Modelling, simulation and optimization perspectives of an industrial steam network

Case study at a major oil refinery on the West Coast of Sweden

Riccardo Subiaco

...per zio Stefano e
per mio cugino Luca.

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Work carried out at
Department of Energy and Environment
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CHALMERS UNIVERSITY OF TECHNOLOGY

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ABSTRACT (Swedish and Italian abstract available afterwards)

Steam is a heat carrier for industrial plants that is relatively cheap to produce and distribute, compared to other heat transfer media aimed for the same temperature range. It is the most used medium in thermal power plants, but can also be used in a utility network in, for example, a refinery, where it is used to handle the heat distribution. Utility steam can be used to heat process streams up to about 250°C, while also having the ability to generate work. Management and optimization of steam networks can lead to heat, electricity and economic savings. However, many times, there are difficulties associated with data collection and measurements. As a matter of fact, some secondary process variables like the outlet temperature of a steam turbine, even though useful to check the isentropic efficiency of the machine, could not be measured. This type of lack in information brings difficulties in the plant modelling and analysis. The present master thesis, which has been carried out at the department of Energy and Environment at Chalmers University of Technology, concerns the modelling and optimization of the steam system at the biggest refinery of Sweden. By using engineering and thermodynamic knowledge, a model of the steam network is developed, first in spreadsheet databases, and then aided by a proper modelling software. Assumptions and thermodynamic relations are used to model the different components that the steam system is composed by and to calculate missing values. Several steady state simulations are made with the model. For each of them a comparison with the real behaviour of the system is made by connection of the software output to a validation spreadsheet through a plug-in. Moreover, once the reliability is tested, examples of how the model can be used for analysis of energy retrofit measures are presented. Finally, an economic optimization of the system operation for a given set of inputs is carried out and its results are analysed.

Key words: Steam Network, Refinery utilities, Modelling, Simulation, Optimization.

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SAMMANFATTNING

Ånga är en värmebärare för industrianläggningar som är relativt billig att producera och distribuera, jämfört med andra värmeöverföringsmedier som används inom samma temperaturområde. Ånga är det mest använda mediet i värmekraftverk, men kan även användas i till exempel ett raffinaderi, där det används för att distribuera värme. Ånga kan användas för att värma processflöden upp till ca 250°C, samtidigt som den också har förmågan att generera arbete. God styrning och optimering av ångnätverk kan leda till besparingar av värme, elektricitet samt ekonomiska besparingar. Emellertid finns det ofta svårigheter i samband med datainsamling och mätningar. Vissa sekundära processvariabler, som utloppstemperaturen hos en ångturbin, har inte kunnat mätas, trots att de skulle vara ett bra mått på maskinens isentropiska verkningsgrad. Denna typ av bristfällig information medför svårigheter i anläggningsmodellering och -analys. Det här examensarbetet, som har genomförts vid institutionen för energi och miljö vid Chalmers tekniska högskola, avser modellering och optimering av ångsystemet på Sveriges största raffinaderi. Genom att använda ingenjörsmässig och termodynamisk kunskap har en modell av ett ångnätverk utvecklats, först i kalkylblad, och sedan med hjälp av en riktig programvara för processmodellering. Antaganden och termodynamiska relationer har använts för att modellera de olika komponenterna som ångsystemet består av och beräkna saknade värden. Flera simuleringar av stationära driftfall har gjorts med modellen. För vart och ett av dem har en jämförelse gjorts med det verkliga beteendet hos systemet genom anslutning av programvarans output till ett valideringskalkylblad genom en plug-in. Dessutom, när tillförlitligheten har testats, presenteras exempel på hur modellen kan användas för analys av energibesparingsåtgärder. Slutligen har en ekonomisk optimering av driften av systemet utförts, för en given uppsättning av indata, varvid resultaten har analyserats.

Nyckelord: Ångnätverk, Raffinaderi, Modellering, Simulering, Optimering.

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SOMMARIO

Il vapore d'acqua è largamente utilizzato negli impianti industriali essendo relativamente poco costoso da produrre e distribuire, rispetto ad altri fluidi adibiti al medesimo scopo, a parità di intervallo termico. È il fuido termovettore più utilizzato nelle centrali termoelettriche, ma può anche essere impiegato in una rete ausiliaria come quella di una raffineria, dove ha il ruolo di gestire i carichi termici. La rete di vapore infatti può essere utilizzata per riscaldare i flussi di processo fino a circa 250°C e allo stesso tempo produrre lavoro utile in turbomacchine di piccola taglia. La miglior gestione e l'ottimizzazione della rete possono offrire benefici dal punto di vista sia energetico che economico. Quando entrano in gioco impianti di grossa taglia tuttavia, quale ad esempio una raffineria, difficoltà associate alla raccolta e alla misurazione dei dati sono spesso frequenti. Alcune variabili di processo secondarie, come la temperatura di uscita di una turbina a vapore, vengono talvolta escluse dal processo di misurazione e analisi, anche se utili per verificare l'efficienza dei componenti. Questa mancanza di informazioni comporta molte difficoltà nella modellazione della rete e nell'analisi dell'impianto. La presente tesi di laurea, effettuata nel Dipartimento di Energia e Ambiente presso l'università tecnica di Chalmers a Gothenburg (Svezia), tratta la modellazione e ottimizzazione della rete di vapore della più grande raffineria della scandinavia. Il modello della rete è sviluppato dapprima utilizzando fogli di calcolo e in seguito con l'ausilio di un apposito software per la modellazione di sistemi energetici. Diverse assunzioni legate a considerazioni ingegneristiche sono utilizzate laddove sussiste una carenza di dati empirici, mentre bilanci termodinamici vengono utilizzati per modellare i diversi macchinari che compongono la rete di vapore. Simulazioni stazionarie vengono in seguito analizzate e confrontate con il reale comportamento del sistema, tramite connessione diretta del software con un foglio di calcolo adibito alla convalida dei dati. Inoltre, una volta testata l'affidabilità del modello realizzato, quest'ultimo viene utilizzato per l'analisi energetica di un retrofit. La tesi conclude con la presentazione di una possibile strada per intraprendere un'ottimizzazione economica del funzionamento della rete di vapore, relativa a un dato insieme di carichi prestabiliti. Segue l'analisi dei risultati.

Parole chiave: Rete di vapore, Raffineria, Modellazione,Simulazione, Ottimizzazione.

Contents

Foreword

The petroleum refining industry integrates many process operations required for refining crude oil into a number of products, in particular liquid fuels such as gasoline and diesel. Advancements made in refining technologies allow utilization of resources such as heavy oil and bitumen sands that were considered economically and technically unsuitable in the middle decades of the past century. To meet these challenges, it is imperative for the refinery companies to raise their operations to new levels of performance and continue to optimize all processes [1]. This, sometimes, within a big chemical plant like a refinery, implies a paradox. On the one hand, most of the chemical processes are divided into several different sections that have to be kept independent as much as possible for different technical reasons; on the other hand, energy savings can be achieved by integration of process sections through heat exchange between different flows, in which steam is involved as a powerful heat transfer medium and utilities network fluid. This complex scenario makes it necessary to have a good understanding of the utility system behaviour and to analyse the energy utilization of such system [2]. Focusing on Preem's refinery located in Lysekil, on the west coast of Sweden, the purpose of this Master's Thesis is therefore to develop a reliable model for the steam utility system, and to look at an economic optimization possibility for the utilities operation.

Chapter 1 presents an overview of the work that has been carried out, including background, purpose, research questions and scope of the project. Chapter 2 describes the data collection process conducted at the refinery and how the different streams have been catalogued. Chapter 3 focuses on the model of the steam system and the components of the steam network. Mass and energy equations used for each of them are described in this part, and a first layout of the steam system is obtained. An implementation of the model into a commercial steam modelling software is described in Chapter 4, in which models for fuel consumption and electrical energy imports are also added. Chapter 5 describes the first steady state simulation, with all the input used for the model, the results obtained and how the data validation and model reliability have been handled. In Chapter 6, the steam network model is used for predictive purpose, to analyse possible plant retrofits. Chapter 7 deals with the economic optimization of the steam network configuration for given inputs, and the possibility to achieve a minimization of the utility system running cost. Chapter 8 presents comments and further discussion about this thesis. Chapter 9, finally, is the conclusion Chapter.

Before leaving this report to the reader I would like to express my special thanks of gratitude to the Professors who have made this experience in Sweden possible (Umberto Desideri and Simon Harvey) as well as to all the IEST division at Chalmers. I also want to mention all the people, both at Chalmers (Fredrik Bengtsson, Sofie Marton, and Elin Svensson), CIT-IE (Eva Andersson, Anders Åsblad, and Karin Eriksson), and at Lysekil's refinery (Per-Olof Eriksson), who helped me in doing such project. I came to know about so many new things and I'm really thankful to them. Last but not least I embrace my family and friends, who are always present in my life. Heading the list is my mother, Cinzia.

Göteborg, March 2016

Riccardo Subiaco

Notations

Abbreviations

EC	European Commission
EU	European Union
CHP	Combined Heat & Power
CIT-IE	Chalmers Industriteknik - Industriell Energi AB
DVR	Data Validation and - Reconciliation
DWT	Dead-Weight Tonne
GHG	Green House Gas
HRSG	Heat-Recovery Steam Generator
IEST	Industrial Energy Systems and Technologies
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas Generator
MILP	Mixed Integer linear programming

General variables

$C_V\ or\ K_V$	Valve's flow factor
C_T	Turbine Constant
E	Error variable
$\dot{W}$	Power/Shaft Power
$\dot{Q}$	Thermic Power
h	Specific enthalpy
s	Specific entropy
P	Pressure
v	Specific volume
η	Efficiency
$\dot{m}$	Mass flow-rate
Δh	Specific enthalpy drop
ΔH	Enthalpy drop
ΔP	Pressure drop
SR	Steam Rate
TSR	Theoretical Steam Rate
χ	Dimensional ratio
SG	Specific Gravity
$\dot{V}$	Volumetric flow-rate
x	Variable for error analysis
unm	Unmeasured variable

Refinery units

CDU	Crude Distillation Unit
CRU	Catalytic Reforming Unit
FCC	Fluid Catalytic Cracking Unit
HPU	Hydrogen Production Unit
ICR	Iso-Cracking Unit
ISO	Isomerization Unit
MHC	Mild Hydrocracker Unit
SGU	Steam Generation Unit
VDU	Vacuum Distillation Unit

Refinery component variables

G-	Steam Boiler-
HRSG-	Heat-Recovery Steam Generator-
E-	Heat Exchanger- /Reboiler-
HEX	Heat Exchanger /Reboiler
T-	Fractionation Tower- / Stripper-
V-	Vessel-
EJ-	Ejector-
DS-	Desuperheater-
V-	Valve-
BT-	Turbine driven Blower-
CT-	Turbine driven Compressor-
PT-	Turbine driven Pump-

Pressure Levels

HS or HP	High pressure steam level
TS or TP	Medium-High pressure steam level
MS or MP	Medium pressure steam level
LS or LP	Low pressure steam level
COND	Condenser pressure

Figures

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Chapter 1

INTRODUCTION

1.1 Background

This Master's Thesis project aims at developing a model of the steam system at Preem's oil refinery in Lysekil, Sweden. A general overview of the industrial development of the country is important to better understand the context of the project.

1.1.1 Energy use and consumption in the industrial sector: Sweden

In 2013, the use of energy by industry in Sweden amounted to 144 TWh corresponding to 39% of the country's total final energy use. As seen in Figure 1.1, the major energy use in the Swedish industry sector is related to the pulp and paper industry (roughly 50%). Steel and metals use about 15% and the same amount (approximately 15%) is used in the engineering and chemical industry. The energy consumption in oil refineries is included in chemical industry until 2004. Thereafter, in the national energy balance, it is included in "Energy sector own use" and not shown in Figure 1.1. For a comparison, in the third quarter of 2015 the fuel consumption for refineries and crackers was 3,1 TWh (consisting of 0,25 TWh of electricity and 2,88 TWh of fuels) [3].

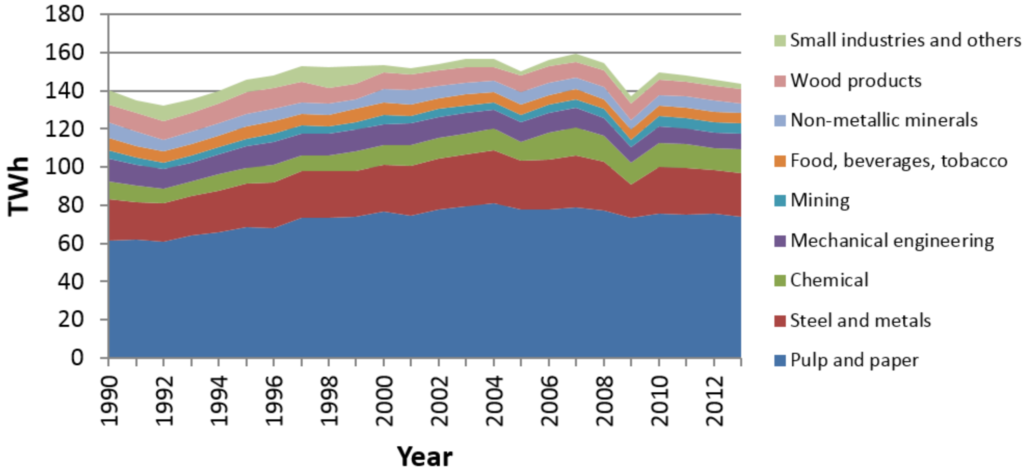


Figure 1.1 Energy use in industry, by sector, 1990–2013[4].

Energy use by industry has remained relatively constant since 1970, despite increasing industrial output. This is a result of improvements in the efficiency of energy use, coupled with a progressive change from oil to electricity. Since 1970, electricity use has increased from 21% to 36% of total energy use by industry. This trend started in connection with the oil crises of the 1970s, which resulted in both state and business starting intensive work aimed at reducing the use of oil and at increasing the use of biomass products and district heating. In 1970, the use of oil provided 48% of industry's total energy use, which can be compared with the present proportion of fossil fuels of 10% (about 7% for oil and 3% for natural gas) [5].

Electrical Energy

Sweden produces and consumes a higher amount of electrical energy per capita than the average of EU countries. In 2008, for instance, the consumption of electricity in Sweden was 16 018 kWh per capita, compared to EU average 7 409 kWh per capita. Almost 78% of the electricity in Sweden came from nuclear power and hydroelectric power, with low greenhouse gas emissions. Cogeneration in combined heat and power plants (CHP) accounted for somewhat above 10% of the electricity generation in Sweden, and these were mainly powered by biomass fuels. About 8 per cent of the electricity was imported, and the remainder, about 4 per cent, came from wind power [5]. An overview of the energy production along the years is shown in Figure 1.2.

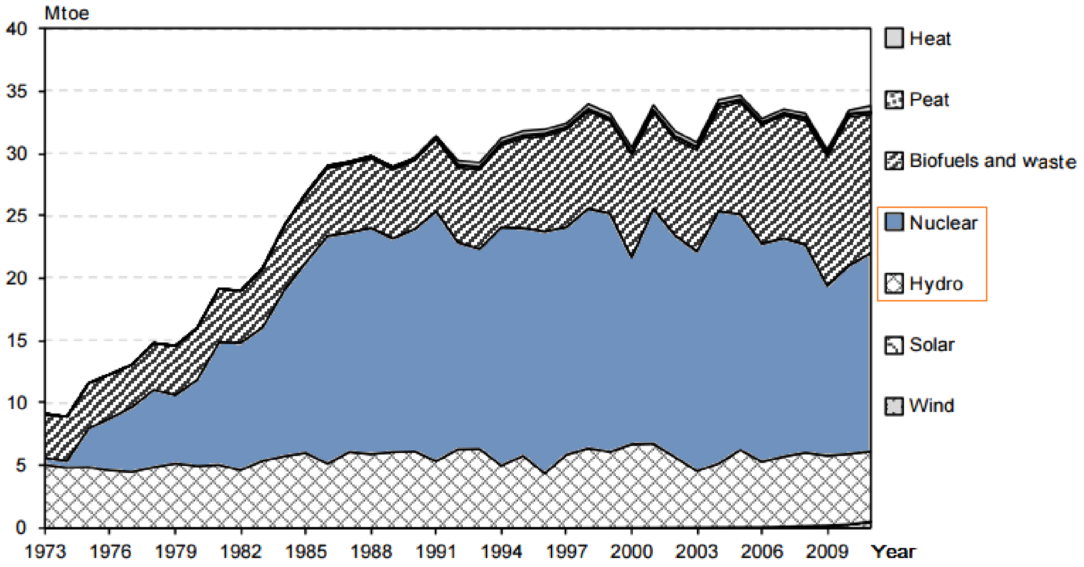


Figure 1.2 Primary energy supply for electric power generation, 1973-2011 [6].

In 2013, Sweden was net exporter of electricity. This easy access to such cheap and largely reliable electric power, with low or zero CO_2 emissions, has meant little incentive to industries to generate their own power (using fossil fuels), instead of importing it.

Climate

In 2009, the Council of the European Union decided that greenhouse gas emissions must be reduced by 20% in 2020, in comparison with 1990. The Emissions Trading

Directive (2003/87/EC) was also revised, with Sweden being given a target for its emissions from activities not covered by the emissions trading scheme to be reduced by 40% relative to 1990 emission levels. Finally, the year also saw the introduction of the Carbon Capture and Storage Directive (2009/31/EC). The companies covered by the emissions trading scheme are energy intensive industries, together with electricity and heat producers. In addition to them, other companies, individual persons and organisations may also participate in the scheme.

With a big utilization of hydro and nuclear power, Swedish GHG emissions per capita are low compared with those of other countries. The country now also aims to have a vehicle fleet that is not dependent on fossil fuels by 2030 [7].

1.1.2 Preem company

Preem is the largest fuel refining company in Sweden: 80 percent of the Swedish refinery capacity and 30 percent of the Nordic refinery capacity is operated by Preem. The company processes approximately 18 million cubic meters of crude oil per year, and two-thirds of the products are exported outside Sweden. The refinery processes take place in two big plants: “Preemraff-Göteborg” and “PreemRaff-Lysekil”, where a total of around 345,000 barrels of petroleum products (corresponding to 15% of Sweden’s total energy consumption, equal to 375 TWh) are produced per day [8]. The crude oil arrives at the refineries by ship and then it is processed and exported, or delivered to storage, also by sea. The plants in Lysekil and Göteborg are operated jointly.

Lysekil refinery

PreemRaff Lysekil is located at Brofjorden, near the city of Lysekil. It began operation in 1975 and was originally called “ScanRaff”. The site was selected because of its excellent natural harbour, which could accept super-tankers up to 500,000 tonnes deadweight (DWT), full of crude oil. More than 25 years later, in 2003, the facility was acquired by Preem. The refinery in Lysekil is the largest oil refinery in Scandinavia, with a refining capacity of 11.4 million tonnes of crude oil per year. The major process units of the refinery have a net heat demand of around 400 MW which is supplied by firing fuel gas. Steam is also generated in the process by cooling process streams. The major part of this generated steam (167 MW) is used within the process and 17 MW is expanded in backpressure turbines or used for heating purposes outside the main process. In Figure 1.3 an illustration of the energy balance for the main process units of the refinery is given.

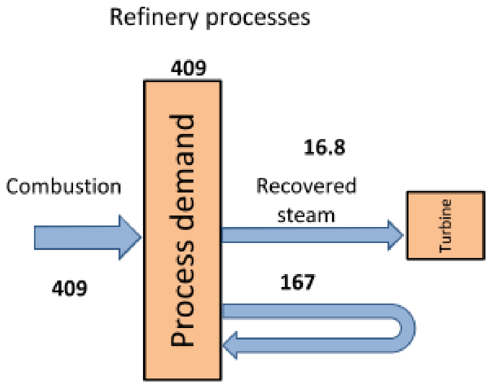


Figure 1.3 Heat balance for the refinery [MW].

A process integration study conducted using pinch analysis tools by CIT-IE (Chalmers Industriteknik - Industriell Energi AB) in 2014 [9] shows that the oil refinery has a theoretical minimum heat demand that is less than half of the current net heat demand. The greatest part of current heat demand is provided by direct heating in process furnaces and steam which is produced in steam boilers, flue-gas-heat recovery boilers and process coolers. An overview of the refinery in Lysekil, is shown in Figure 1.4.

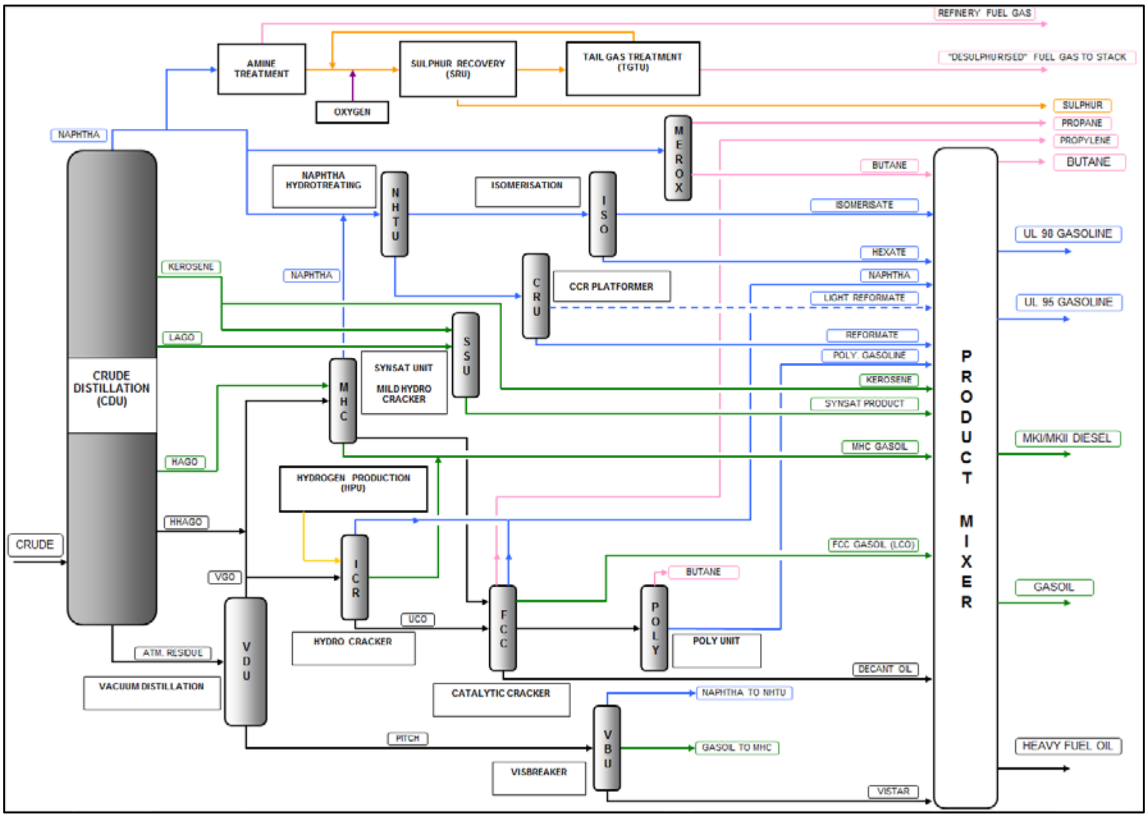


Figure 1.4 The refinery of Lysekil.

