Hot Water Heat Exchanger Data

Process Hot Water HX	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Duty (MJ/h)	4.27×10^2	4.27×10^2	4.27×10^2	4.27×10^2
Tube Side Feed Mass Flow (kg/h)	2.27×10^4	2.27×10^4	2.27×10^4	2.27×10^4
Shell Side Feed Mass Flow (kg/h)	1.02×10^4	1.02×10^4	1.02×10^4	1.02×10^4
Tube Inlet Temperature (°C)	40	40	40	40
Tube Outlet Temperature (°C)	44.50	44.50	44.50	44.50
Shell Inlet Temperature (°C)	60	60	60	60
Shell Outlet Temperature (°C)	50	50	50	50

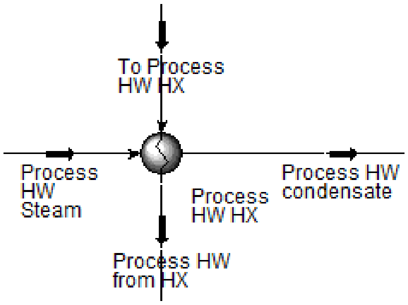

Figure E.22 Process Hot Water Heat Exchanger and Associated Material Streams

In Table E.22, the heat exchanger parameters are shown for the four case studies shown. The HYSYS depiction of this heat exchanger and the associated streams can be seen in Figure E.22.

Table E.23 Primary Heat Exchanger Data

Primary SW HX	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Duty (MJ/h)	4.89×10^2	4.89×10^2	4.89×10^2	4.89×10^2
Tube Side Feed Mass Flow (kg/h)	1.94×10^4	1.94×10^4	1.94×10^4	1.94×10^4
Shell Side Feed Mass Flow (kg/h)	6.81×10^3	6.81×10^3	6.81×10^3	6.81×10^3
Tube Inlet Temperature (°C)	7	7	7	7
Tube Outlet Temperature (°C)	13	13	13	13
Shell Inlet Temperature (°C)	44.8	44.8	44.8	44.8
Shell Outlet Temperature (°C)	27.61	27.61	27.61	27.61

Table E.24 Secondary SW HX Data

Secondary SW HX	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Duty (MJ/h)	5.69×10^2	5.69×10^2	5.69×10^2	5.69×10^2
Tube Side Feed Mass Flow (kg/h)	1.94×10^4	1.94×10^4	1.94×10^4	1.94×10^4
Shell Side Feed Mass Flow (kg/h)	2.27×10^4	2.27×10^4	2.27×10^4	2.27×10^4
Tube Inlet Temperature (°C)	13	13	13	13
Tube Outlet Temperature (°C)	20	20	20	20
Shell Inlet Temperature (°C)	46	46	46	46
Shell Outlet Temperature (°C)	40	40	40	40

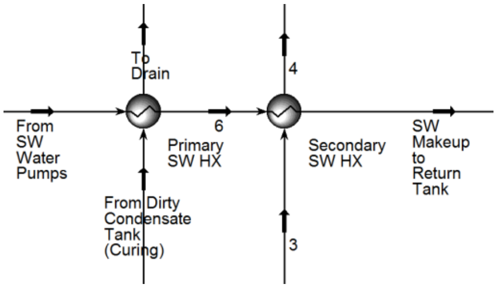

Figure E.23 SW Heat Exchangers (Primary and Secondary)

In Table E.23 and Table E.24 the heat exchanger flows are shown for the Primary and Secondary Soft Water Heat Exchangers. The HYSYS representation of these heat exchangers and their associated material streams can be seen in Figure E.23.

Table E.25 Domestic Hot Water Heat Exchanger Data

Domestic Hot Water	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Duty (MJ/h)	2.02×10^2	2.02×10^2	2.02×10^2	2.02×10^2
Tube Side Feed Mass Flow (kg/h)	2.80×10^3	2797.036726	2797.036726	2797.036726
Shell Side Feed Mass Flow (kg/h)	9.96×10^1	9.96×10^1	9.96×10^1	9.96×10^1
Tube Inlet Temperature (°C)	38.11	38.11	38.11	38.11
Tube Outlet Temperature (°C)	55.4	55.4	55.4	55.4
Shell Inlet Temperature (°C)	186.60	186.60	186.60	186.60
Shell Outlet Temperature (°C)	179.88	179.88	179.88	179.88

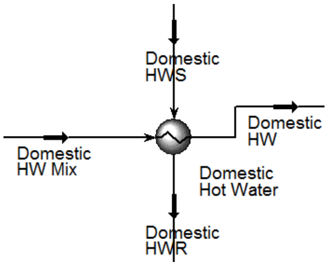

Figure E.24 Domestic Hot Water Heat Exchanger

The Domestic Hot Water Heat Exchanger operation conditions are shown in Table E.25 for the four case studies. The HYSYS representation of this heat exchanger can be seen in Figure E.24.