1.1.3 Studies about the refinery

Past Studies

Chalmers University of Technology and Preem have been collaborating with respect to energy issues for almost a decade. Within this collaboration, several energy related studies about the refinery in Lysekil have been carried out. At Chalmers, the Division of Industrial Energy Systems and Technologies is involved in process integration studies related to the use of surplus heat for integration of various bio-refinery concepts as well as an analysis of the technical driving forces and barriers associated with energy retrofit projects.

CIT IE has been actively engaged in the research activities for stream data collection and heat-integration analysis purposes. In 2012, CIT IE compiled stream data for the refinery in Lysekil based on process flow diagrams and screen shots from the process information system. The screen shots showed the situation for a specific day in October 2010. The chosen date was considered representative for the current mix of refinery products. The purpose was to supply the researchers at Chalmers with energy data from the refinery, in a form that is suitable for different types of pinch analysis ("stream data"). The data was further refined in 2014. A comparison between actual and minimum utility consumption based on a pinch analysis showed a large theoretical improvement potential in the heat recovery network [9]. In a study conducted in 2014 by CIT-IE, pinch analysis methods such as the "Matrix Method" and "Advance Composite Curves" were applied to identify concrete improvements in the heat recovery network. Furthermore, some specific suggestions of possible modifications aiming at enhanced heat recovery were identified for two process areas, ICR 810 (Hydro Cracker) and MHC 240 (Mild Hydro Cracker). These areas were selected for further analysis due to their large energy savings potentials [10].

In late June 2015, the Master's Thesis student Cristina Murcia Mayo developed a tool for Data Reconciliation and Gross Error Detection for process stream data, using Visual Basic in Microsoft Excel [11]. The tool is based on the Modified Iterative Measurement Test. A second tool, which is easier for handling large data sets and especially designed for networks with non-linear constraints, was also developed. This second tool is only able to solve Data Reconciliation problems, so it is targeted for sets of data where there are exclusively random errors. Both tools were tested using the data set collected from the refinery's Hydrocracker Unit. These tools will be used again to estimate the reliability of the data which are going to be collected developing this work about the refinery in Lysekil.

Current Studies

Several studies connected to the steam system behaviour are currently being carried out by Chalmers employees.

Ph.D. candidate Sofie Marton, is using the refinery in Lysekil as a case study for her work about "operability issues of heat integration projects". Her project will investigate a number of possibilities for retrofit of heat-exchange units between both the chemical processes and the steam network. To do so, pinch analysis techniques will be used to generate new insights about implementation of heat integration measures. In this context, a detailed understanding of the steam system is essential: the retrofit suggestions will strongly depend on steam balances and on how much the steam balance will change with a different production/consumption regime.

Ph.D. candidate Fredrik Bengtsson is looking at some control aspects of the Lysekil refinery. After some changes are proposed to the heat exchanger network, he will examine how they affect the controllability of the system. He will determine if good controllability can still be maintained with the suggested modifications and will determine how such control could be best carried out. Moreover, if the proposed changes show opportunities to improve or adapt the control of the system, he will investigate these possibilities further. Regarding the steam system his objective is two-fold: firstly he will look at the system and try to determine an optimal strategy for switching between steam turbine and electrically driven pumps and compressors. To achieve this objective a good model of the steam network is necessary.

Other projects which are carried out together with Lysekil's refinery are connected to the use of renewable raw material as a feedstock (for instance, seaweed from the west coast of Sweden), using actual units present in the refinery, like the Fluid Catalytic Cracker. Another study regards the possibility to use a new type of renewable fuel from tall-oil, completely without oxygen, using catalyst reactions. This fuel should be completely equivalent in composition to a diesel [12].

1.2 The steam utility network at PreemRaff-Lysekil

The steam network at the refinery, shown in Figure 1.5, consists roughly of four main pressure levels: HS, TS, MS and LS. Steam at the high pressure level is produced mainly by using steam boilers and recovering heat from process furnace flue gases. The other levels of pressure are fed by steam generated in heat exchange with process streams. The headers are connected by let-down valves and turbines, the latter used in direct drive configuration to operate more than fifty compressors and pumps. With the exception of the TS level, which is a local header recently built only to supply steam at the newest Hydrocracker unit, the main headers are extended along the entire refinery, and they are equipped with pressure and temperature meters and control valves.

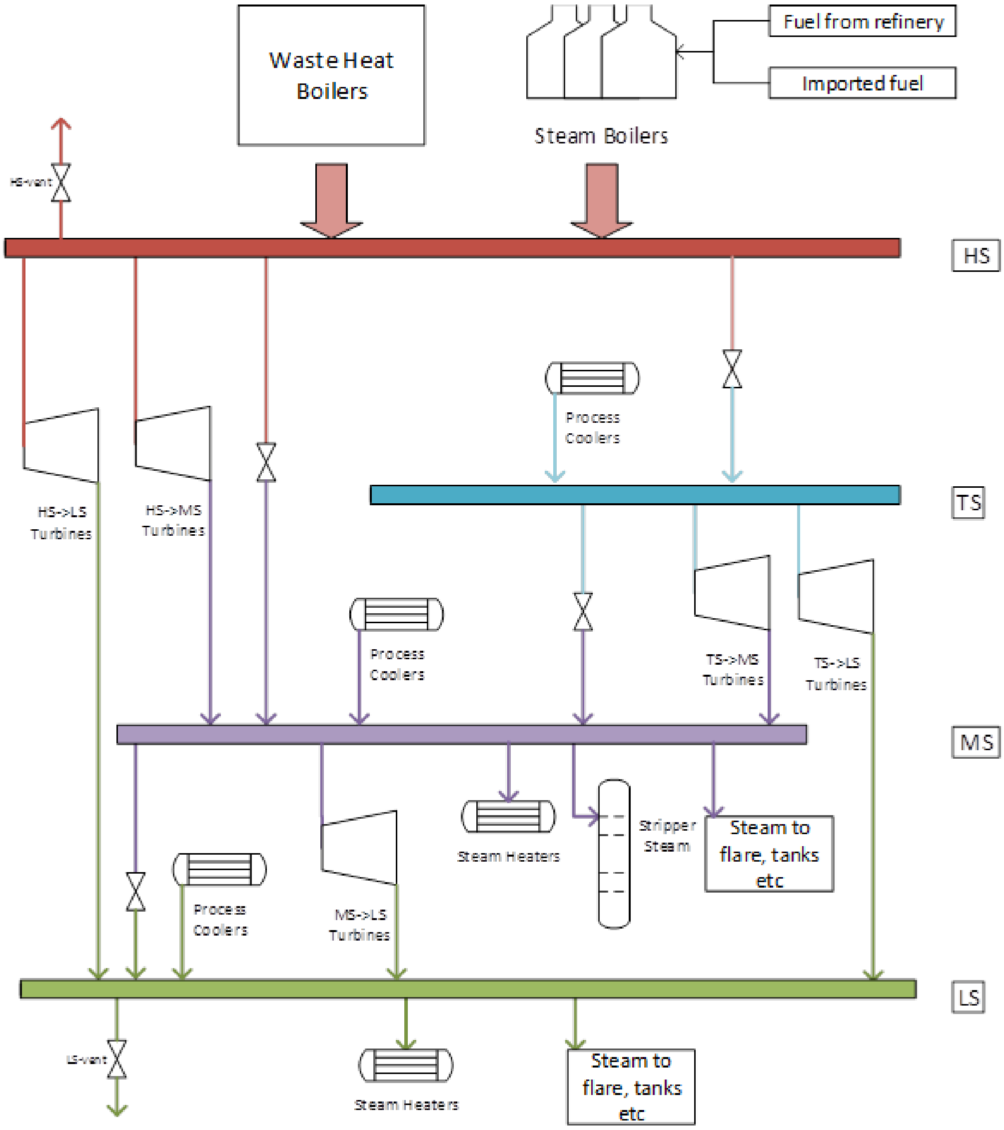


Figure 1.5 General overview of the refinery's steam network.

The thermodynamic conditions of the main headers have not changed since the start-up of the refinery: the same pressures and temperatures of the steam are still used as the original design, although the refinery has experienced several retrofits and modifications along the years. The case is not the same for producers, consumers and turbines in operation: the conditions in which these elements are now operating are quite different from the chosen for the first layout of the plant.

However, the refinery has the advantage of being able of modulate the steam load within the network, using a large number of switchable drivers. In fact, when either the steam supply is low or electric power is cheap, operation of a significant number of turbo-machines can be switched to electrical motors, which give the refinery significant flexibility. A parallel configuration like the one shown in Figure 1.6 for most of the pumps and compressors guarantees the possibility of drive-switching.

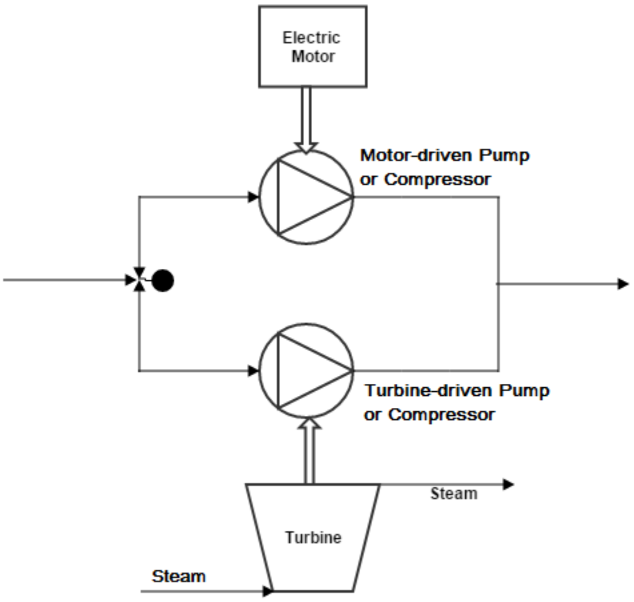


Figure 1.6 Example of double-drive set-up for a generic process machine.

The steam production can also be managed by turning the waste heat boilers on and off. The following Figure shows an overview of the main energy flows within the plant:

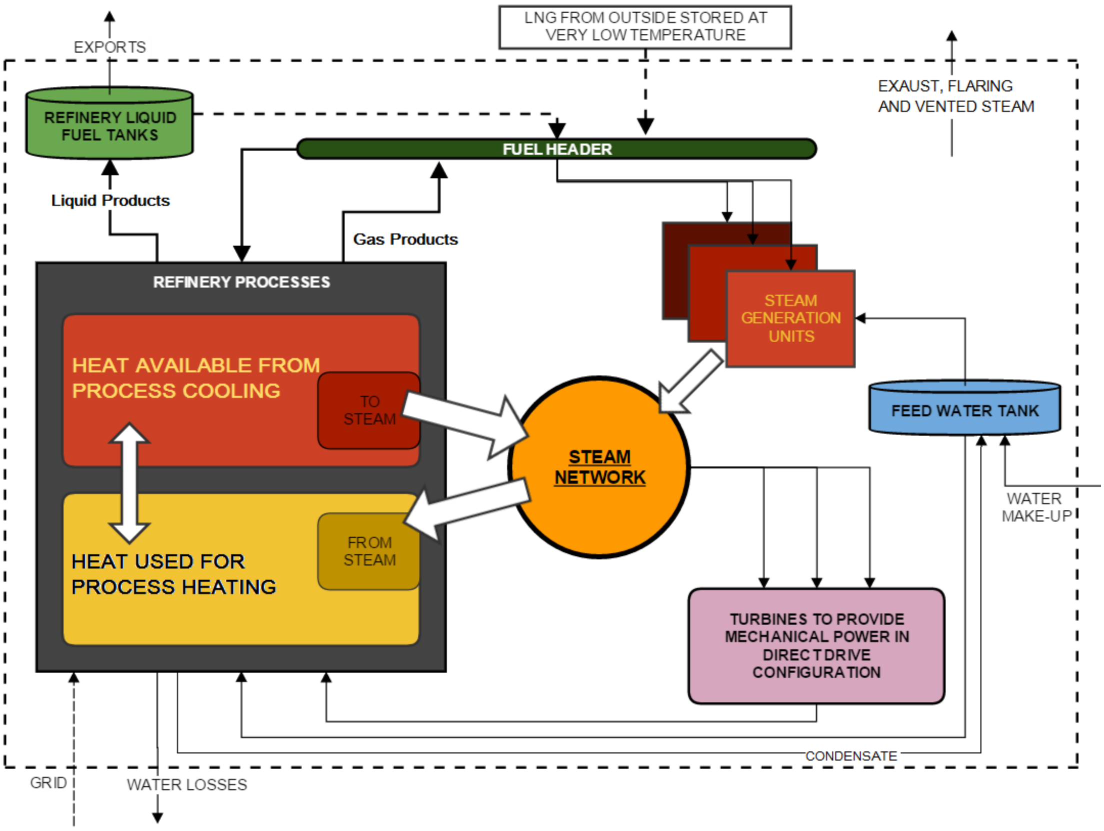


Figure 1.7 Overview of energy flows within the Refinery in Lysekil.

Steam is the main utility at the refinery site. In the fractionation columns, as well as in many heat exchangers, steam is used as a heat source, and the condensate can be recovered and reused; in other units, such as strippers, it is injected to improve the process. When the condensate leaves the strippers it is often contaminated and must be sent to a water treatment unit. The water is thus replaced by make-up feed water.

The refinery uses mainly fuel gas (also called refinery gas) as fuel for the boilers, while these latter are aimed at steam production. There is no electrical energy production on site, therefore when either the steam power is not enough, or if there is an economic advantage, electricity is imported to drive the pumps and the compressors.

1.2.1 Refinery’s fuel balances

The uncondensable gases leaving several distillation columns contains lighter petroleum products (such as hydrogen, methane and ethane), but also smaller amounts of valuable products (such as propane and butane). This mixture, also called refinery gas, is the main fuel gas used in the refinery as fuel for both steam boilers and process furnaces.

When there is not a sufficient amount of refinery gas coming from the separation processes, the refinery utility boilers can be fed by adding to the mixture either purchased LNG or vaporized liquid products, like 99% pure propane. This latter one, however, as the other expensive products, has a commercial value only when it is in the liquid phase.

Since the distillation units are equipped with an air cooling system, the amount of products that can be condensed depends, besides the crude oil formula, on the temperature of the outside air. This temperature can be fairly variable between the summer and the winter. Figure 1.8 shows a sketch of the distillation light products.

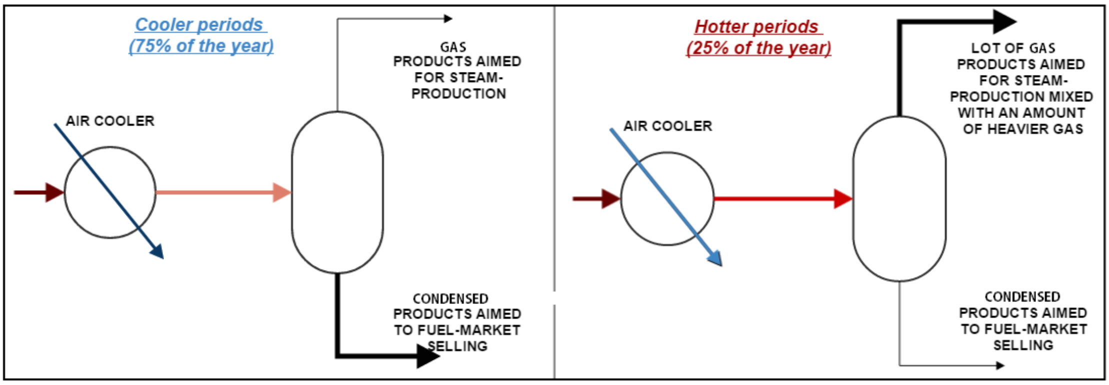


Figure 1.8 Air cooling makes the production of LPG and steam variable.

As it is shown in this picture, the difference between the hot season and the cold season production lies in the ratio of products: when the outside air temperature is high, less condensable products and more fuel gas are obtained from the product condensers. On warm days, the refinery operators in Lysekil reduce refinery’s production from the beginning of the morning, in order to avoid a large excess of fuel gas that the fuel system cannot handle due to its limited capacity. It should also be noted that the environmental permit of the refinery does not allow prolonged flaring of excess fuel gas: fuel gas cannot be stored and must be fired in the steam boilers. Excess steam can be vented in limited amounts, if necessary.

Summarizing, a delicate balance occurs between the production of steam and the production of fuel gas:

- In over-production periods of refinery-gas (hotter periods), as there is no opportunity to export gas products from the plant and the excess of fuel gas cannot be flared due to the environmental laws, a large amounts of high-pressure steam is produced in the steam generator. The steam is let down to the lower steam levels through valves and finally vented. The waste-heat-recovery boilers are totally bypassed in this configuration and consequently the hot flue gases are released to the atmosphere at high temperature, with a big energy loss. All the switchable machines should be driven by steam turbines during this configuration, which occurs for approximately twenty-five percent of the year.

- The remaining seventy-five percent of the year (cooler periods) the amount of fuel gas produced is not enough to satisfy the boiler fuel demand, and LNG must be purchased . In this period, therefore, the strategy concerning the switchable mechanical drives is very important (the greater is the use of steam for drives, the lower is the electric energy use, but the higher is the amount of bought LNG for steam production), since it can be favourable to use the electric-driven pumps to minimize the LNG use.

1.3 Aim of the master’s thesis

The primary objective of this work has been to create a model of the steam network, which can handle mass and energy balances within the entire plant, and to test its reliability for different *stationary* working conditions. To do so, it has been necessary to collect a large amount of data within the plant and to use thermodynamic relationships to estimate the steam flows under various operational scenarios. The possibility to optimize the operation of the system has also been evaluated.

The work, started in late September 2015, has proceeded according to the following milestones.

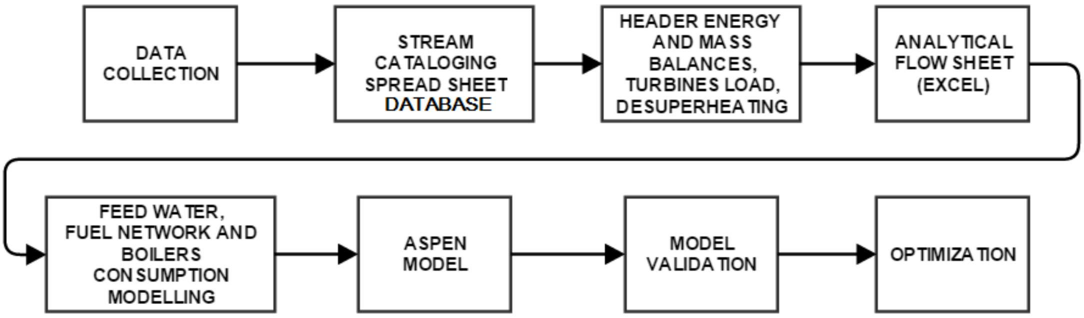


Figure 1.9 Milestones of the Master’s Thesis.

Requirements of the model

This Master’s Thesis has focused on several key-points, all of them related to a set of possible and relevant operating conditions for the steam network. The model is aimed as a tool for future research to be able to answer the following questions:

- *How will changes to steam balances at different pressure levels affect the overall steam balances and the steam headers capacity.*
- *How will changes to steam balances at different pressure levels affect generation of shaft power in the turbines and the electricity demand of the plant?*
- *How will changes to the steam balances at different pressure levels affect the consumption of fuel gas?*

Scope and limitation

The steam network model developed in this work includes:

- A database of all the main steam flows for each level of pressure, catalogued according to the different headers and accompanied with their mass and energy content;
- an overall flowsheet diagram showing the layout of the refinery plant steam system, documented in an Excel spreadsheet;
- the capability to calculate mass and energy balances for the steam system operating at non-nominal steady-state operating conditions.
- a complete model of the steam network implemented in AspenTech’s steam network model software, which includes fuel consumption in the boilers, electric energy consumption and make-up water;
- the creation of a set of editors directly connected to the model interface and to an optimizer, which, for a given set of inputs (like relative prices of LNG and electric energy), can calculate the best configuration of switchable pumps and steam production.

The following points are excluded from my work:

- “dynamic” behaviours of the system units;
- petroleum product balances for the different operating conditions.

Chapter 2

DATA COLLECTION

Preem with the refinery in Lysekil participates in a data collection process called "Solomon Benchmarking", which has the aim to collect and normalizes measurements across all plant sizes, types, and geographies, giving the owners the insight to understand if they stand against the competition. The Solomon study aims to identify specific retrofit areas where a performance enhancement could be done, as well as to evaluate the overall energy efficiency according to the performances of all similar plants in the world [13]. These types of measurements, collected along an entire year with average annual values, could not be used to analyse a layout and build a steady state model, since every fluctuation in the values along the period had been drastically flattened. An "instant" working condition had to be used for this data collection purpose.

The refinery has a large number of meters and controls for every unit. Production of oil distillates within the towers and yield of several chemical components is measured up to 3 times a second. Data arrives directly in the control room, where they are stored in a different frequency: the more the time goes by, the less is the storage frequency. More than hundred employees can access both the real time and the saved data. The system automatically collects an entire set of measurements each minute, for a period of six months. Afterwards the data are saved by the system using average values, up to two years' time. With the aid of a specific software in the office building it is possible to move the time line and navigate through all the different saved working points, as well as to plot one or more curves for a chosen time period. The possibility to access this database has been gently given by Preem, for research purposes. As it will be described later on, the steam network in the refinery is not as well equipped with meters as the petroleum distillation units, thus some assumptions and calculations have been made.

2.1 System behaviour analysis

To obtain a proper layout of the steam network a single working condition corresponding to an instant point has been chosen. To find out which condition could be assumed as a significant and stable working set-point a period of six months has been taken into consideration, in which the data were stored minute per minute without average values. The condition has been chosen in discussion with Preem staff, using criteria of steady flow through the valves and steady steam production at the main boilers and HRSGs. Then, after discarding some quite unstable condition (due to bypassing or turning off of some component), as well as stable periods related to overproduction or underproduction regimes, the point chosen as a reference stable condition in the network has been the 13th of September of 2015, at 3:10am. The network production during this period is shown in Figure 2.1.

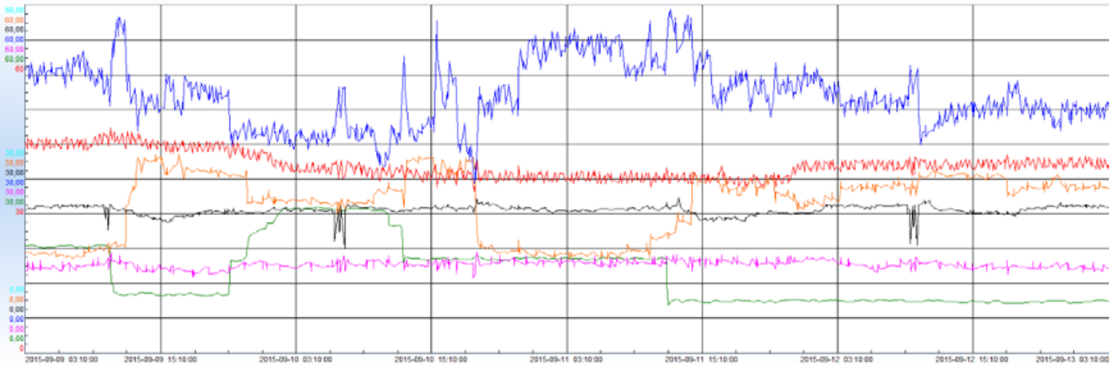


Figure 2.1 Measured steam production in the refinery.

The time scale in the picture goes from the 9th September at 3:10am to the 13th September at the same hour. The period shown is then four days, and there is a vertical line every twelve hours. Measured steam flows leaving steam generators and waste heat recovery exchangers are plotted in the graph (blue and red line are for the two working steam generators, while pink and green for the main HRSGs). Variables can have a different scale in this graph.

Looking at the 13th September time-instant, which is at the right-end of the graph, it can be easily understood the fairly stability of the point. Another graph, showing the valves behaviour during the same instant, is shown in the Figure 2.2.

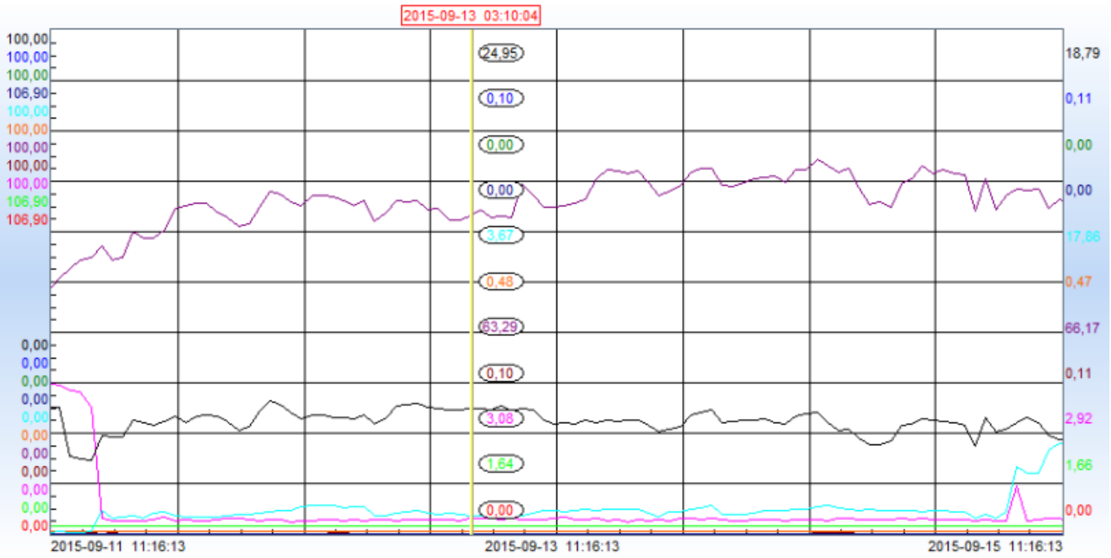


Figure 2.2 Valves behaviour within the refinery.

In this second graph, in which the time scale is the same of the previous one (four days), the flows through the main refinery's valves are shown: the purple line represents the low-pressure venting valve while the black one is the make up steam coming from the medium pressure level to the low pressure header. Both the flows are quite stable during this period. Other valve flows are approximately zero in this period.

Every measured variable in the steam system during such period has been collected, besides all the main screenshots regarding the control room screens.

2.2 Databases and classification

The refinery presents a large number of units, separately located and relatively far from each other, which require steam from the network for processes and heating/cooling streams. For this reason and for further optimization purposes the cataloguing of all the streams has not only concerned the flow and energy amount related to each stream and its type, but also the geographic location of pipes and turbines. This is done by dividing the refinery into four main sections, named with cardinal directions (north, west, east and south). In this way it has been possible to identify the main steam production and consumption areas, and, for example, estimate the distance between the production and the utilization location for every single steam stream. This division has been very useful for optimization purposes.

All the data have been transferred into a spreadsheet and the energy calculations have been done using the X-Steam plug-in, which included thermodynamic properties and steam tables.

2.2.1 Refinery's section localization

With the exception of the feed and product tanks, all the main units at the refinery (more than 17) can be localized in a square area, where the corners are oriented towards the cardinal points. The production of steam (section 320) is located in the West dial. Starting from this section, steam is distributed in main steam headers to the other sections. Every unit in the model has been linked to its dial, which has the name of one of the cardinal points. The Figure 2.3 shows the layout.

SOUTH - CATALYTIC-CRACKING	
FCC 150	Catalytic Cracker
FL 190	Flaring Systems

EST - HYDRO-CRACKING	
ICR 810	Hydrocracker
HPU 820	Hydrogen

WEST - STEAM PRODUCTION	
SGU 320	Steam Generation Unit
CDU 210	Crude Distillation
VDU 220	Vacuum Distillation
SUR 260	Solphur Recovery
ARU 270	Amine Recovery

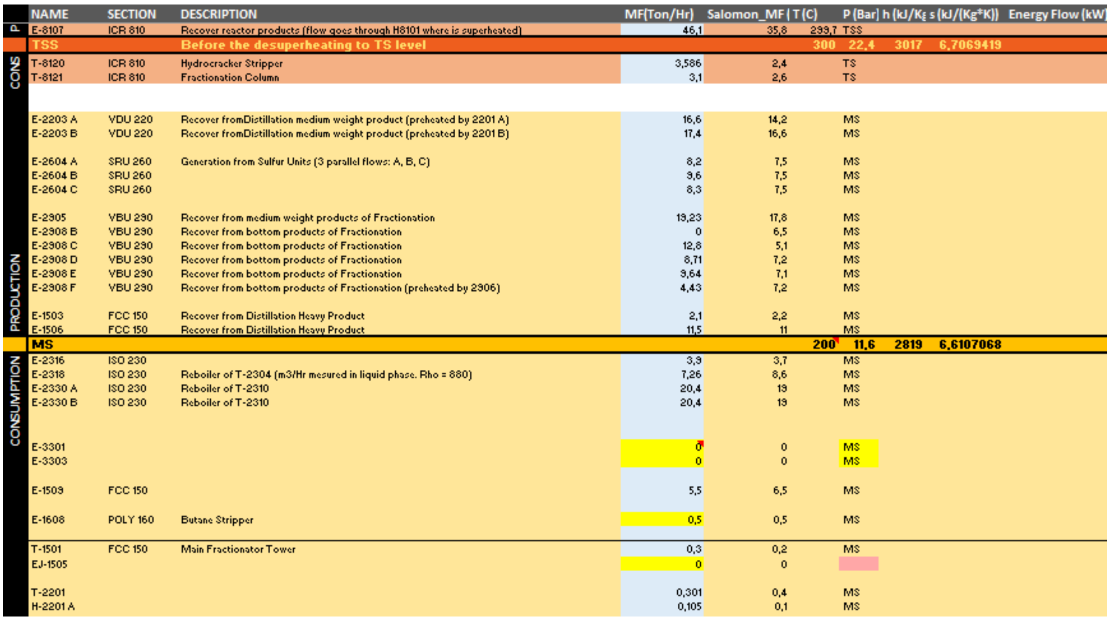
NORTH - POST SEPARATION	
POLY 160	Polymerization
MEROX 180	LPG Mercaptans Ox.
MEROX 250	LPG Mercaptans Ox.
UNIT 230	
NHTU 231	Naphta Hydrotreat.
CRU 232	Catalytic Reformer
ISO 233	Isomerisation
MHC 240	Mild Hydrocracker
SSU 280	Synsat
VBU 290	Visbreaker

Figure 2.3 Geographical division of the refinery main units into four dials.

This classification will be fundamental in the optimization case: it is very important to have an idea about the distance between a possible steam-production area and the location of available consumers.

2.2.2 Production and consumption within the headers

Every header has been classified in a spreadsheet with its production and consumption, together with its thermodynamic condition, specified clearly in 3.1.2. Heat exchangers, reboilers, towers, strippers, ejectors, vented steam and flaring steam will be described below. Turbines and valves will be described in 2.2.3. The Figure 2.4 presents a part of the spreadsheet used for these streams:



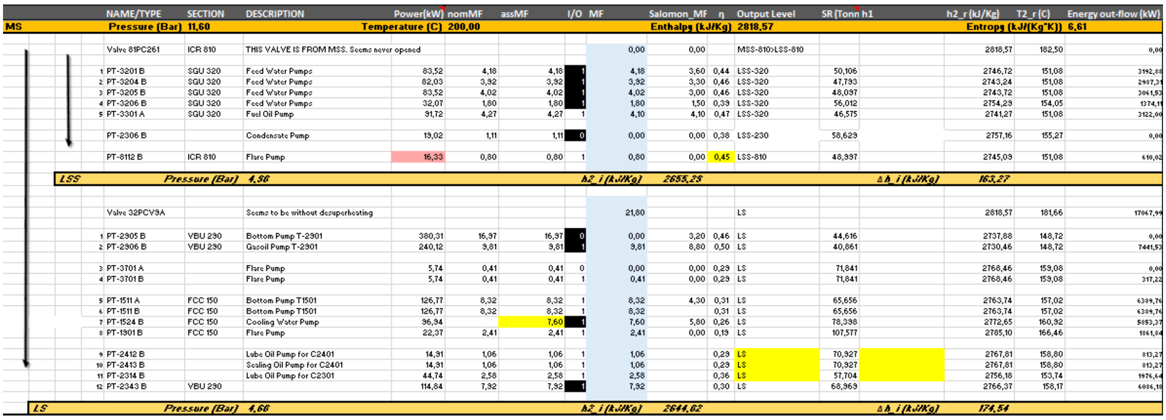
	NAME	SECTION	DESCRIPTION	MF(Ton/Hr)	Salomon_MF	T (C)	P (Bar)	h (kJ/Kg	s (kJ/(Kg*K))	Energy Flow (kW)
P	E-8107	ICR 810	Recover reactor products (flow goes through H8101 where is superheated)	46,1	35,8	299,7	TSS			
	TSS		**Before the desuperheating to TS level**			**300**	**22,4**	**3017**	**6,7069419**	
CONS	T-8120	ICR 810	Hydrocracker Stripper	3,586	2,4		TS			
	T-8121	ICR 810	Fractionation Column	3,1	2,6		TS			
PRODUCTION	E-2203 A	VDU 220	Recover fromDistillation medium weight product (preheated by 2201 A)	16,6	14,2		MS			
	E-2203 B	VDU 220	Recover fromDistillation medium weight product (preheated by 2201 B)	17,4	16,6		MS			
	E-2604 A	SRU 260	Generation from Sulfur Units (3 parallel flows: A, B, C)	8,2	7,5		MS			
	E-2604 B	SRU 260		9,6	7,5		MS			
	E-2604 C	SRU 260		8,3	7,5		MS			
	E-2905	VBU 290	Recover from medium weight products of Fractionation	19,23	17,8		MS			
	E-2908 B	VBU 290	Recover from bottom products of Fractionation	0	6,5		MS			
	E-2908 C	VBU 290	Recover from bottom products of Fractionation	12,8	5,1		MS			
	E-2908 D	VBU 290	Recover from bottom products of Fractionation	8,71	7,2		MS			
	E-2908 E	VBU 290	Recover from bottom products of Fractionation	9,64	7,1		MS			
	E-2908 F	VBU 290	Recover from bottom products of Fractionation (preheated by 2906)	4,43	7,2		MS			
	E-1503	FCC 150	Recover from Distillation Heavy Product	2,1	2,2		MS			
	E-1506	FCC 150	Recover from Distillation Heavy Product	11,5	11		MS			
	MS					**200**	**11,6**	**2819**	**6,6107068**	
CONSUMPTION	E-2316	ISO 230		3,9	3,7		MS			
	E-2318	ISO 230	Reboiler of T-2304 (m3/Hr mesured in liquid phase. Rho = 880)	7,26	8,6		MS			
	E-2330 A	ISO 230	Reboiler of T-2310	20,4	19		MS			
	E-2330 B	ISO 230	Reboiler of T-2310	20,4	19		MS			
	E-3301			0	0		MS			
	E-3303			0	0		MS			
	E-1509	FCC 150		5,5	6,5		MS			
	E-1608	POLY 160	Butane Stripper	0,5	0,5		MS			
	T-1501	FCC 150	Main Fractionator Tower	0,3	0,2		MS			
	EJ-1505			0	0					
	T-2201			0,301	0,4		MS			
	H-2201 A			0,105	0,1		MS			

Figure 2.4 Data classification: Constant pressure productions and consumptions.

Every flow has been classified with the name of the concerned component, the unit in which it is located, a short description and mass flow measurements at the chosen instant (blue column). Moreover, the Solomon study's average mass flow has been included to make a comparison between the year average and the measured data. In this case (which mostly describes heat exchanger and consumption in towers) the instant values are not much different from the Salomon-study average-year-values. For this reason, whenever a measure was missing, the value has been chosen as equal to the Salomon study (also in agreement with Preem engineers and components' datasheet). These assumed values are the yellow ones in the table.

2.2.3 Turbines and valves between the headers

As far as turbines and valves are concerned, another type of cataloguing has been done, with the introduction of several superheated pressure levels in the spreadsheet. Turbines operating between the same thermodynamic levels have been put together in the same list. This cataloguing is shown in Figure 2.5: here the difference between the measured mass flows and the Solomon's mean-values is evident, since the latter values for all the switchable devices are lower than the measured values. The necessity to collect instant values becomes obvious.



		NAME/TYPE	SECTION	DESCRIPTION	Power(kW)	nomMF	assMF	I/O	MF	Salomon_MF	η	Output Level	SR (Tonn	h1	h2_r (kJ/Kg)	T2_r (C)	Energy out-flow (kW)
MS		**Pressure (Bar)**	**11,60**		**Temperature (C)**	**200,00**				**Enthalpy (kJ/Kg)**		**2818,57**			**Entropy (kJ/(Kg*K))**		**6,61**
		Valve 81PC261	ICR 810	THIS VALVE IS FROM MSS. Seems never opened					0,00	0,00		MSS-810>LSS-810			2818,57	182,50	0,00
	1	PT-3201 B	SGU 320	Feed Water Pumps	83,52	4,18	4,18	1	4,18	3,60	0,44	LSS-320	50,106		2746,72	151,08	3192,88
	2	PT-3204 B	SGU 320	Feed Water Pumps	82,03	3,92	3,92	1	3,92	3,30	0,46	LSS-320	47,793		2743,24	151,08	2987,31
	3	PT-3205 B	SGU 320	Feed Water Pumps	83,52	4,02	4,02	1	4,02	3,00	0,46	LSS-320	48,097		2743,72	151,08	3061,53
	4	PT-3206 B	SGU 320	Feed Water Pumps	32,07	1,80	1,80	1	1,80	1,50	0,39	LSS-320	56,012		2754,29	154,05	1374,11
	5	PT-3301 A	SGU 320	Fuel Oil Pump	91,72	4,27	4,27	1	4,10	4,10	0,47	LSS-320	46,575		2741,27	151,08	3122,00
		PT-2306 B		Condensate Pump	19,02	1,11	1,11	0	0,00	0,00	0,38	LSS-230	58,629		2757,16	155,27	0,00
		PT-8112 B	ICR 810	Flare Pump	16,33	0,80	0,80	1	0,80	0,00	0,45	LSS-810	48,997		2745,09	151,08	610,02
LSS		*Pressure (Bar)*	*4,96*						*h2_i (kJ/Kg)*	*2655,29*				*Δh_i (kJ/Kg)*	*163,27*		
		Valve 32PCV9A		Seems to be without desuperheating					21,80			LS			2818,57	181,66	17067,99
	1	PT-2905 B	VBU 290	Bottom Pump T-2901	380,31	16,97	16,97	0	0,00	3,20	0,46	LS	44,616		2737,88	148,72	0,00
	2	PT-2906 B	VBU 290	Gasoil Pump T-2901	240,12	9,81	9,81	1	9,81	8,80	0,50	LS	40,861		2730,46	148,72	7441,53
	3	PT-3701 A		Flare Pump	5,74	0,41	0,41	0	0,00	0,00	0,29	LS	71,841		2768,46	159,08	0,00
	4	PT-3701 B		Flare Pump	5,74	0,41	0,41	1	0,41	0,00	0,29	LS	71,841		2768,46	159,08	317,22
	5	PT-1511 A	FCC 150	Bottom Pump T1501	126,77	8,32	8,32	1	8,32	4,30	0,31	LS	65,656		2763,74	157,02	6389,76
	6	PT-1511 B	FCC 150	Bottom Pump T1501	126,77	8,32	8,32	1	8,32		0,31	LS	65,656		2763,74	157,02	6389,76
	7	PT-1524 B	FCC 150	Cooling Water Pump	96,94		7,60	1	7,60	5,80	0,26	LS	78,398		2772,65	160,92	5853,37
	8	PT-1901 B	FCC 150	Flare Pump	22,37	2,41	2,41	1	2,41	0,00	0,19	LS	107,577		2785,10	166,46	1861,84
	9	PT-2412 B		Lube Oil Pump for C2401	14,91	1,06	1,06	1	1,06		0,29	LS	70,927		2767,81	158,80	813,27
	10	PT-2413 B		Sealing Oil Pump for C2401	14,91	1,06	1,06	1	1,06		0,29	LS	70,927		2767,81	158,80	813,27
	11	PT-2314 B		Lube Oil Pump for C2301	44,74	2,58	2,58	1	2,58		0,36	LS	57,704		2756,18	153,74	1976,64
	12	PT-2343 B	VBU 290		114,84	7,92	7,92	1	7,92		0,30	LS	68,969		2766,37	158,17	6086,18
LS		*Pressure (Bar)*	*4,66*						*h2_i (kJ/Kg)*	*2644,62*				*Δh_i (kJ/Kg)*	*174,54*		

Figure 2.5 Data classification: internal valves and turbines.

In addition to the parameters above, a "nominal condition" isentropic efficiency has been taken into account for all turbines, calculated using the nominal mass flow (which is the product of steam rate and the nominal power, both in the datasheet of the machines) and isentropic enthalpy drop, as described in equation (2.1):

$$\eta_{is,nom} = \frac{Nominal\ Power}{\dot{m}_{nom}(\Delta h_{id})} = \frac{P_{nom}}{P_{nom} \cdot SR \cdot (\Delta h_{id})} = \frac{1}{SR \cdot (\Delta h_{id})} \qquad (2.1)$$

The (2.1) makes sense only if the steam ratio unit is kg/(s*kW), and the ideal enthalpy drop, calculated assuming isentropic expansion, is measured in kJ/kg.

For each turbine’s flow, downstream enthalpy and temperature have been calculated, using the nominal efficiency as a starting point. The errors generated by this assumption, however, will be estimated and corrected afterwards, with the aid of measured flow rates at the desuperheater outputs.

Chapter 3

STEAM MODEL

The steam system at the refinery is a utility system. PreemRaff-Lysekil has expanded significantly during the last years through several major retrofits, aimed to increase the diesel and gasoline production. A lot of processes run continuously and it can be costly to shut them down: besides safety problems or operational issues, the maintenance and calibration of steam system meters at large refinery plants is quite rare [14]. Hence, mass flow rates, pressures and especially temperatures are not measured for all the steam equipment and this lack has led to several issues. Just to give an example, temperatures are key to the equipment's isentropic efficiency: higher discharge temperatures imply lower efficiency and extra operating cost. They could even indicate possible issues.

An important step for the completion of the flowsheet data is therefore to estimate as accurate as possible the missing values along all the steam pipes, together with the isentropic efficiency of the turbines. To do so, mass and energy balances had to be used. This made it possible to determine almost all the fluid-thermodynamic data along the steam lines.

3.1 Steam network components: mass and energy balances

3.1.1 High pressure steam production

Boilers

The refinery has three boilers which can work either together or independently, and can use both natural gas and fuel gas produced within the plant to generate steam. In the boilers production of steam $\dot{m}_s$ and consumption of fuel $\dot{m}_f$ are continuously monitored, and they are related by the basic efficiency equation (3.1).

$$\eta_{Boiler} = \frac{\dot{m}_s(h_{s,out} - h_{s,in})}{\dot{m}_f(\mathrm{LHV})} \tag{3.1}$$

Giving a look at this equation, the enthalpy of the steam leaving a working boiler, $h_{s,out}$, can be reasonably assumed quite constant (being the temperature a set point that must be controlled), as well as the inlet enthalpy $h_{s,in}$, representing energy increased due to pumping and pre-heating of feed water. The LHV instead depends strongly on the type of fuel used into the boilers. However, in the refinery is present a monitoring system to measure the composition of the fuel gas before being fired in the boilers, and it is possible to calculate the LHV by the composition. A data analysis over one year period shows that the values of the fuel gas mixture used to generate steam are located in the range 32÷50 MJ/Sm^3 and they vary very slowly, with a mean value of 43 MJ/Sm^3 (37 MJ/kg).

Table 3.1 Boiler's datasheet (assuming LNG use, 5% Blow-down and 10% excess of air).

EFFICIENCY (DATASHEET)	TOTAL LOAD (STEAM PRODUCTION)
90,25%	100%
90%	60%
89,75%	45%

Using this mean value and assuming a fairly constant efficiency for the boiler (the Table 3.1 shows values from datasheet that are very stable), the last equation can be reformulated connecting in a linear way the steam production to the fired fuel. The (3.2) is indeed the equation of a straight line, with a constant slope represented by the term $\eta(\text{LHV})/\Delta h$.

$$\dot{m}_s = \dot{m}_f \cdot \left(\frac{\eta_{Boiler}(\text{LHV})}{h_{s,out} - h_{s,in}} \right) \tag{3.2}$$

Furthermore, to verify the reliability of this assumption, a set of data collected in the refinery has been plotted in the Figure 3.1, using measured values of steam production and fuel consumption for the boiler which has been always in operation. As seen from the graph, two main slopes can be individuated, depending on the amount of secondary natural gas in the mixture (which has a higher LHV and leads to a steeper line).