Table E.26 Process Hot Water Heat Exchanger Stream Data

Process HW HX	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Duty (MJ/h)	4.45×10^3	3.75×10^3	5.20×10^3	5.20×10^3
Tube Side Feed Mass Flow (kg/h)	2.83×10^4	2.52×10^4	3.17×10^4	3.17×10^4
Shell Side Feed Mass Flow (kg/h)	2.19×10^3	1.84×10^3	2.56×10^3	2.56×10^3
Tube Inlet Temperature (°C)	22.47	22.47	22.47	22.47
Tube Outlet Temperature (°C)	60	60	60	60
Shell Inlet Temperature (°C)	186.60	186.60	186.60	186.60
Shell Outlet Temperature (°C)	179.88	179.88	179.88	179.88

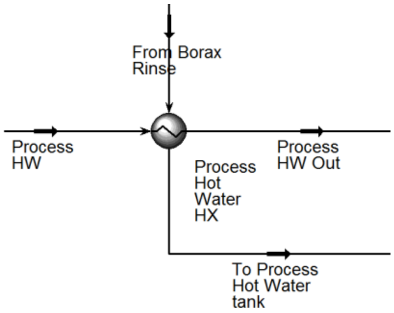

Figure E.25 Process Hot Water Heat Exchanger (HX) and Associated Material Streams

The Process Hot Water Heat Exchanger operating parameters for the four case studies can be seen in Table E.26. Figure E.25 depicts the configuration of the heat exchanger in HYSYS.

Table E.27 E-101 Stream Data

E-101	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Duty (kJ/h)	3.67×10^6	3.67×10^6	3.67×10^6	3.67×10^6
Tube Side Feed Mass Flow (kg/h)	1.81×10^6	1.81×10^6	1.81×10^6	1.81×10^6
Shell Side Feed Mass Flow (kg/h)	5.61×10^6	5.61×10^6	5.61×10^6	5.61×10^6
Tube Inlet Temperature (°C)	186.60	186.60	186.60	186.60
Tube Outlet Temperature (°C)	179.88	179.883	179.88	179.88
Shell Inlet Temperature (°C)	24.34	24.34	24.34	24.34
Shell Outlet Temperature (°C)	40	40	40	40

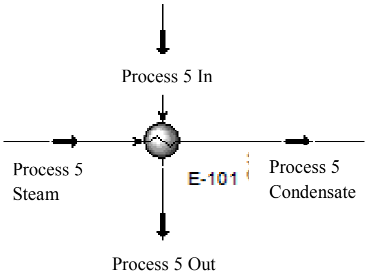

Figure E.26 E-101 Heat Exchanger and Material Streams

The Process 5 heat exchanger (E-101) is shown in Figure E.26, with the operating parameters in Table E.27. A heat exchanger was used in place of individual pieces of equipment that use steam to heat water.

Table E.28 Process 4 Heat Exchanger Data

Process 4 HX	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Duty (kJ/h)	1.19×10^5	1.05×10^5	1.33×10^5	1.33×10^5
Tube Side Feed Mass Flow (kg/h)	1.42×10^4	1.26×10^4	1.59×10^4	1.59×10^4
Shell Side Feed Mass Flow (kg/h)	1.42×10^4	1.26×10^4	1.59×10^4	1.59×10^4
Tube Inlet Temperature (°C)	60.00	60.00	60.00	60.00
Tube Outlet Temperature (°C)	62.00	62.00	62.00	62.00
Shell Inlet Temperature (°C)	65.42	65.85	65.06	65.06
Shell Outlet Temperature (°C)	63.42	63.85	63.06	63.06

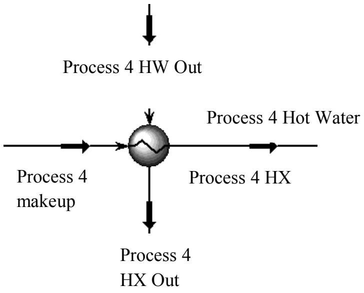

Figure E.27 Process 4 Heat Exchanger and Associated Streams

The Process 4 Heat Exchanger parameters used in the four case studies can be seen in Table E.28. The HYSYS representation can be seen in Figure E.27, along with the associated material streams.

Table E.29 Process 4 Hot Water System Data

Process 4 Hot Water system	Full Heat	No Heat	Half Heat	Half Heat Double Steam
Duty (kJ/h)	2.03×10^5	2.03×10^5	2.03×10^5	2.03×10^5
Tube Side Feed Mass Flow (kg/h)	1.42×10^4	1.26×10^4	1.59×10^4	1.59×10^4
Shell Side Feed Mass Flow (kg/h)	100.00	100.00	100.00	100.00
Tube Inlet Temperature (°C)	62.00	62.00	62.00	62.00
Tube Outlet Temperature (°C)	65.42	65.85	65.06	65.06
Shell Inlet Temperature (°C)	186.60	186.60	186.60	186.60
Shell Outlet Temperature (°C)	179.88	179.88	179.88	179.88

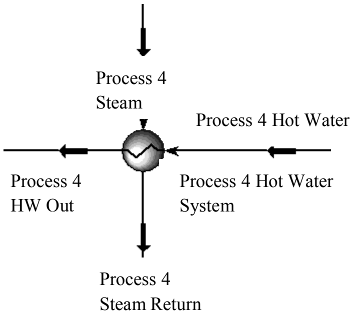

Figure E.28 Process 4 Hot Water System Heat Exchanger and Associated Streams

In Table E.29, the parameters for the Process 4 Hot Water System are shown for the four case studies. The HYSYS representation of this heat exchanger, with the associated material streams, can be seen in Figure E.28.

Recycles and Adjusts

The recycles and adjusts shown in the model (Fig. E.29) were initial used to find operating parameters for certain flows. Once the final model configurations were determined, these operators were not used.

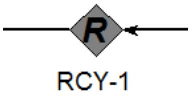

Figure E.29 Recycle Loop, Domestic Hot Water Return (DHWR) to DHWR to Mix