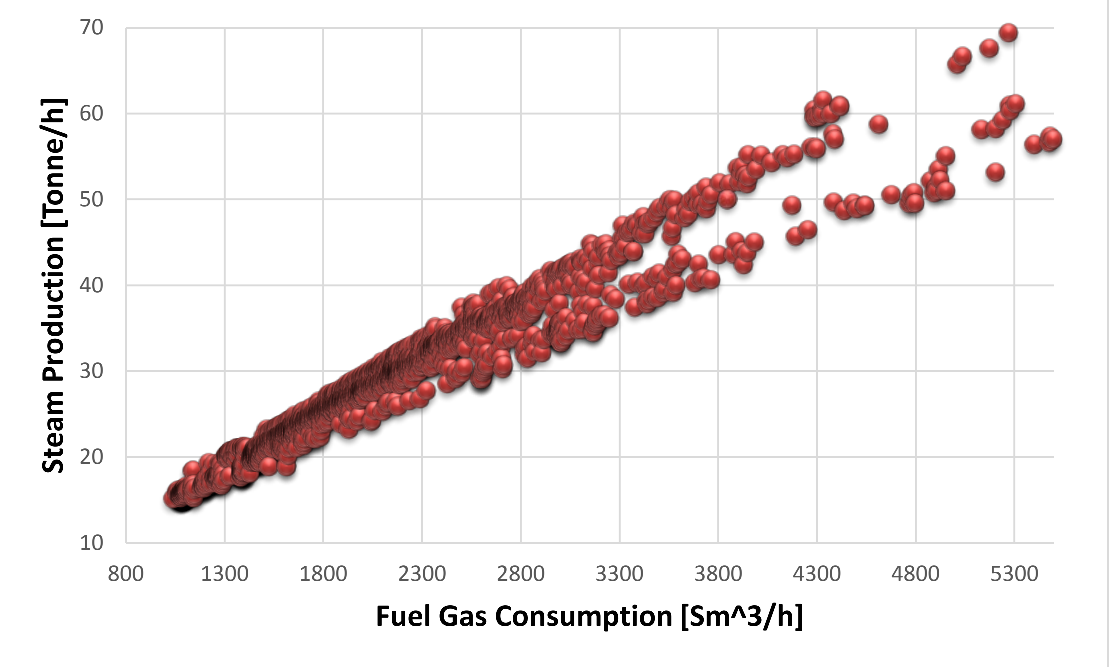


Figure 3.1 Plotted measurements of boiler's main variables.

How to handle the different quality of fuels will be discussed later. So far, it is important to point out that only a fixed efficiency will be used for the boilers, together with a blow-down ratio of 1% and an air excess of 30% based on Preem employees' suggestions. It should be pointed out that the boilers in the refinery never work at the nominal load, which is 90 Tonne/h of steam production. The maximum production registered is around 70 Tonne/h (77,77%) and the assumed efficiency will take count of this. The efficiency used as fixed variable in the steam boilers has been set at 88%.

Heat recovery steam generators (HRSGs)

The heat recovery steam generation from flue gases is carried out in two boilers used for the production of high pressure steam. These heat recovery boilers, located in different areas of the refinery (main distillations area and reformers area) use the heat of the flue gas leaving the refinery's processes to generate steam. The maximum production is around 50 steam Tonne/h for the two of them together, with a bypass before the economizer section of the generator that allow to exclude an amount of flue gas from the heat recovery and send it directly to the stack. The steam production can be then regulated, and, in some cases (when a lot of fuel has to be used in the steam boilers) these recovery boilers can be bypassed completely. The model will not take into account the details of the HRSGs, since their production is not related to the fuel consumption in the refinery. In addition, looking at the analysed scenarios as snap shots of the refinery in quite stable conditions, the heat recovered within the HRSGs (equal to the heat provided to the steam side) is a quite stable value and can be reasonably assumed constant.

3.1.2 Headers

A steam header is the main steam supply pipeline for a certain steam pressure level. Its function is to deliver steam at a necessary level of quality (dryness) to the general areas where steam is needed. There are two types of header in the refinery: the principal ones, called HS, MS, TS and LS are large headers and they are extended along the entire plant (With the exception of TS, the one aimed to feed the ICR section). The other type of headers are relatively small and locally distributed. They mostly receive steam from the different units of the refinery.

The Figure 3.2 is a sketch of a header structure, in which the “i-1” and “i+1” headers could be both main headers and superheated ones. The valves represent all the streams which are throttled with no production of shaft work (including the desuperheaters’ ones), while the turbines represent all the streams in which an expansion takes place, with shaft work production.

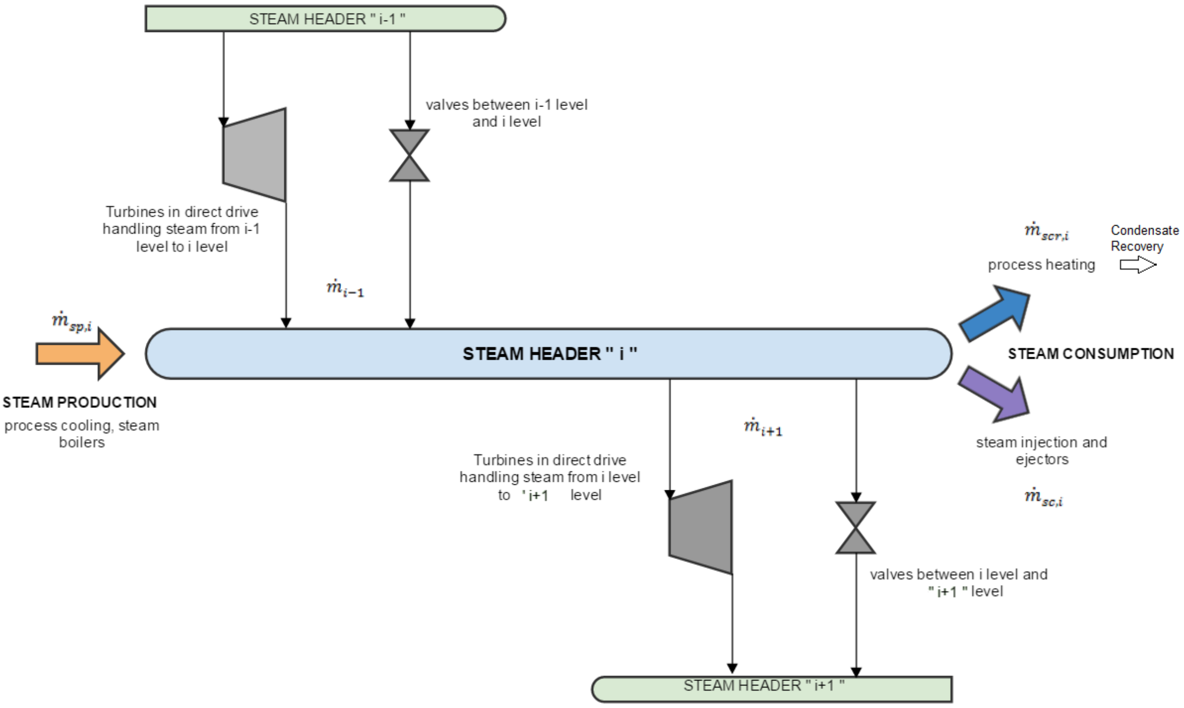


Figure 3.2 Simple header schematics with equation used nomenclature.

Using the figure nomenclature, the basic equation (3.3) for the steady-state mass balance over the header “i” is:

$$\dot{m}_{i-1} + \dot{m}_{sp,i} = \dot{m}_{i+1} + \dot{m}_{sc,i} + \dot{m}_{scr,i} \tag{3.3}$$

Once the mass flow rates have been determined for all flowsheet locations, and have been characterised by calculation of their thermodynamic properties, energy balance has to follow. At last feed water and make-up water balances will close the balance of the entire steam network. Energy balance for each header is calculated according to (3.4):

$$\dot{m}_{i-1}h_{i-1} + \dot{m}_{sp,i}h_{sp,i} = \dot{m}_{i+1}h_{i+1} + (\dot{m}_{sc,i} + \dot{m}_{scr,i})h_{sc,i} + \dot{Q}_{loss,i} \qquad (3.4)$$

The equation above is the first law of thermodynamic applied to a steam header, where no work is obtained within the system (there could be work only between each level, in the turbines), hence the term"$\dot{W}$" $\rightarrow 0$. The term "$\dot{Q}_{loss}$" includes heat loss in the piping network, measurement errors and approximations. "h" is the specific enthalpy for mass unit, given in kJ/kg for a certain temperature and pressure in a steam-table (in the saturated vapor area, instead, another variable like the vapor-fraction or the entropy will have to be specified).

Different thermodynamic states are required by the different equipment at the plant: the best heat transfer coefficient is related to saturated vapor condition, which is important for the best heat exchangers efficiency; on the other hand, a superheated steam is required by the turbines to avoid nozzles and blades damage. To meet both of the different type of demands (saturated or superheated steam), a saturated steam condition is kept within the main low-pressure steam headers (which are connected to all the heat exchangers), while the high-pressure steam headers are used to feed the turbines and receive production from the boilers and HRSGs.

Main headers

The main headers provide thermodynamic power to the refinery units and turbines, feeding them with steam wherever and whenever they need it. Their temperature and pressure are kept constant with desuperheaters and let-down valves, thus their thermodynamic state are fixed and can be easily localized in a Temperature (T) - Specific Entropy (s) plane, as in Figure 3.4. The main condensate header pressure is the same of the low pressure header.

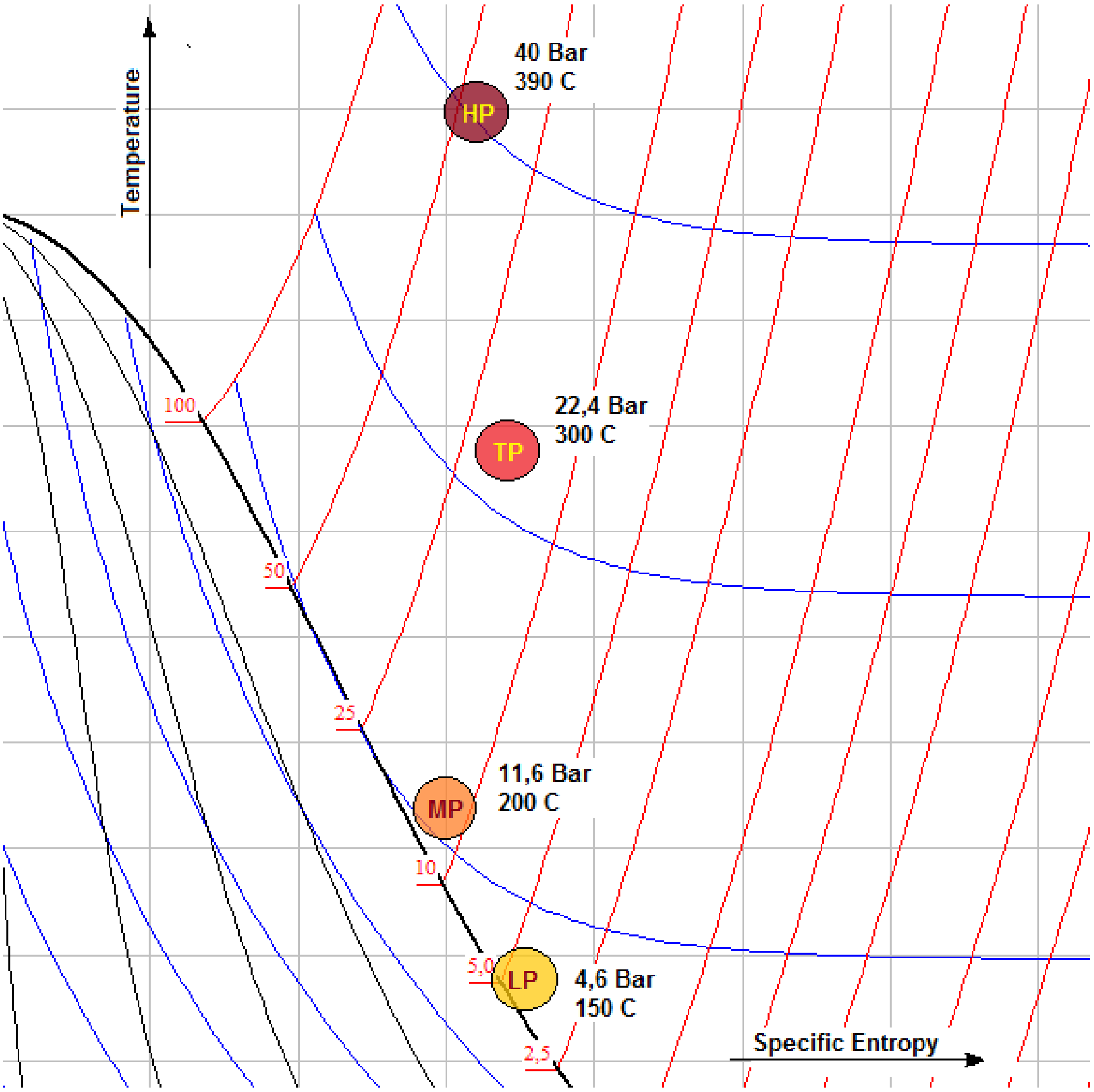


Figure 3.3 Thermodynamic localization of the main headers in a Temperature – Entropy plane.

A part from some minor fluctuations, all the flows leaving the main headers are at the header temperature and pressure. For the medium and low temperature headers, some “condensate trap” like the one in Figure 3.3 are placed along the pipes, in order to maintain the optimal condition of saturated vapor. The blow-down condensate caught in this trap has been assumed negligible compared to all the other flow in the steam network.

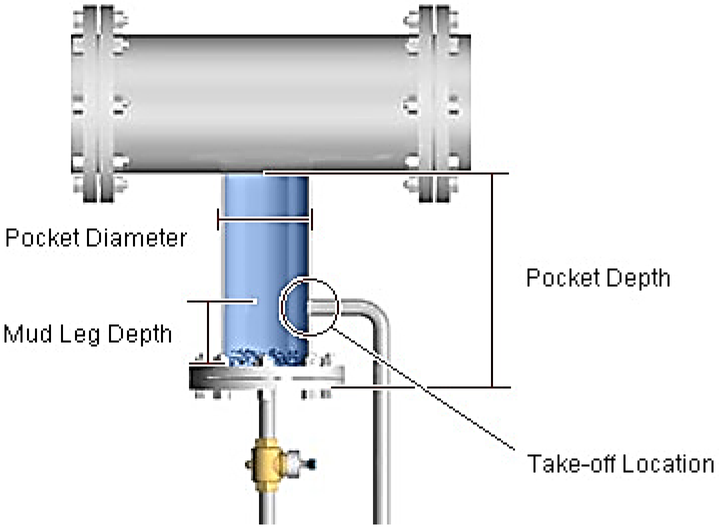


Figure 3.4 Condensate trap placed along a header.

Superheated headers

The superheated headers are local, and their thermodynamic conditions are not constant. They receive the outlet stream coming from the turbines, which can be in operation or not, depending on the working condition of the refinery. All the superheated headers have approximately the same pressure, which is usually close to the pressure of the main header downstream. This latter receives the flow from the superheated header after a desuperheating station, whom objective is to control the temperature within the main header. Besides the temperature control the desuperheating stations always present a flow-meter to control the production steam rate within the main header.

The enthalpy of the superheated header has been calculated as described later on 3.1.4, assuming the thermodynamic conditions of the flow downstream well known (and equal to the main header), and using the measured mass flow rate after the desuperheating process.

After calculating this thermodynamic condition, a revaluation of the turbine isentropic efficiencies upstream has been possible. This important step, applied to every group of small turbine with a layout like the one in the Figure 3.5, is based on the calculation of the total amount of steam leaving the desuperheater downstream (which is measured). The pressure drop due to an eventual partial throttling has been assumed negligible, and the temperature constant with the enthalpy (quite reasonable for superheated steam condition). A lower isentropic efficiency, in fact, leads to a higher value of entropy, enthalpy and temperature, and so a greater amount of water used in the desuperheating process.

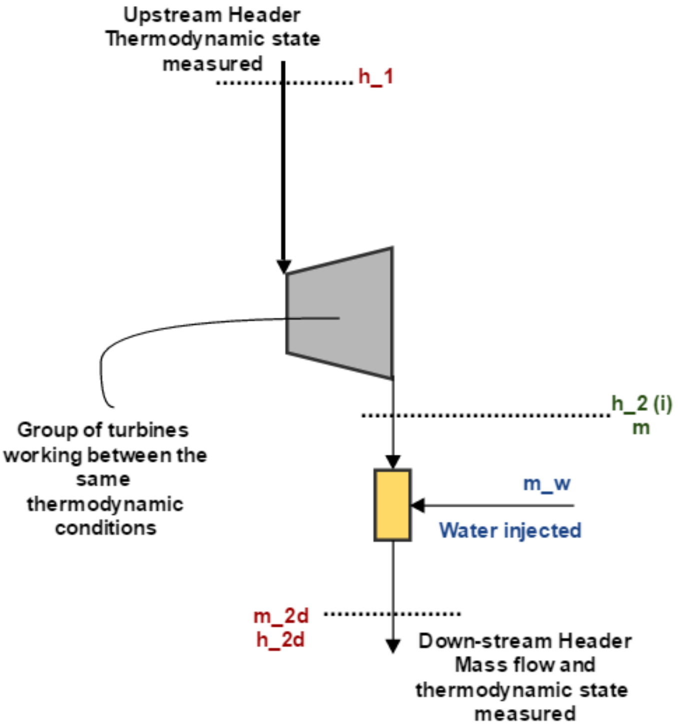


Figure 3.5 General layout representing a group of relative low-power-turbines at the refinery.

3.1.3 Turbines

A large number of turbines are used in the refinery to drive compressors, pumps and some blowers in order to save electric energy when excess steam is available. No electricity is generated at the plant since there are no turbo-generators on-site. Around the refinery are fifty-five turbines, whom name is an indication of the unit the turbine is located, and the component it is driving (CT for compressor-turbine, PT for pump turbine, BT for blower turbine). An important distinction has been made regarding the assumptions used to connect the flow through the machine to the shaft-mechanical power. They have been separated into two sections.

Direct-drive high-power compressor turbines

Two big reaction turbines drive two of the largest compressors at the refinery, the Hydrocracker one and the Catalytic Reformer one. The latter, unlike all the other refinery turbines, is a condensing turbine. The two compressors are always in operation, but the power they require can change according to the compressor load. The turbine power output is controlled by steam throttle vales at the turbine inlet. The datasheet pressure drop will change due to this type of control, in a constant enthalpy process (throttling), while the outlet pressure will be kept fixed, as it is connected to the downstream steam header. The process is illustrated in Figure 3.6, using a Mollier diagram.

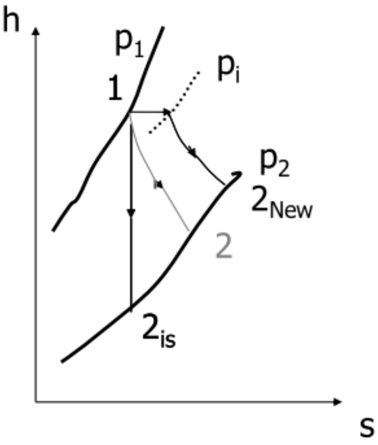


Figure 3.6 Throttling process to load control.

It is important to estimate a value for the isentropic efficiency that characterizes the expansion process in the turbines. A method developed at Chalmers [15] is used, based on the dimensional ratio χ (3.5).

$$\chi = \frac{\dot{m}_{st} \cdot \Delta h_{is}}{\Delta p_{is}} \quad \left[\frac{[kg/s] \cdot [kJ/kg]}{[bar(a)]}\right] \tag{3.5}$$

The pressure drop Δp_{is} is the one that takes place through the turbine for nominal operating conditions (i.e. $p_1 - p_2$), and the enthalpy drop corresponds to ideal isentropic expansion (i.e. $h_1 - h_{2,\,is}$). It can be shown that χ corresponds to the average specific volume flow through the turbine. Table 3.2 presents the principal characteristic of nominal load operation for the two turbines in the refinery. The corresponding value of χ is 92,1 for the first turbine, and 114,5 for the second one.

Table 3.2 Characteristic of the main turbines at the refinery (Nominal Condition - datasheet).

TURBINE	NOMINAL MASS FLOW	DESIGN PRESSURE DROP	ISENTROPIC ENTHALPY DROP	NOMIN. POWER	NOMINAL EFFIC
CT-2301	16 Tonne/h	39,3 bar	816,4 KJ/kg	2,9 MW	0,8
CT-8101	30 Tonne/h	35,1 bar	482,3 KJ/kg	2,75 MW	0,75

Based on this data, a curve can be constructed showing how the isentropic efficiency varies at turbine part-load, as described in Appendix A. The curve obtained for one of them, which will be placed into the model, is shown in Figure 3.7.

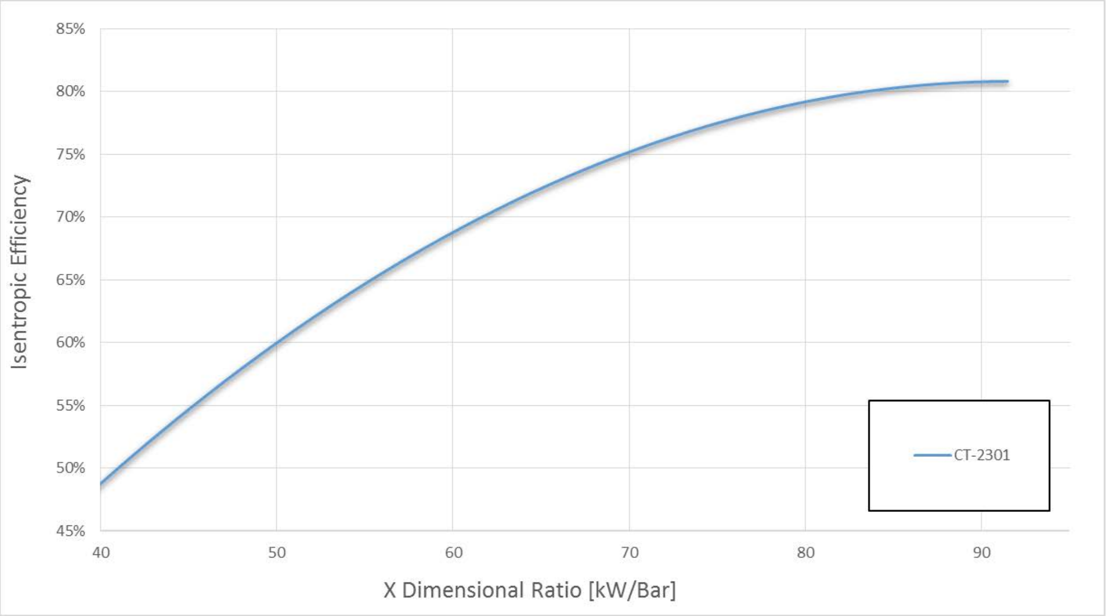


Figure 3.7 Isentropic curve in function of the dimensional ratio X, for the condenser turbine CT-2301.

Single-stage backpressure low-power turbines

The other fifty-three turbines are spread all around the plant, thirty-four of them in parallel configuration with an electric motor. However, all of them are single-stage backpressure turbines, and present a relative low-power and a modest isentropic efficiency. The flow through these turbines is usually not varied, as they are used only to power small process pumps. A general schematic for the turbine is shown in Figure 3.8.

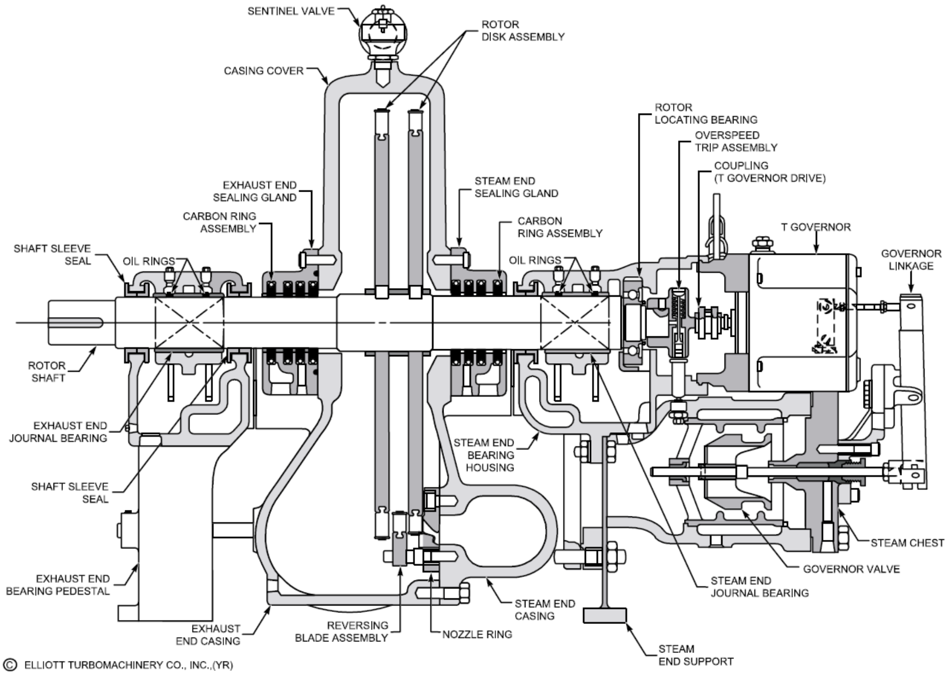


Figure 3.8 Schematic for a single stage turbine as the ones used in the refinery.

While isentropic efficiencies of large central station power plant steam turbines can approach ninety percent, a single-stage turbine peaks at around sixty percent and isentropic efficiencies of less than thirty percent are not uncommon [16]. Since the datasheet was available for operational variables, data for real “Steam Rate” (SR) and nominal shaft power were used. The “Theoretical steam rate” (TSR) expresses the amount of flow that would be needed if the turbine expansion was completely isentropic, and it is related to the SR through the isentropic efficiency η as follows:

$$SR = \frac{Mass\ Flow\ [Tonne/h]}{Shaft\ Power\ [MW]} = \frac{TSR}{\eta} \quad \left[\frac{Tonne}{MW \cdot h}\right] \tag{3.6}$$

Using nominal values for SR and Shaft Power in equation (3.6), the nominal mass flow can be calculated. The SR represents an advantage against the use of the isentropic efficiency, since it provides information about the flow rate inside every turbine for a given power output. Moreover, it is a quite constant coefficient. Datasheets like the ones in Table 3.3 have been used for all the single stage turbines at the refinery:

Table 3.3 Datasheets used for almost all the steam turbines.

NAME	PRESSURE INLET [bar(a)]	PRESSURE OUTLET [bar(a)]	POWER [kW]	STEAM RATE [Tonne/(MW*h)]
CT-3402	42,5	4,8	422,81	14,12
PT-1511 A	11.5	4,8	126,77	65,65
PT-1511 B	11.5	4,8	126,77	65,65

As is can be easily seen comparing some values, a bigger enthalpy drop is usually associated with a better isentropic efficiency, leading to a lower SR value.

It should be pointed out that most of the turbines operating between the same enthalpy levels, even though some of them are located in different areas of the plant, will be grouped together in the network model, to better handling their switchability.

3.1.4 Valves and desuperheaters

In the refinery it is very important to keep the temperature and the pressure of the steam as steady as possible within the headers. In fact, a good control of the thermodynamic conditions leads to a better efficiency of the processes. Throttling valve and desuperheaters are used in the network to control pressure and temperature respectively, connected to temperature and pressure meters as shown in Figure 3.9.

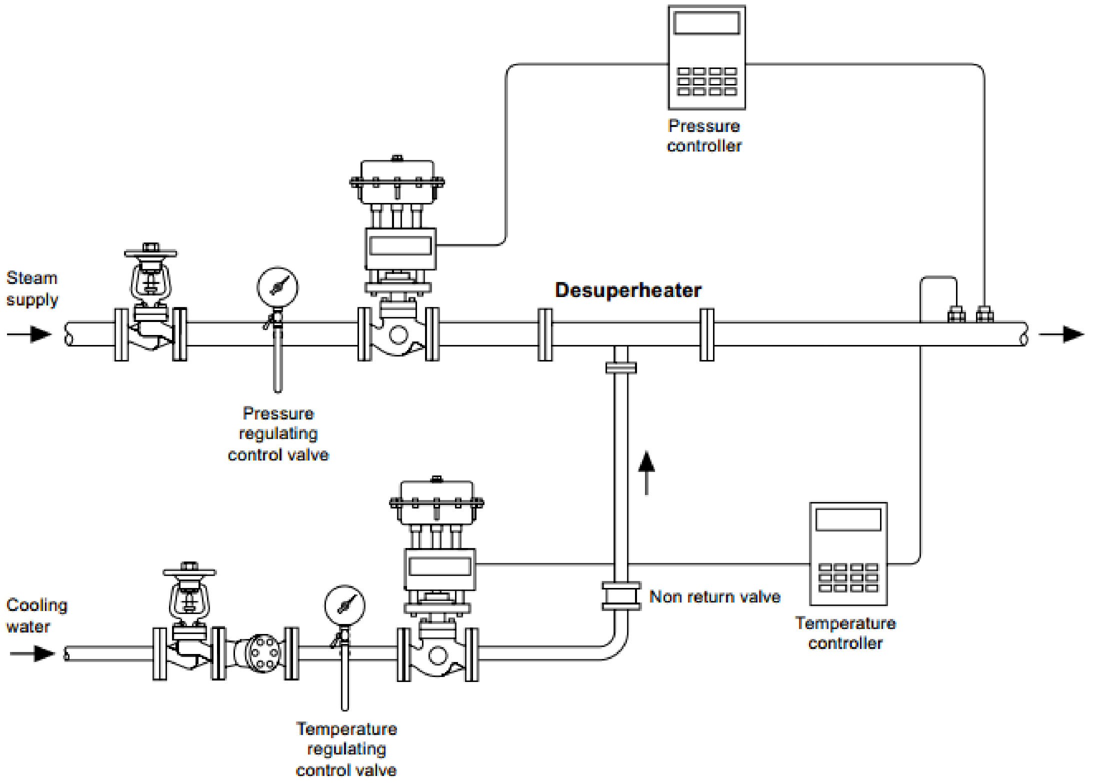


Figure 3.9 Schematic about temperature and pressure control within the network.

Valves

Important letting down valves are located between the several headers in the steam system for a “cascade” control of the pressure from upstream to downstream and to increase the pressure in case it goes below a set-point level. The more the pressure rises upstream, the more the related valve will open and let more amount of steam go downstream. For these components no particular assumption has been made: ideally the flow through them undergoes an isenthalpic expansion ($\Delta H_{valve} = 0$), and the pressure drop has been assumed simply as the difference between the pressures of the headers. It should be pointed out that the meters for some of the valves do not measure the value of the flow through them, but only the opening percentage. In these cases the flow has been evaluated using the valve’s characteristic, like the one in Figure 3.10.

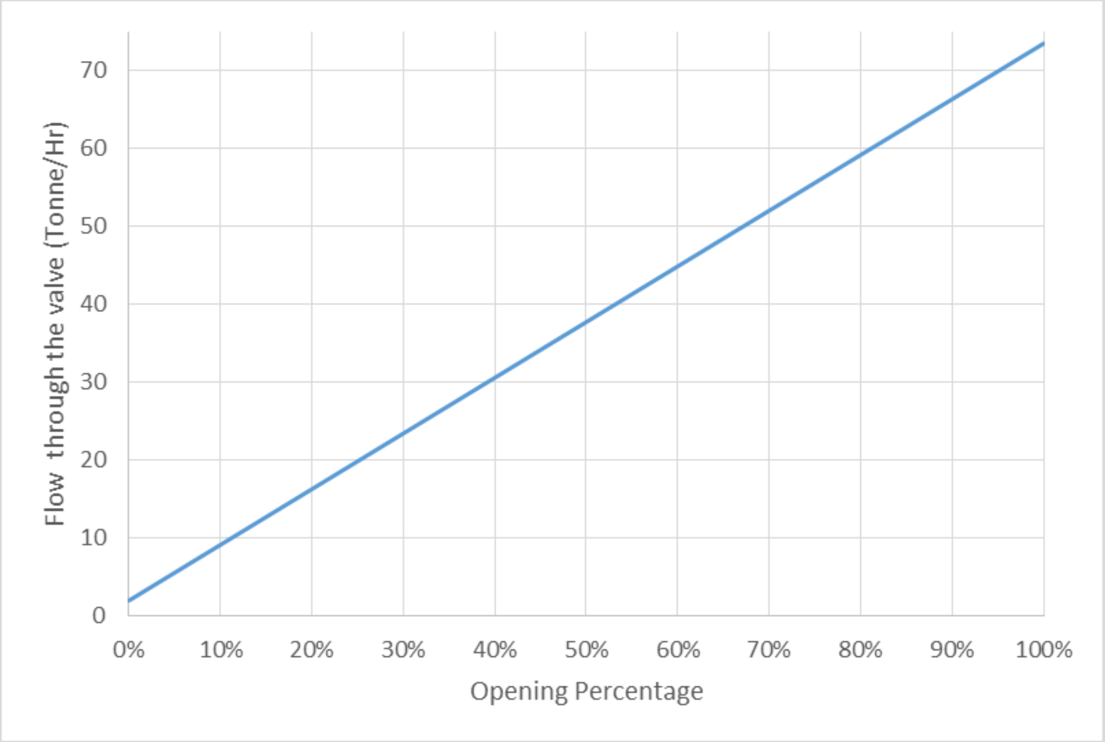


Figure 3.10 Valve characteristic, curve for 32PCV9A, make up from MS to LS level.

Even though most of the control valve at the refinery have a linear characteristic, like the one which is shown in the picture above, some of them present an equal-percentage curve. In those cases, where equal increments of valve travel produces equal percentage changes in the valve C_V, the flow has been evaluated being known the new value of C_V and using the generic formula:

$$C_V = \dot{V} \sqrt{\frac{SG}{\Delta P}} \tag{3.7}$$

Where $\dot{V}$ is the flow rate in cubic meters and SG is the specific gravity.

Some valves at the refinery present a minimum flow not equal to zero to preclude hysteresis effect that might result from total closing (This condition is fairly typical for control valves[17]). Because of this, sometimes a minimum aperture of the valve does not indicate a small value of flow, but instead a value close to the minimum.

Desuperheaters

In the desuperheating processes, in which a superheated steam is restored to its saturated state by the injection of water at the same pressure, an energy balance is necessary to calculate the amount of feed water supply (usually not measured). A typical desuperheater, like the ones used in PreemRaff, is shown in Figure 3.11.

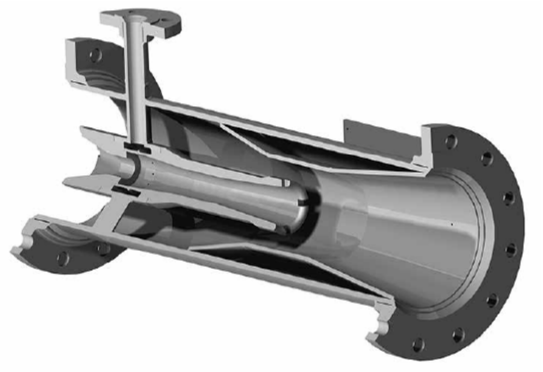


Figure 3.11 Section-view of a Venturi-type desuperheater.

Because of the Venturi type shape in the middle section, a little pressure drop takes place in the device (approximately 0,3 ÷ 0,7 bar), that changes a bit the pressure in the related down-stream header [18].

In the refinery all the desuperheaters are located before each header to control the thermodynamic level of the incoming steam, operating on the temperature. The injected water is reasonably assumed at 25°C (the temperature increasing due to the pumping is negligible) and at the header pressure. A simple system of energy and mass balances concerning the different stream enthalpies rules the variables in every desuperheater. Indicating with "sh" subscript the superheated stream, with "w" the pressured water and with "ds" the desuperheated stream:

$$\dot{m}_{sh} + \dot{m}_w = \dot{m}_{ds} \tag{3.8}$$

$$\dot{m}_{sh} h_{sh} + \dot{m}_w h_w = \dot{m}_{ds} h_{ds} \tag{3.9}$$

Every desuperheater present in the steam network has been handled with the equations (3.8) and (3.9) in the model, where the discharging enthalpies have been calculated assuming the downstream condition the same of the downstream header. An example of the calculations made is in the Figure 3.12.

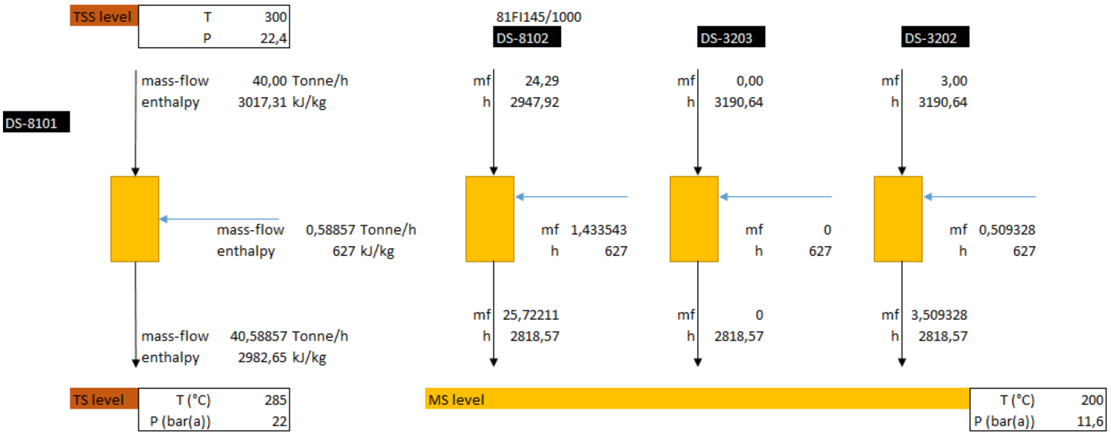


Figure 3.12 Desuperheater calculations for the TS and the MS levels at the refinery. The upstream values depend on the turbine efficiency upstream, and have been calculated separately in another section of the spreadsheet.

3.1.5 Heat-exchanger and steam consumers

Steam flows generated by process heat in heat exchangers are measured within the refinery and update in the control room screen three times every second. The steam consumptions, both in the heat exchanger or reboilers where steam is condensed and recovered; and in the several tower or strippers where it is injected, are often measured as well. Sometimes meters are missing and some assumptions have been made to estimate a value. As already mentioned in 2.2.2, the comparison between the data collected as momentary values at the refinery and the values in the Solomon studies (which deals with year-average data) shows that the flows through these components are fairly steady. For these reason, with the exception for the maintenance periods, a Salomon value has been used every time a measurement was missing.

3.2 Water supply

The steam network model must include a complete balance for the make-up feed water consumption and the condensate return. In the refinery there are two separate tanks for the water management: the first one receives recovered condensate from the lowest pressure header, while the second tank is connected to the water treatment system and supplies the make-up water. The water streams leaving the two tanks are sent to a deareator, and then to a system of pumps that introduce the high pressure water to the main headers production equipment (including boilers and HRSGs). Before reaching the boilers, part of the high pressure water feed the Reformer and the Pre-reformer units. A picture of the water network is in Figure 3.13.

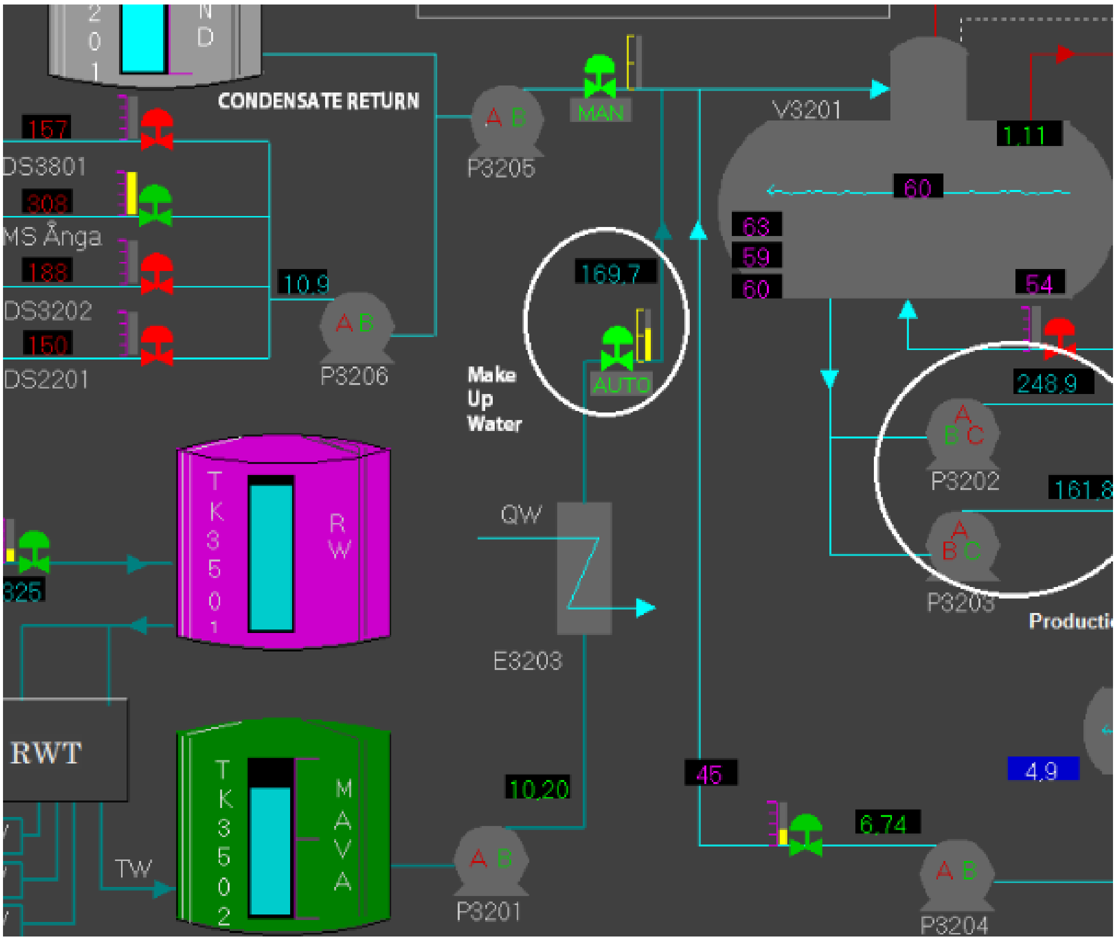


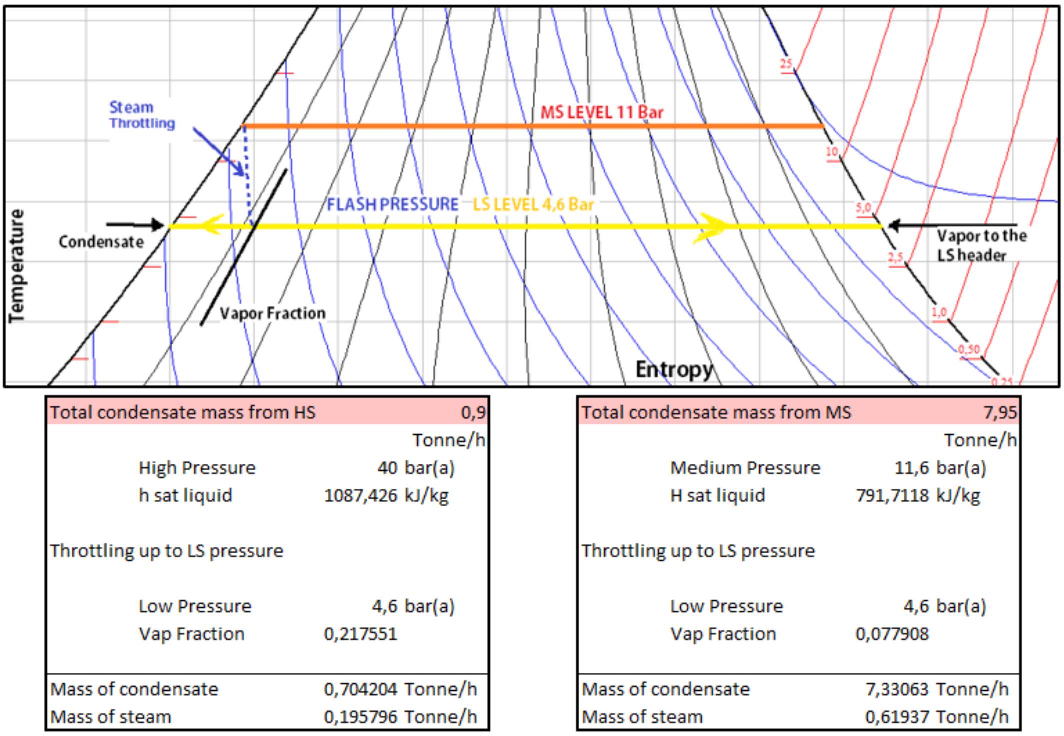
Figure 3.13 Feed water network and water treatment.

Steam recovered by flash separators

The condensed steam leaving the heat exchangers and the reboilers of the high and medium pressure headers is flashed in a vessel and partially recovered as low pressure steam. In the steam network, therefore, several low pressure vessels receive higher pressure condensate. The flash separation can be simply treated as an isenthalpic process, in which the amount of recoverable steam corresponds to the vapor fraction of the stream, which is calculable intersecting the low pressure isobaric with the curve at the same enthalpy of the saturated liquid at medium or high pressure steam.

In the model these calculations have been made assuming a common vessel for each level of pressure (one for the high pressure and one for the medium pressure header). No heat exchangers or reboilers are located downstream of the “TS” header, thus no steam is recovered.

The calculation handled within a spreadsheet, where the vapor fraction, the enthalpy and pressure have been determined with X-Steam plug-in, are shown in Figure 3.14.



Total condensate mass from HS		0,9
		Tonne/h
High Pressure	40	bar(a)
h sat liquid	1087,426	kJ/kg
Throttling up to LS pressure		
Low Pressure	4,6	bar(a)
Vap Fraction	0,217551	
Mass of condensate	0,704204	Tonne/h
Mass of steam	0,195796	Tonne/h

Total condensate mass from MS		7,95
		Tonne/h
Medium Pressure	11,6	bar(a)
H sat liquid	791,7118	kJ/kg
Throttling up to LS pressure		
Low Pressure	4,6	bar(a)
Vap Fraction	0,077908	
Mass of condensate	7,33063	Tonne/h
Mass of steam	0,61937	Tonne/h

Figure 3.14 Flash separation calculations within a spreadsheet.

Feed water balances

In the model the total mass of condensate has been calculated as the sum of the condensate return from the LP level, the liquid fraction of condensate at 4,6 bar(a) leaving the flash vessels (these first two include the amount of water injected to the desuperheaters for the temperature control systems), the return from the condenser turbine CT-2301 and the low pressure condensate return. The rest of the required water is make-up feed water from the water treatment plant. This also include steam vented into the atmosphere, steam used in the flare-towers and the “steam tracing”. Steam tracing, in fact, is used to avoid freezing and to keep the oil product warm during their flow within the pipes and before being pumped.

High-pressured feed water is used for the Pre-Reformer and the Reformer units in the hydrogen production unit (HPU). The supplied water and the percentage of the water that is recovered happen to be measured, and have been taken into account to obtain the correct amount of feed water and make-up water to the steam network. The Figure 3.15 represents the situation.

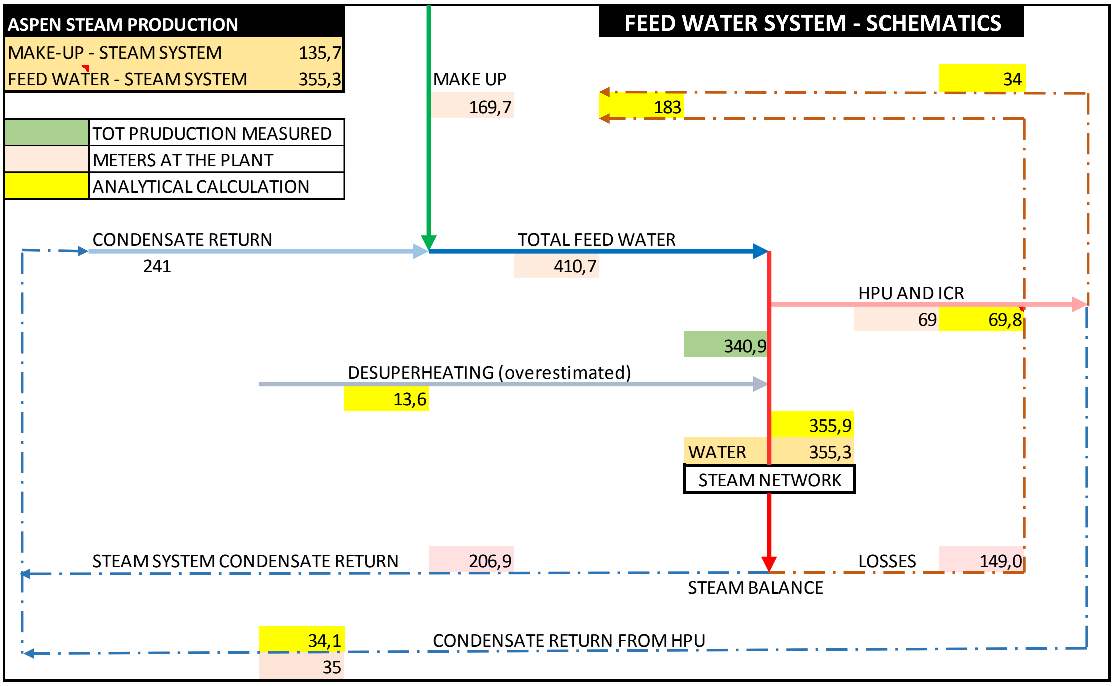


Figure 3.15 Part of the pressured water is used as a process fluid within the Hydrogen Production Unit. All the flows are in Tonne/h. Pink background indicate a variable which is measured. Make up and feed water inserted into Aspen model concern only the steam system.

3.3 Steam layout and general assumption

Now that the water balance has been described, a first schematic of the model flowsheet is drawn. The flowsheet, as can be seen in the Figure 3.16 and Figure 3.17, includes:

- All the main headers;
- all the superheated headers;
- every desuperheater;
- every let-down valve;
- all the turbines present at the refinery (both fixed and switchable, the latter with an indication about how many of them are using steam at the moment);
- productions and consumptions for each header, the latter split between recoverable streams and not (blue and grey arrows);
- vented steam;
- flash separation outputs.

A proper schematic for the boilers (with used fuel gas connection) and the HRSGs is still missing. Every turbine in the spreadsheet is actually a group of turbines operating between the same thermodynamic level and pressure drop (they can even be different located within the plant). Every header presents a mass balance written inside the schematic.

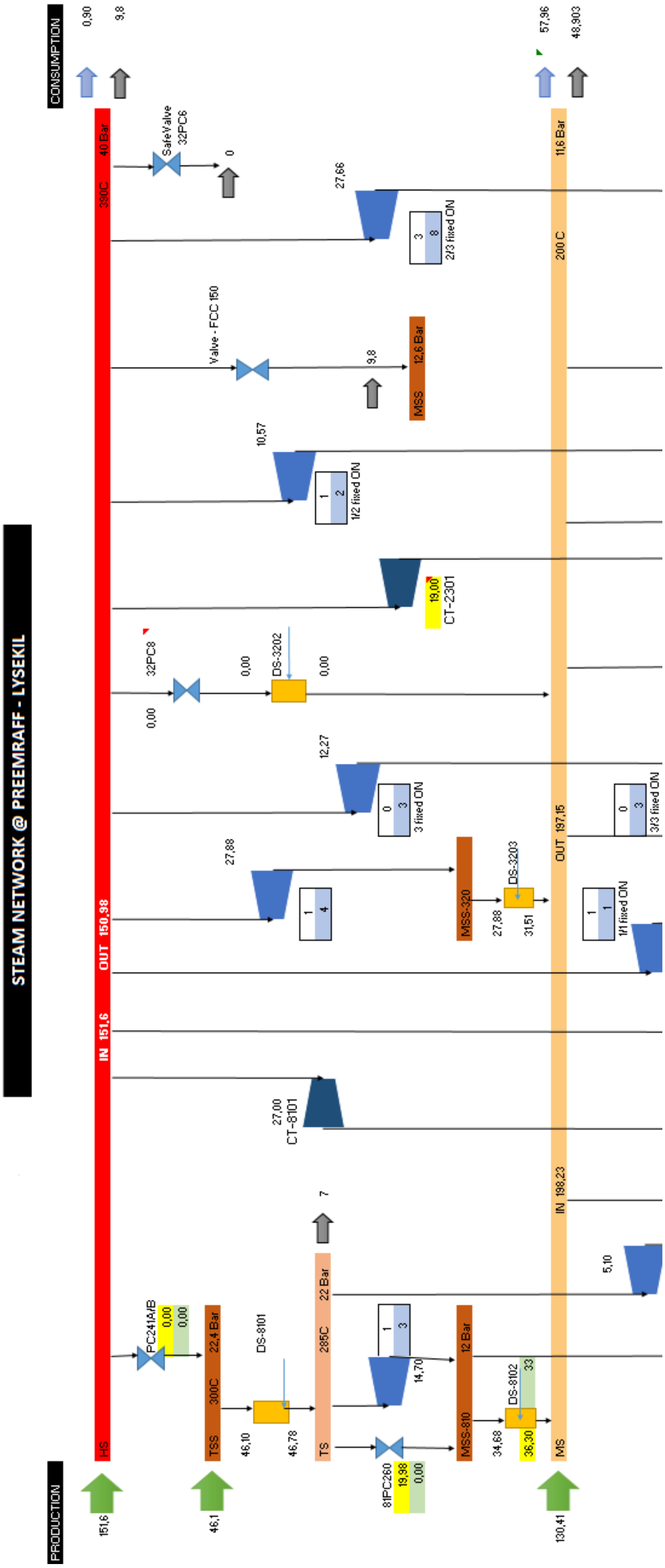
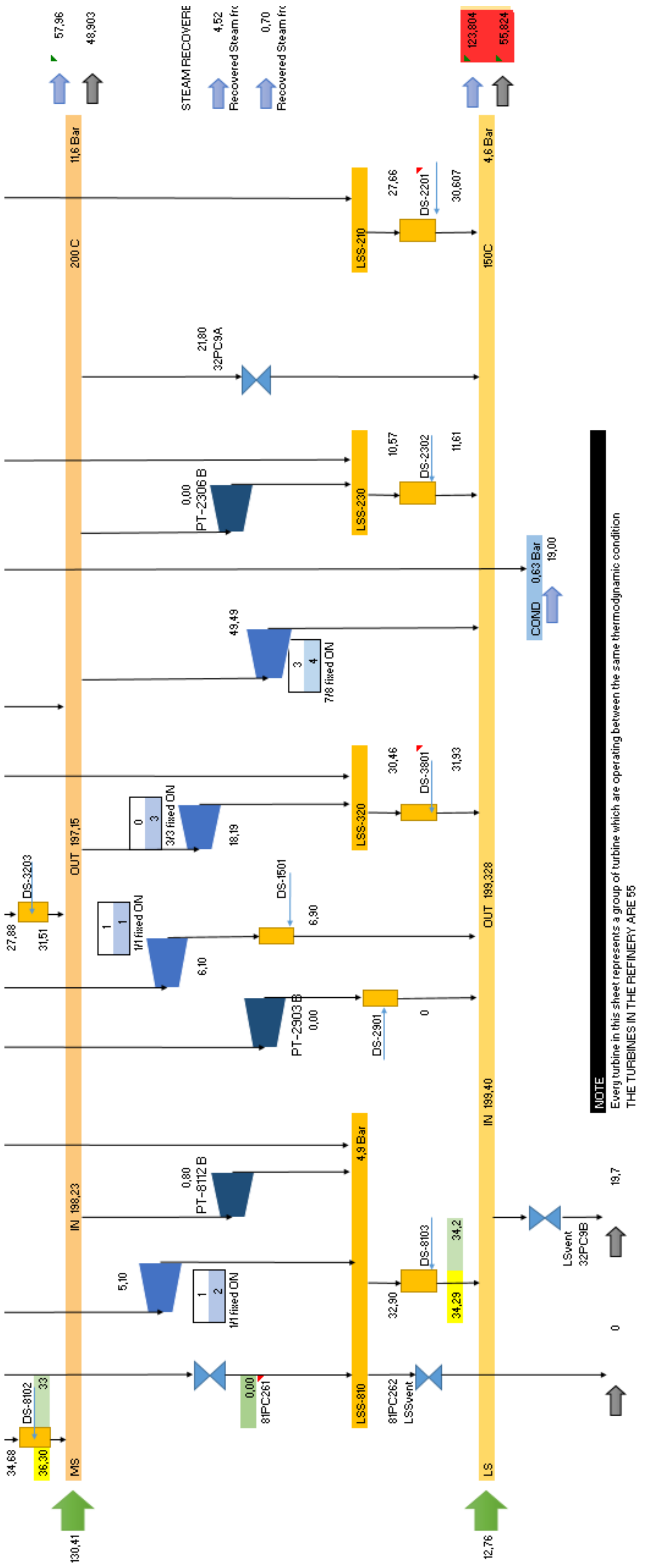


Figure 3.16 Refinery flowsheet: schematic of the high pressure side.



NOTE

Every turbine in this sheet represents a group of turbine which are operating between the same thermodynamic condition

THE TURBINES IN THE REFINERY ARE 55

Figure 3.17 Refinery flowsheet: schematic of the low pressure side.

3.4 Leaks and measurements

Once a complete set of measurements and calculated flows has been collected, some assumptions have to be made to complete the steam balances. Not all steam consumers have a flow meter (especially not the smallest one, such as injectors and small strippers) and sometimes the difference between the production (always well measured) and the consumption is not zero. Targeting a model which comprehends recirculation of water within the steam network and make-up calculation, this differences must be zero. To achieve this, another model (as far as the input data were concerned) has been used to identify the amount and location of steam consumed without being measured. This model, built in Aspen, has been only finalised to data validation and reconciliation (DVR). To do so, all the measured variables at the plant (such as vented steam, streams leaving desuperheaters, letting down valves, and make up water) have been set as input parameters, while two general consumers (one for the condensable steam and one for the unrecoverable steam) has been added to each header. The consumptions within these latter are unknown variables for the DVR-model, whom purpose is to calculate them.

The Figure 3.18 illustrates an example of the described process. Since it is not possible to add other independent equation for these consumers, the only way to solve the system (to have number of unknown variables equal to the number of equations) is to specify other flow rate variables, like the make-up and the vented steam.

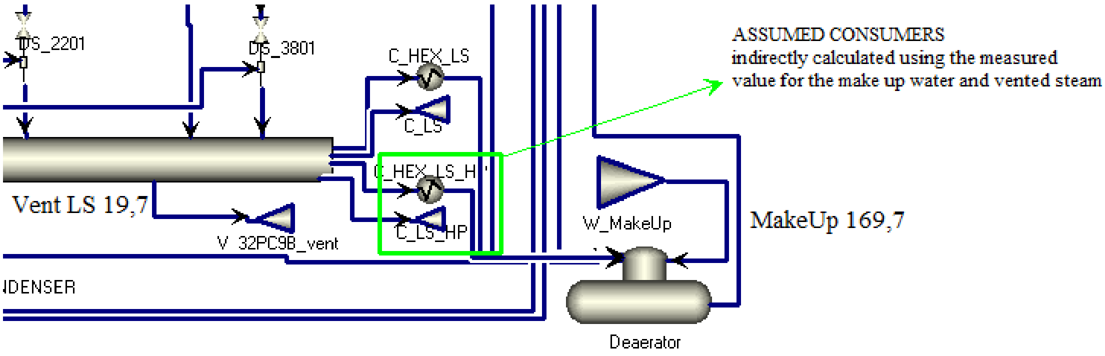


Figure 3.18 Leaks calculation using different model inputs.

The DVR-model outputs are the consumers added to the system and assumed as unmeasured within the refinery. They are listed in the following table:

Table 3.4 Assumed consumptions calculated by the DVR model.

ASSUMED CONSUMERS	HEAT EXCHANGERS CONSUMPTION [Tonne/h]	OTHER CONSUMPTIONS [Tonne/h]
HS HEADER	0	0
TS HEADER	0	0
MS HEADER	0	0
LS HEADER	15	20

These consumers are mostly located in the low pressure header, as there are a number of users without flow meters. This steam:

- Losses spread all around the refinery steam network;
- atmospheric safe valves located in every header and main pipe (not to be confused with venting valves);
- condensate trap along the headers, described in 3.1.2;
- accuracy in turbine calculations, since nominal flow value have been used regarding the smallest turbines. The incoming flow in the downstream header is then overestimated, and could modify the mass balances;
- deareator steam consumption (which is around 10/15 Tonne/h for a medium steam production), used to remove gases (oxygen and other dissolved gases) from the feed-water (steam from low pressure level is also consumed in the deareator).

In the second model, object of the entire thesis, these calculated consumptions (which fix mass and energy balances) have been assumed as a “fixed” variables, besides the measured one. A rigorous data validation process has been made at the end of the first simulation. This process, described in Figure 3.19, designed to find schematic errors within both the flowsheet and the measurements, has pointed out some hot spots at the refinery where the measurements can be questioned.

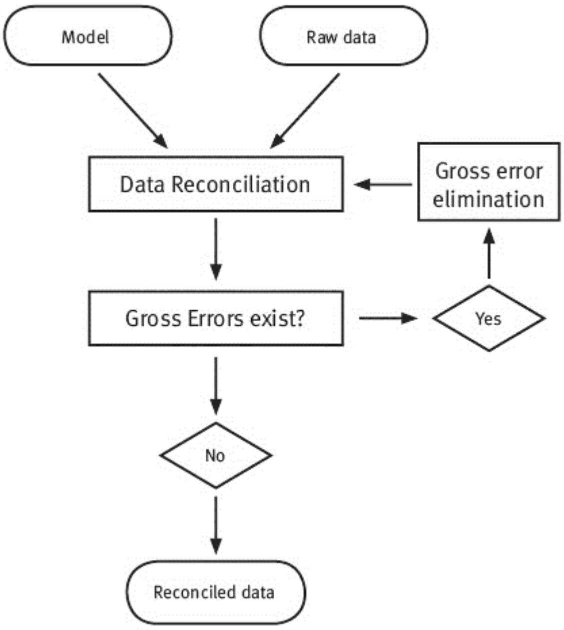


Figure 3.19 Logic process used to detect errors within the model.

Chapter 4

IMPLEMENTATION OF THE MODEL INTO COMMERCIAL STEAM SYSTEM MODELLING SOFTWARE

The AspenTech software packages has been chosen as a software to build up the model in, as these programs are used at the refinery for monitoring and collecting data. In fact, it is important for Preem employees to be able to handle the model and to eventually integrate it in the software availability of the refinery.

4.1 Aspen Utilities Planner

For this modelling the Aspen Utilities Planner has been used either alone or directly integrated with AspenTech’s major software packages, like Aspen-Plus and Aspen HYSYS. These programs are designed to handle steam balances using a method based on the Steam Tables data, which are implemented like any other equation-of-state [19]. To add to this, they include an Excel plug-in that permits the user to link both of the software programs, using for example the Aspen Utilities Planner optimizer to manage Excel spreadsheets data.

Aspen Utilities Planner is an equation-oriented tool for the simulation and optimization of Utility Systems (Fuel, Steam and Power), specially designed to address all the business processes related to the operation and management of utility systems. It can be used to address all the key issues in the purchase, supply and usage of fuel, steam and power within environmental constraints, and provides a single tool to optimize energy business processes and substantially improve financial performance [20].

Like Aspen Plus, Aspen Utilities Planner works upon the flowsheet with a batch simulation, using several blocks (one for each component of the flowsheet) with a proper transfer function for each of them. These functions reflection the behaviour of the unit which they simulate, and the calculation is thoroughly mono-directional, being every block's results the update-inputs for the followers. Every block has a lot of variables that can be easily manipulated. Moreover, it is possible to set upper and lower limits for some blocks, as well as to add an efficiency curve for the ones which are simulating turbines, pumps or compressor. The solver is a linear, oriented solver type and the process is completely iterative: all starts from an input file, which is submitted for processing to the process simulator; the results from the simulation are set to another file, and then the results file is viewed to observe any errors or the calculated results. If errors have occurred or the calculated results are nor reasonable, then the batch simulation must be restarted by updating the input file.

To build the model directly in Aspen Utilities Planner would have been impossible for several reasons: first of all, Aspen Utilities Planner does not have a fully interactive interface like, for example, Aspen Hysys. The program does not permit instant calculation of thermodynamic properties before the simulation is started and finished without errors. Another problem comes from the dimension of the flowsheet and the large number of turbines and the different levels of pressure (four main levels plus several superheated levels). The amount of date the user have to insert into the Aspen model, for each component, is very large. Building the model directly in Aspen without pre-calculation would have led to errors.

4.2 Used Aspen models

The Aspen Utilities Planner incorporates all the main utility components of a steam system such as a refinery's one. Every component is called itself "model" and present a large list of parameters which can be modified by the user according to his purpose. Within the component’s list, every variable can be “fixed” or “free”. The latter ones are calculated indirectly by the program, while the fixed ones are used like input and they make the model under-constrained, “squared” or over-constrained. Each block can be seen like being composed by several components, as shown in the Figure 4.1.

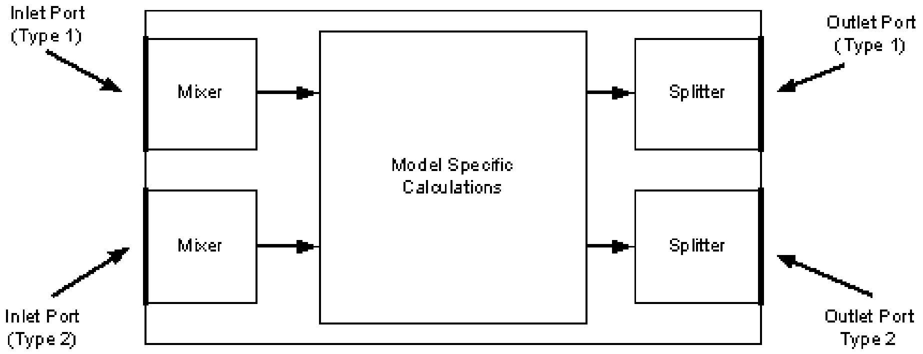


Figure 4.1 Basic scheme for an Aspen Utilities’ Block

For some blocks it is possible to set upper and lower limit for the free variables (used by the optimizer) as well as add an efficiency curve to the blocks.

A description of the blocks used for the steam network modelling and the principal assumption made for each of them will be briefly described.

Steam headers

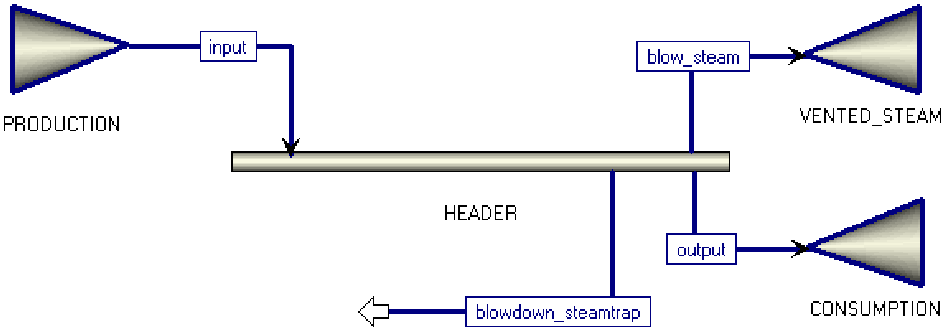


Figure 4.2 Main header model

Main and superheated headers are treated differently in the model. For the *main headers* a lot of measured data are available regarding the inputs and the outputs flows. The output thermodynamic conditions is fixed and the software, reading the inputs from other models in the flowsheet, will estimate heat losses and pressure drop (which must be set as free variables in this case).

For the small, local and always *superheated-steam headers*, the output conditions cannot be fixed since they depend strongly on the number of turbines in operation during every working condition, as well as on the amount of flow coming from the blow-down valves. Thus, since two conditions are missing to solve the header-model, the pressure drop and the heat loss must be set as “fixed”. A lower heat transfer coefficient (due to the superheated condition of the steam) and a smaller dimension will keep these values really small and negligible at the beginning. The output thermodynamic conditions, which will be the incoming flow for the desuperheaters, will be calculated by the software.

The condensate captured in the main headers using steam trap (the blow-down ration measures this percentage) has been assumed equal to zero, while some words have to be pronounced when vented steam is concerned. In fact, the header block presents a dual output for the steam: the main one is the one directly connected with the consumption at the refinery, while the other is a “blow-steam” and represents the vented steam, which is released into the atmosphere due to excesses of steam production and to avoid high pressure. To control this secondary port, some equations have been added manually (Appendix B) and the software will calculate the vented flow backwards starting from the other balances. The variable “blow-steam” has been chosen equal to zero and “fixed” whenever no venting was present at the header.

Pumps for feed water and other services have not been included in the model, if not necessary. Water headers with fixed outlet conditions handle the pressure drop due to a not included pump; in addiction they work as mixers and splitters.

“FixInbalanceFlow” command, in the Aspen block has been set on “yes” for every block and chosen equal to zero, which means that a rigorous mass balance will be made in every header (This consideration is the same for the Power and Water headers).

Steam production

The block chosen to model the *boilers* could also handle the air balance and the flue gas output, but this possibility has not been taken into account, being the purpose of the model focuses on steam side and fuel consumption. The boilers have been modelled with a very simple structure, without adding proper equation for air recirculation or dual fuel possibility. Every boiler is assumed to operate between two different limits of working condition, with a constant efficiency (88%), and they can also be shut down. The consumption of the fuel depends only on the LHV of the fuel. Outlet temperature of the steam and inlet water pressure are fixed, since they are controlled by the process control system, and the blow-down rate is assumed to be 1% as suggested from Preem employees.

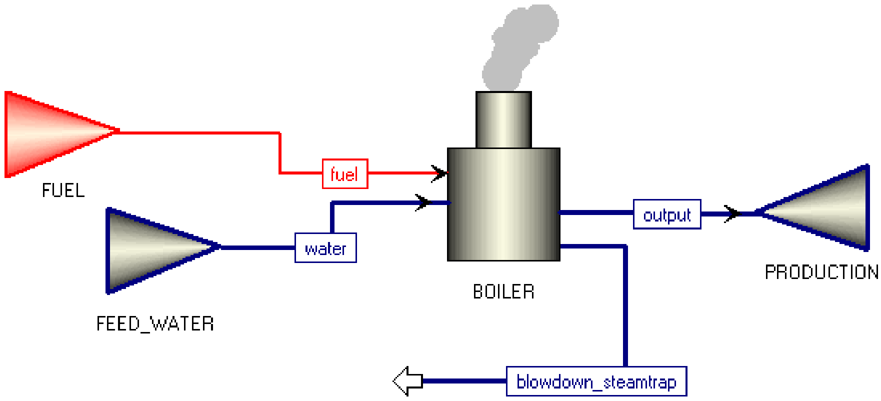


Figure 4.3 Boiler model.

For the *HRSGs* the same assumptions have been made, with the exception that no fuel streams are connected to the blocks. As for the boilers, it is possible to shut them down, bypassing them without the steam network be influenced downstream. Production within these units is assumed fixed during the simulation.

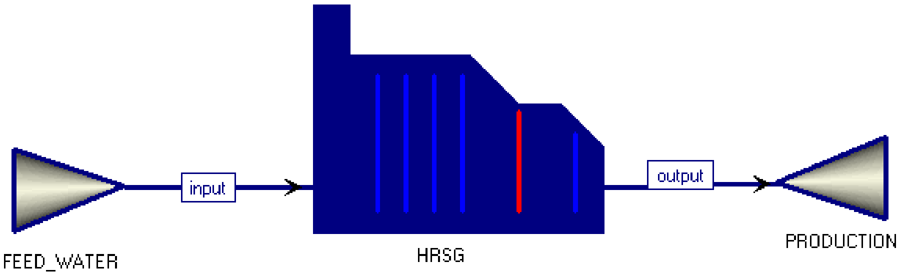


Figure 4.4 HRSG's model.

For the *heat exchangers* producing steam the blocks present different variables, but nothing has been assumed about the "duty" of these components, which have been also grouped into a sole block for each level of pressure. Instead to operating at fixed duty the model will handle fixed outlet temperature, constant pressure and fixed mass flow rate, which is a well measured variable within the plant.

Steam consumption

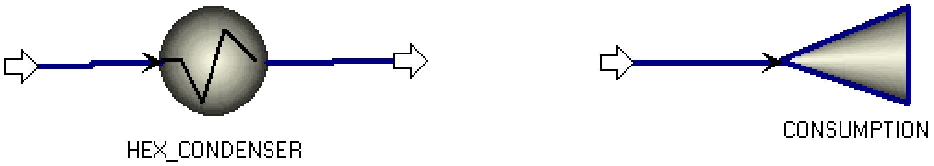


Figure 4.5 Different types of consumption in the model.

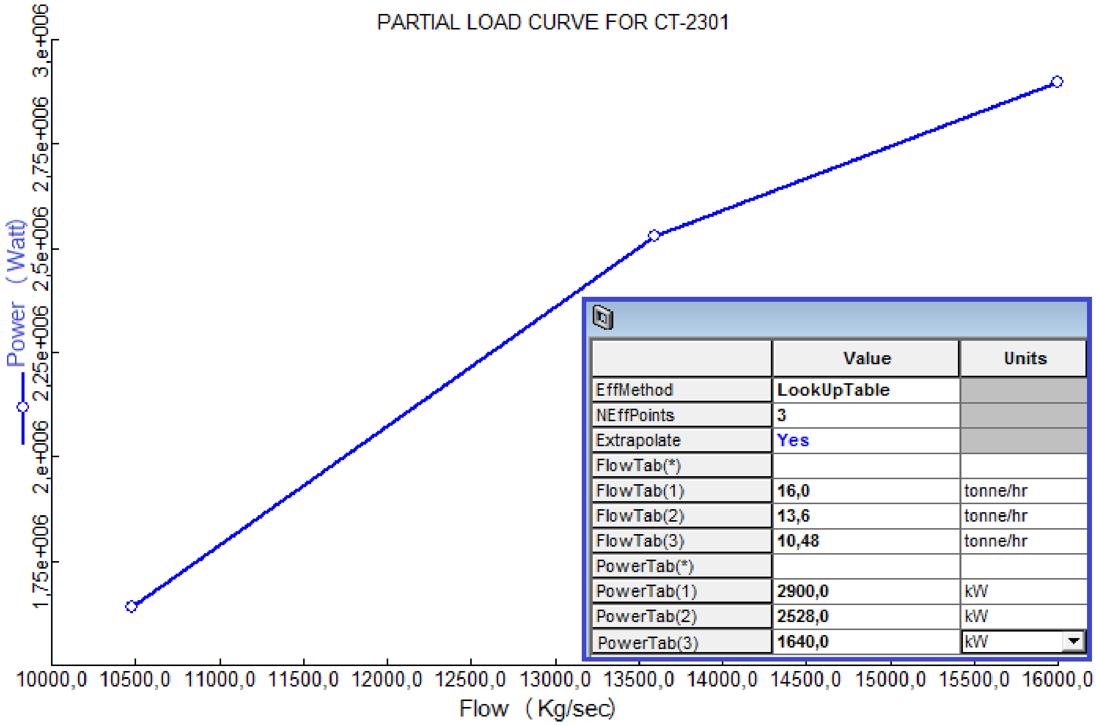
For the heat exchangers consuming steam, a condenser model has been used in the model, in which the only specified variables have been the pressure drop within the exchanger (assumed zero) and the flow rate. The steam is automatically condensed in this block, and the output is saturated liquid.

The other consumers, like towers, strippers, etc., have been considered using a block of "demand", in which only the flow rate must be set. This mass flow is considered lost since it is leaving the network, and it will be replaced using the make-up water. The same consideration have been used for vented steam.

Once again all the streams of the same type, concerning the same header, have been grouped within the same block.

Drivers

For the *high power turbines* at the refinery, a proper turbine block has been used, with the possibility to include the efficiency curve equation. The simulation engine will calculate at every step the value of the mass flow according to the required power and the partial load condition. The Power–Steam flow curve has been interpolated within the turbine block by giving three main point of the efficiency curve obtained in the 3.1.3. The results are shown in Figure 4.6.



	Value	Units
EffMethod	LookUpTable	
NEffPoints	3	
Extrapolate	Yes	
FlowTab(*)		
FlowTab(1)	16,0	tonne/hr
FlowTab(2)	13,6	tonne/hr
FlowTab(3)	10,48	tonne/hr
PowerTab(*)		
PowerTab(1)	2900,0	kW
PowerTab(2)	2528,0	kW
PowerTab(3)	1640,0	kW

Figure 4.6 Curve for the turbine CT-2301 used in the turbine model in Aspen.

For the *switchable pumps*, instead, every group of turbines that can drive pumps and are operating between the same thermodynamic conditions have been places in the block “PumpList” of Aspen (Figure 4.7). The model does not allow to insert an equation for the efficiency of the turbine, but instead use the steam rate and the power required at the shaft in a linear relation, like the (3.6). Moreover, for each pump in the list, it is possible to indicate if it is driven either by electric motor or by steam turbine. The block represents an input for the electric power, and all of them are connected to the main power header.

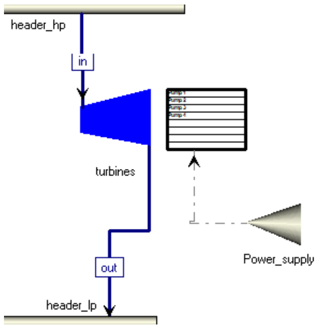


Figure 4.7 PumpList model in Aspen.

Both inlet and outlet pressure are fixed in these drivers blocks. Inlet temperature is fixed and assumed to be very close to temperature in the upstream header.

Flash vessels, deareator and make-up

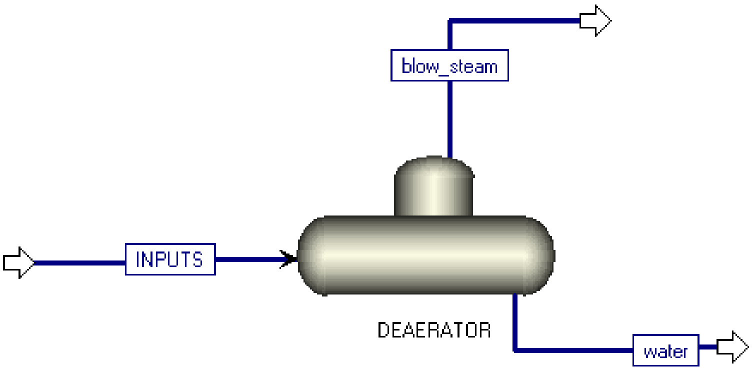


Figure 4.8 Deaerator/Flash vessel Model.

For the *flash vessel*, the only fixed variable is the pressure of the flash, which is the pressure in the downstream low-pressure line and of the condensate line: 4,6 bar(a). The flash block allows two different outlets, one for the steam (connected to the low pressure header), and one for the condensate.

The *deaerator* is handled more or less like a big vessel, in which a lot of equations are added to handle the recirculation of steam within it and the steam vented ratio. Some of these equations have been considered negligible, while another important stream has been added to this block: the *make-up water*.

4.3 Electricity and fuel gas supply

4.3.1 Electrical power consumption

Electricity is used for motor-driven pumps and compressors. To take this consumption of electricity into account a “power header” has been created within the model, and has been connected to all the pumps and compressor in the refinery that could be switched between electricity and steam. To calculate the electrical consumption, the program will have a look at the operating condition of the machine and at an electrical efficiency, as defined in the (4.1), which will handle assumed losses within the electrical network. Other electricity costs, for example regarding the machines always in operation, have not been taken into account.

$$\eta_{Electric} = \frac{Machine\ power\ consumption}{Electrical\ power\ supplied\ from\ grid} = 0{,}98 \qquad (4.1)$$

A “Power feed” block, connected directly with the header, will give information about the Electrical Power consumed in drivers. Since there is no electric energy production within the plant, it is important to take into account the economic impact due to a higher use of the electric drivers. This impact will be analysed in Chapter 7, where Optimization is concerned.

4.3.2 Fuel network

Fuel is consumed only within the steam boilers, as far as the steam system is concerned. The interconnections between the production of fuel gas (composed by several different light distillation products) and the process furnaces spread all around the refinery are not simple to handle and they have not been included in the model. The modelling of the combustion inside the boilers would have to be made carefully and would require more time, overwriting proper equations that suit the real boilers onto the Aspen's ones. Anyway, some different tests have been made on the boiler model and with the aid of a "performance factor" (taken equal to 0,74) it has been possible to reproduce as close as possible the real steam production-fuel gas consumption ratio.

In the model two main type of fuel have been schematized, copying the structure shown in Figure 4.9 that presents a common fuel-header:

- The first one is the mixture of the refinery light products (Hydrogen, Propane, Butane, etc.) and it has been called "Fuel Gas". Its properties, given in the Table 4.1, are calculated using a mean composition of the mixture.
- The second one, called "LNG", represent a make-up fuel, which can actually be either natural gas or liquid expensive product (evaporated to be fireable). It is used as a make-up when the production of the main fuel is poor.

Table 4.1 Fuels used into the model.

FUEL	**FUEL GAS**	**LNG**
LHV [MJ/kg]	37	43
MOLECULAR WEIGHT [kg/Kmol]	35	20

The model has been configured exactly with this purpose: for a given percentage of LNG supplied to the fuel network, it will calculate the total fuel consumption, following fuel-power balances.

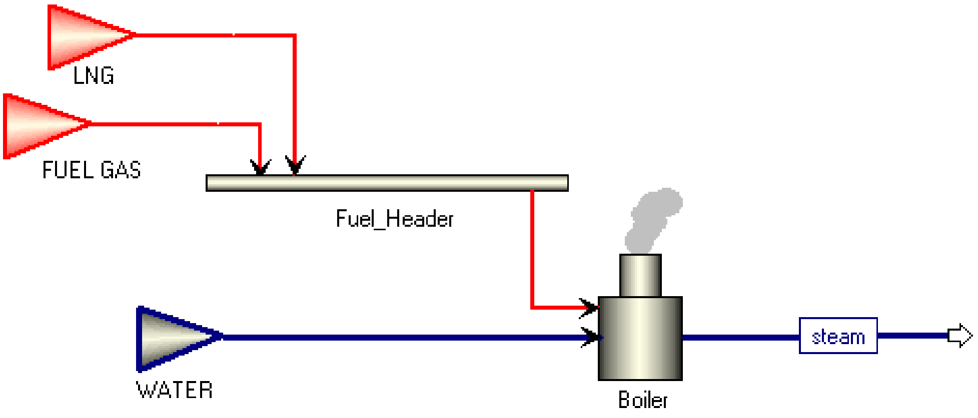


Figure 4.9 Simplified fuel network schematic.

Chapter 5

STEADY STATE SIMULATION

Once every component in the steam network has been modelled and connected, the resulting flowsheet in Aspen can be seen in Figure 5.1:

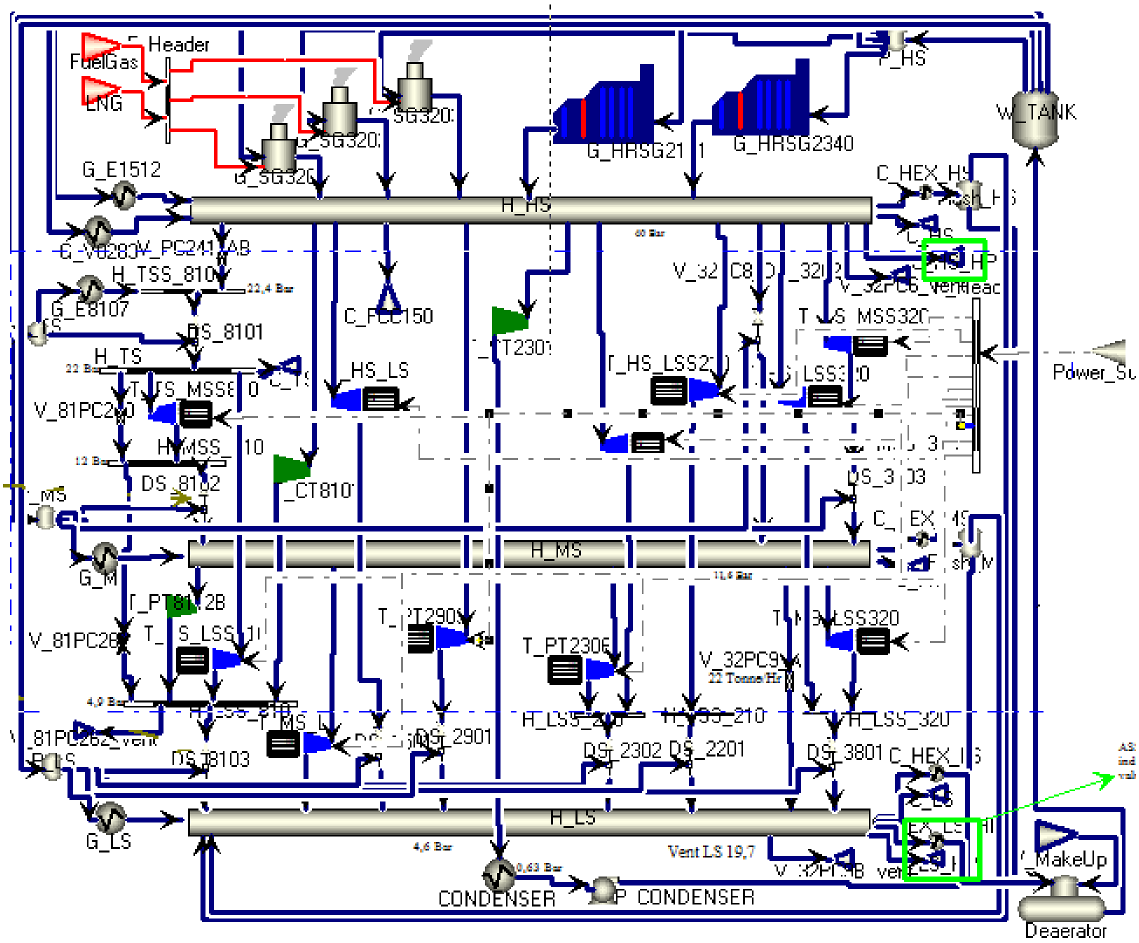


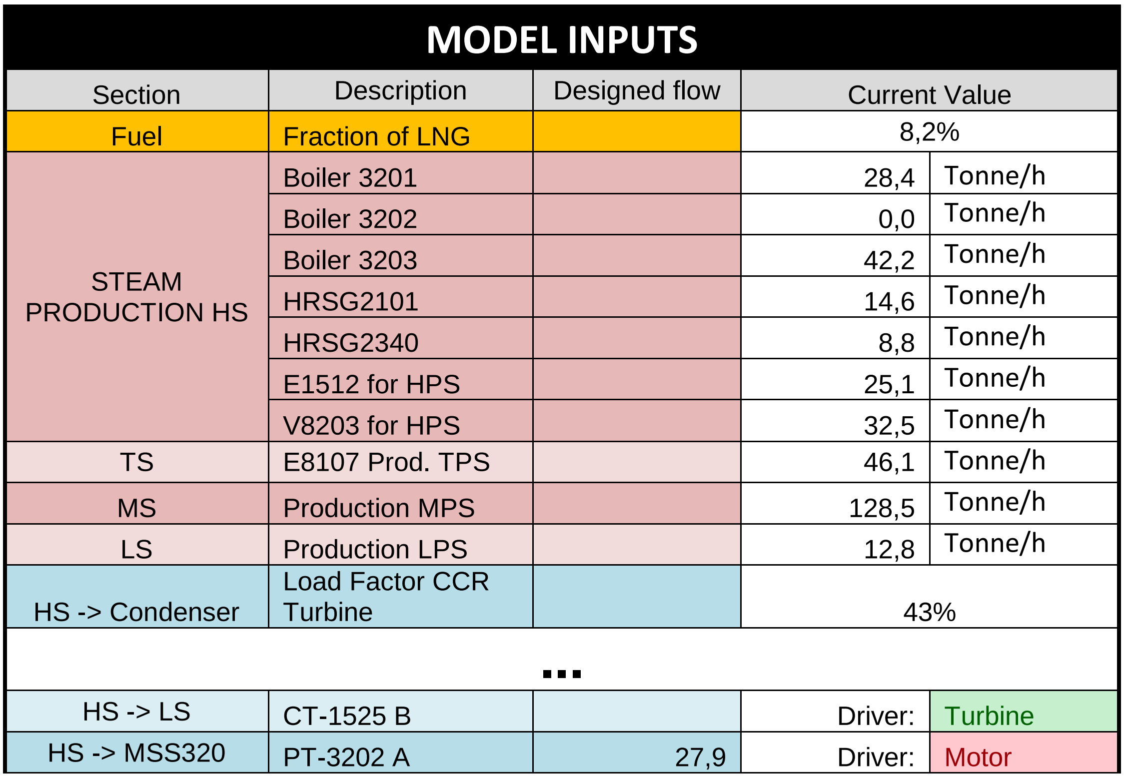
Figure 5.1	Aspen Utilities steady state model.

All the previous blocks described in Chapter 4 have been put together in this model and can be easily observed. Moreover, every block includes a set of equations, which cannot be observed from the picture. This model was first set up with the first working condition chosen, with the data collected the 13th of September at the plant. Then it has been validated with other real working states at Lysekil, to check its reliability. For all the cases the variables in Aspen has been separated into two groups:

- The **fixed parameters**, in turn divided into input parameters (organized in an "Input spreadsheet" directly connected to the Aspen engine through a plug-in) and model parameters. The input parameters (steam consumption, turbine load factor, driver configurations, etc.) will be changed by the user to test different operating condition. The model parameters (concerning the specifications of the components, such as efficiency data, flow limits, etc.) instead, will be kept fixed within the blocks and will not be changed anymore.
- The **free parameters**, which are the unknown values the software-engine will calculate (fuel and power consumption, as well as vented steam and make-up water).

Table 5.1 presents the input spreadsheet used for the model. Note that the LNG fraction is an estimation of the amount of natural gas mixed into the total fuel gas addressed to the steam boilers. For the bigger turbine the power required at the shaft is put as input (through the load factor), while the small ones are assumed to operate at fixed load, with the possibility to turn them on or off in the input spreadsheet (activating the electric motor to move a parallel pump). Some turbines are not included in the Table 5.1: they are the ones that are always in operation with a constant flow of steam. Therefore, there will never be a reason to change the input data for these turbines in the model.

Table 5.1 List of the model inputs.



MODEL INPUTS				
Section	Description	Designed flow	Current Value	
Fuel	Fraction of LNG		8,2%	
STEAM PRODUCTION HS	Boiler 3201		28,4	Tonne/h
	Boiler 3202		0,0	Tonne/h
	Boiler 3203		42,2	Tonne/h
	HRSG2101		14,6	Tonne/h
	HRSG2340		8,8	Tonne/h
	E1512 for HPS		25,1	Tonne/h
	V8203 for HPS		32,5	Tonne/h
TS	E8107 Prod. TPS		46,1	Tonne/h
MS	Production MPS		128,5	Tonne/h
LS	Production LPS		12,8	Tonne/h
HS -> Condenser	Load Factor CCR Turbine		43%	
...				
HS -> LS	CT-1525 B		Driver:	Turbine
HS -> MSS320	PT-3202 A	27,9	Driver:	Motor

	PT-3202 B	27,9	Driver:	Turbine
	PT-3203 A	2,9	Driver:	Motor
	PT-3203 B	2,9	Driver:	Motor
MS -> LS	PT-2905 B	17,0	Driver:	Motor
	PT-2906 B	9,8	Driver:	Turbine
	PT-2343 B	7,9	Driver:	Turbine
HS	Consumption at FCC150		9,8	Tonne/h
	Consumption HPS - HEX		0,9	Tonne/h
	Consumption HPS		9,8	Tonne/h
TS	Consumption TPS		6,7	Tonne/h
MS	Consumption MPS - HEX		58,0	Tonne/h
	Consumption MPS		44,9	Tonne/h
LS	Consumption LPS - HEX		98,5	Tonne/h
	Consumption LPS		48,7	Tonne/h

For a steady state simulation in Aspen Utilities all the variables, both fixed and free, must generate a “squared” system of equation, in which the number of equations must be equal to the number of unknown variables. To do so, no over-constraints must be set into the model, and at the same time enough variables have to be fixed without linear dependencies between them. The engine in some cases will make an iteration to calculate a local solution.

The let-down valves call for a special solution since from some headers steam is let down through more than one valve, and therefore a hierarchical order has been used with a series of equation and an “If - Else” statement written in Visual Basic language. The details of this scripts are in Appendix B.

The added equations allow the model to behave like the real system, letting down steam using a different valve when the main one is at its maximum capacity. The hierarchy followed to make this possible is:

1. Valve or desuperheater of make up between two main headers.
2. Valve of make up between a main header and a secondary, superheated one.
3. Safe valve aimed to vent steam into the atmosphere, when the network is full (these ones in order from the lowest level of pressure to the highest).

5.1 First simulation results

The first steady state simulation concerned the data collected from the working condition of the 13th of September 2015. The results are shown in Table 5.2, and they represent only a part of all the main “free” variables. The turbine outlet flows have been merged together for each group of turbines. In addition to the most important variables (such as vented steam, fuel consumption, etc.) in the general results table some other flows have been listed; these are the ones that have been used for model validation. For these validation variables a flow meter is present at the refinery, for which the measurement is presented in the fourth column of the table.

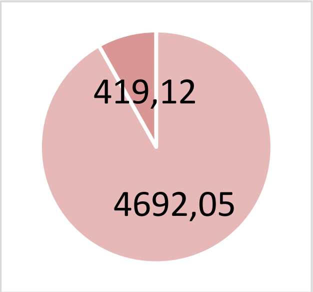
Table 5.2 Output and validation for the first simulation. Relative errors greater than 10% are underlined by red cells. “unm” means unmeasured value.

MODEL OUTPUTS AND DATA VALIDATION

VARIABLE	UNIT	OUT-PUT	MEASUR	ABS ERR	REL ERR
Utilized Feed Water	Tonne/h	352,76	355,16	2,40	0,67%
Utilized Make up	Tonne/h	137,65	134,1	3,55	2,65%
LS venting	Tonne/h	19,33	19,7	0,37	1,88%
LSS810 venting	Tonne/h	0,00	0	0,00	0,00%
HS venting	Tonne/h	0,00	0	0,00	0,00%
HS -> MS valve	Tonne/h	0,73	0	0,73	0,00%
HS -> TS valve	Tonne/h	0,00	0	0,00	0,00%
TS -> MSS valve	Tonne/h	9,00	unm	#VALUE!	#VALUE!
MSS -> LSS valve	Tonne/h	0,00	0	0,00	0,00%
MS -> LS valve	Tonne/h	11,43	21,8	10,37	47,59%
Turbine ICR CT8101	Tonne/h	27,17	27	0,17	0,64%
Turbine TS -> MSS810	Tonne/h	14,70	14,7	0,00	0,01%
Turbine TS -> LSS810	Tonne/h	12,39	5	7,39	147,85%
DS 8102 Steam-out	Tonne/h	24,80	33,2	8,40	25,31%

FUEL CONSUMPTION

Available FuelGas	
4692,05 Sm3/h	
Used LNG	
419,12 Sm3/h	



WATER CONSUMPTION

Utilized Feed Water	
352,7	Tonne/h
Make Up Water	
137,65	Tonne/h

DS 8103 Steam-out	Tonne/h	41,98	34,2	7,78	22,75%
Electric Energy	kW	5531	unm	#VALUE!	#VALUE
Fuel	Sm3/Hr	5111	5132	21,43	0,42%

MAKE UP PERCENTAGE	45,5%

5.1.1 Data validation

In Table 5.2 the results are compared with the real measurements: a fist validation of data has been done by comparing the results of the model with some screenshots of measured values from the refinery. For each value, an error has been calculated, according to the following definition of “absolute error” and “relative error” [21]:

$$E_{absolute} = |x_{simulation} - x_{measured}| \tag{5.1}$$

$$E_{relative} = \frac{E_{absolute}}{x_{measured}} \cdot 100\% \tag{5.2}$$

It should be pointed out that Eqs. (5.1) and (5.2) in addition to the simulation results, use the value of $x_{measured}$ which represents a variable that can be imprecise as well. The real, correct values are unknown and the errors will be in relation to the flow-meter outputs.

This validation process has been useful for identifying some possible equipment failures, such as broken flow meters in the refinery or broken indicators for pump driver switches. In this table, for example, the thirteenth and fourteenth row show a significant relative error and they refer to the same area of the plant. These large errors have been underlined with red cells in the table. The steam flow through the group of turbines working between the TS level and the superheated header LSS810 given by the model is higher than the measured one, and in the parallel desuperheater the result is the opposite. As seen in Figure 5.2, a change of some of the pump drivers operating from the TS to the LS level (in the bottom right-hand corner) from a “turbine-driver” condition to a “motor-driver” condition could fix the error and lead to the conclusion that the indicator for the pump driver is non-working. To add to this, an increment of flow in the DS-8102 would lead to have more steam in the MS header, incrementing in turn the mass flow in the make-up valve between the MS and the LS header. Indeed, the first simulation shows an underestimated value for this valve, indicated in the tenth row of the table.

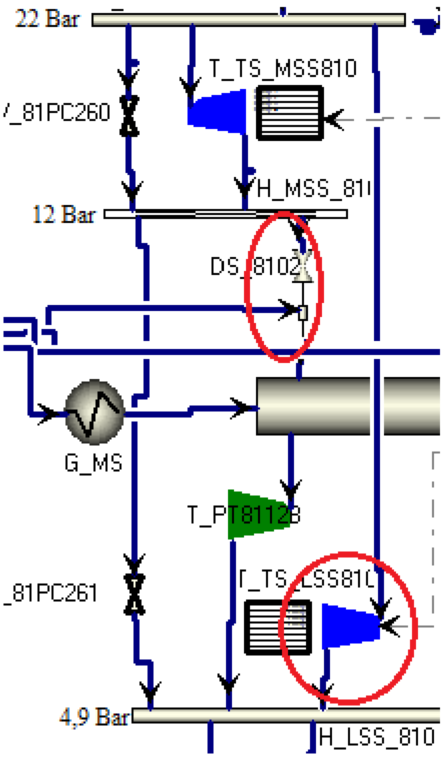


Figure 5.2 Data validation in a model section.

The change of only one of the drivers (the CT-8350) leads to the following results:

Table 5.3 Different output due to a change of the driver.

VARIABLE	UNIT	OUTPUT VALUE	MEAS VALUE	ABS ERROR	RELAT ERROR
Turbine TS -> LSS810	Tonne/h	5,10	5	0,10	1,94%
DS 8102 Steam-out	Tonne/h	32,53	33,2	0,67	2,01%
DS 8103 Steam-out	Tonne/h	34,42	34,2	0,22	0,65%
MS -> LS valve	Tonne/h	21,06	21,8	0,74	3,39%

This data validation step is necessary to check the input parameter data before starting working with any operating case, and it has been repeated for every simulation made.

5.2 Energy flows distribution obtained

For the first, complete, steady state simulation a Sankey diagram shows the distribution of the power (throught steam flows) along the different levels of pressure. Every flow is colored according to the pressure of the header it leaves.

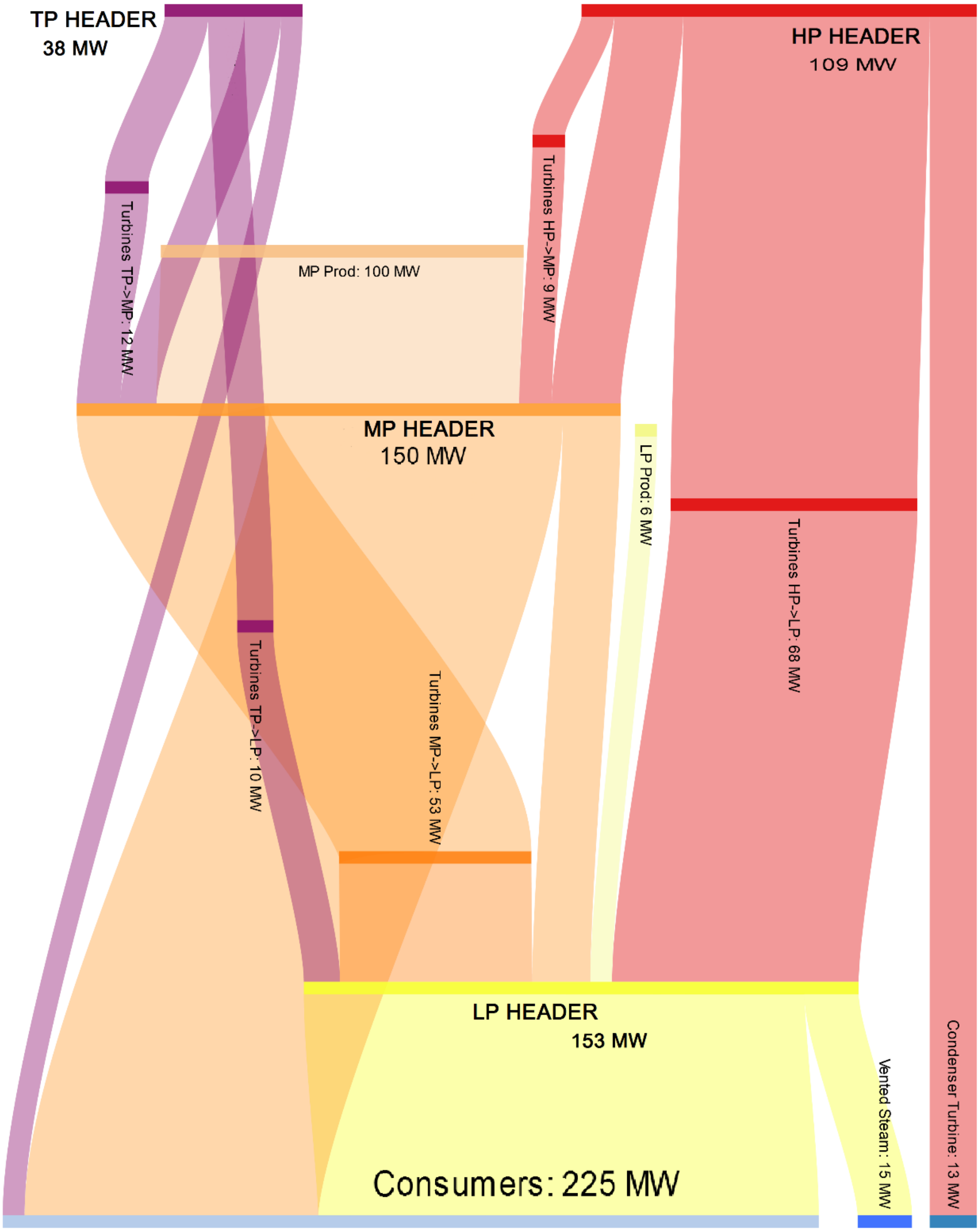


Figure 5.3 Sankey diagram of the steam network showing the results of the first simulation.

As can be seen from the diagram, most of the production takes place in the HS and the MS header (around 100 MW_{th} in each). While the production in the medium pressure header depends a lot on the primary refinery processes, the production in the HS is partially left to the steam boilers. Almost all the steam present in the LS header is used for the various consumers within the refinery (a fraction is vented as well), while as far as the TS level is concerned, it is mostly used to feed turbines discharging steam to the medium and low pressure levels.

5.3 Test with other working condition

Once the model has been validated, it is essential to test it with other different condition. To make this possible another collection of a specific set of measurements has been done. Moreover, the new instants chosen as "real working scenarios" for the model should have been quite different from the first one, in order to investigate the reliability of the steam network model close to the operational limits. With this purpose the following working conditions have been chosen for testing:

- 14th of July 2015: medium steam production (around 200 Tonne/h) condition during a summer night.
- 16th of April 2015: low production condition due to maintenance for some units in the northern area of the refinery (230). Total steam production:100 Tonne/h.
- 12th of January 2016: high production condition during a period in which some components of the hydrocracker unit were off. Steam production: 250 Tonne/h.

The low and high production conditions have been chosen looking at the global high-pressured steam production of the refinery from the control room. The graph obtained putting together the boilers, the HRSGs and the two heat exchangers of the HS level is shown in the Figure 5.4. The blue circles underline the chosen instants.

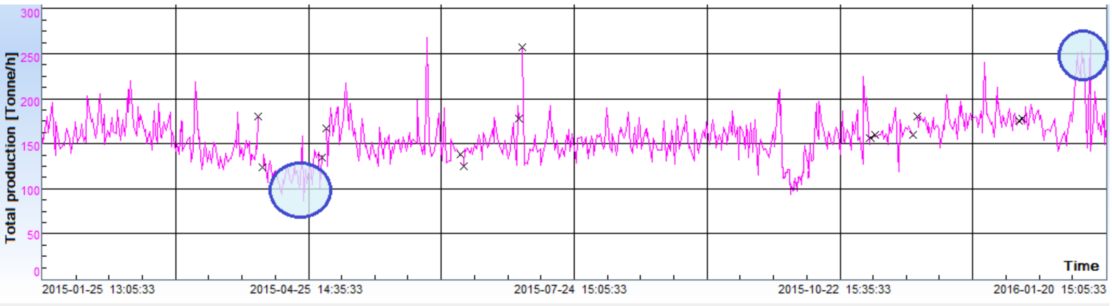


Figure 5.4 Steam production in the high pressure header for an year period.

To handle all the different conditions studied (called scenarios), and especially to compare them, an interactive interface has been built in a spreadsheet with the aid of some useful functions such as "IF, ELSE" and "OFFSET" statements. The interface, shown in Table 5.4, is completely connected to the software engine of Aspen Utilities and has a main cascade selection menu that can completely switch the entire configuration of the steam system from a certain scenario to another one with a mouse click. By changing the configuration the model will receive as input the new production and consumption data related to the selected scenario, as well as the new operating modes for the switchable pumps. The temperatures of produced steam and steam headers have been assumed to be the same for every scenario, as they are controlled in the plant. The left-hand part of the spreadsheet is the active part of the spreadsheet, which will be sent to the model for a new simulation. All the variables listed within this table are model inputs expect the last ones, marked by pink colour: these are the output variables used to check the model reliability and to validate the data; they represent streams within the refinery for which the flow rate is well known from measurement. The right-hand columns list the different scenario input data.

Table 5.4 Interactive interface built within a spreadsheet to switch the model inputs between different scenarios. Light purple in the list underlines production, green consumption and light blue is used for the turbine drivers and loads. Pink at the bottom of the table is used for the data which are measured at the refinery.

SCENARIO SELECTION		**Scenario**		**MedProd Septemb**	**…**	**HighProd January**
		3		**1**	**…**	**4**
		Date	16/04/15	13/09/15	…	12/01/16
		Hour	3:10 PM	3:10 AM	…	7:57 PM
Section	Description	Current Value		Value	…	Value
Fuel	Fraction on LNG	10%		8,2%	…	1%
STEAM PRODUCTION HS	Boiler 3201	11,9	Tonne/h	28,4	…	57,9
	Boiler 3202	12,8	Tonne/h	0	…	72
	Boiler 3203	29,4	Tonne/h	42,2	…	70,9
	HRSG2101	0,0	Tonne/h	14,6	…	0
	HRSG2340	0,0	Tonne/h	8,8	…	21
	E1512 for HPS	19,8	Tonne/h	25,1	…	20,4
	V8203 for HPS	30,9	Tonne/h	32,5	…	0
TS	E8107 for TS level	40,0	Tonne/h	46,1	…	19,1
MS	Production MPS	62,3	Tonne/h	130,41	…	27,41
LS	Production LPS	19,0	Tonne/h	12,8	…	36,0
HS -> Condenser	Load Factor CCR Turbine	0,0%		85,0%	…	80,0%
HS -> LSS810	Load Factor ICR Turbine	90,0%		90,0%	…	0,0%
HS -> LSS320	CT-3402	Driver:	Motor	Motor	…	Turbine
	PT-3801 A	Driver:	Turbine	Motor	…	Turbine
	PT-3802 A	Driver:	Turbine	Motor	…	Turbine
HS -> LSS230	PT-2310 A	Driver:	Motor	Turbine	…	Turbine
	PT-2305 B	Driver:	Motor	Motor	…	Motor
HS -> LSS210	PT-2102 B	Driver:	Turbine	Turbine	…	Turbine
	PT-2102 C	Driver:	Motor	Motor	…	Turbine
	PT-2103 B	Driver:	Motor	Motor	…	Turbine
	PT-2104 A	Driver:	Turbine	Motor	…	Motor
	PT-2107 A	Driver:	Turbine	Turbine	…	Motor
	PT-2201 B	Driver:	Motor	Motor	…	Turbine
	PT-2202 B	Driver:	Motor	Turbine	…	Turbine
	PT-2203 A	Driver:	Motor	Motor	…	Turbine
HS -> LSS	PT-2903	Driver:	Motor	Motor	…	Turbine
HS -> LS	CT-1525 B	Driver:	Motor	Turbine	…	Motor
HS -> MSS320	PT-3202 A	Driver:	Motor	Motor	…	Motor
	PT-3202 B	Driver:	Motor	Turbine	…	Motor
	PT-3203 A	Driver:	Motor	Motor	…	Motor
	PT-3203 B	Driver:	Motor	Motor	…	Motor

TS -> MSS810	PT-8122 B	Driver:	Motor	Motor	…	Motor
	PT-8126 B	Driver:	Turbine	Turbine	…	Motor
	PT-8127 B	Driver:	Motor	Motor	…	Turbine
TS -> LSS810	CT-8340 A	Driver:	Turbine	Motor	…	Motor
	CT-8350	Driver:	Motor	Turbine	…	Motor
MS -> LSS320	PT-3201 B	Driver:	Turbine	Turbine	…	Motor
	PT-3204 B	Driver:	Motor	Turbine	…	Motor
	PT-3205 B	Driver:	Turbine	Turbine	…	Motor
	PT-3206 B	Driver:	Turbine	Turbine	…	Turbine
MS -> LSS	PT-2306 B	Driver:	Motor	Motor	…	Motor
MS -> LS	PT-2905 B	Driver:	Motor	Motor	…	Motor
	PT-2906 B	Driver:	Motor	Turbine	…	Motor
	PT-1524 B	Driver:	Turbine	Turbine	…	Motor
	PT-2343 B	Driver:	Motor	Turbine	…	Motor
HS	Consumption at FCC150	10,1	Tonne/h	9,8	…	9,8
	Consumption HPS - HEX	0,9	Tonne/h	0,9	…	0,9
	Consumption HPS	10,1	Tonne/h	9,8	…	9,8
TS	Consumption TPS	6,5	Tonne/h	7	…	0,749
MS	Consumption MPS - HEX	8,0	Tonne/h	57,96	…	56,7
	Consumption MPS	36,7	Tonne/h	48,9	…	49,44
LS	Consumption LPS - HEX	90,0	Tonne/h	113,8	…	103,86
	Consumption LPS	31,1	Tonne/h	35,8	…	22,405
DATA VALIDATION	Utilized Feed Water	235,5	Tonne/h	355,16	…	304,72
	Utilized Make up	110,0	Tonne/h	134,1	…	65,1
	LS venting	5,2	Tonne/h	19,7	…	0
	LSS810 venting	0,0	Tonne/h	0	…	0
	HS venting	0,0	Tonne/h	0	…	0
	HS -> MS valve	3,0	Tonne/h	0	…	108,7
	HS -> TS valve	0,0	Tonne/h	0	…	22,5
	TS -> MSS valve	unm	Tonne/h	unm	…	unm
	MSS -> LSS valve	unm	Tonne/h	0	…	12
	MS -> LS valve	2,7	Tonne/h	21,8	…	23,5
	Turbine ICR CT8101	27,3	Tonne/h	27	…	0
	Turbine TS -> MSS810	unm	Tonne/h	14,7	…	unm

	Turbine TS -> LSS810	unm	Tonne/h	5	…	unm
	DS 8102 Steam-out	28,8	Tonne/h	33,2	…	7,6
	DS 8103 Steam-out	37,6	Tonne/h	34,2	…	3,5
	Used Electric Energy	unm	kW	unm	…	unm
	Used Fuel	3923,5	Sm3/h	5132,6	…	14748,7

To display the results of all these different simulations within the same interface, another, simpler flowsheet has been built directly in the spreadsheet interface, in which focus is put on the high pressure steam production section (it is possible to look at the amount of steam leaving the boilers and the HRSGs separately) and on the consumption of fuel inside the boilers. In addition, to make the general repartition of the flows easier to understand, neither secondary superheated headers nor desuperheaters have been included. The turbines have thus been grouped again, according to their discharging pressures, and the water flow added to the steam through desuperheating and flash-separation processes is not shown at all. All the white cells represent a value that has been calculated by the model, while the coloured ones are the inputs, except the green ones (which show the measurements). Make up water has been taken into account in a separate spreadsheet.

Figure 5.5 shows this simplified flowsheet for Scenario 3. In this case a low steam production period (only 100 Tonne/h on the high pressure level) is analysed: the production in the HRSGs is zero (they were not in operation because some of the main distillation units were off), as are a lot of turbines in the middle pressure level. It is easy to see how most of the production at high pressure is used for providing shaft power for the pumps through several small turbines between the HS and the LS headers. Downstream, the production in the TS level is at standard level (the ICR unit is running as normal) and there is no large flow rate through the let-down valves between the main headers.

The data validation for this scenario is shown in Table 5.5. Excluding the fuel consumption estimation, the maximum error obtained is an absolute error of 3,5 Tonne/h for a flow rate of 25 Tonne/h, through a desuperheater in the ICR section. Errors in the let-down valves present between two main headers are unfortunately very common, due to the hierarchic order that has been chosen for these components and the steady state condition in which the model is operating. Anyway, even though these errors sometimes are relatively big, they represent only a small amount of steam if compared to the incomes and outcomes in every header. An error of 1 or 2 Tonne/h then has been considered completely reasonable as far as the reliability of the model is concerned.

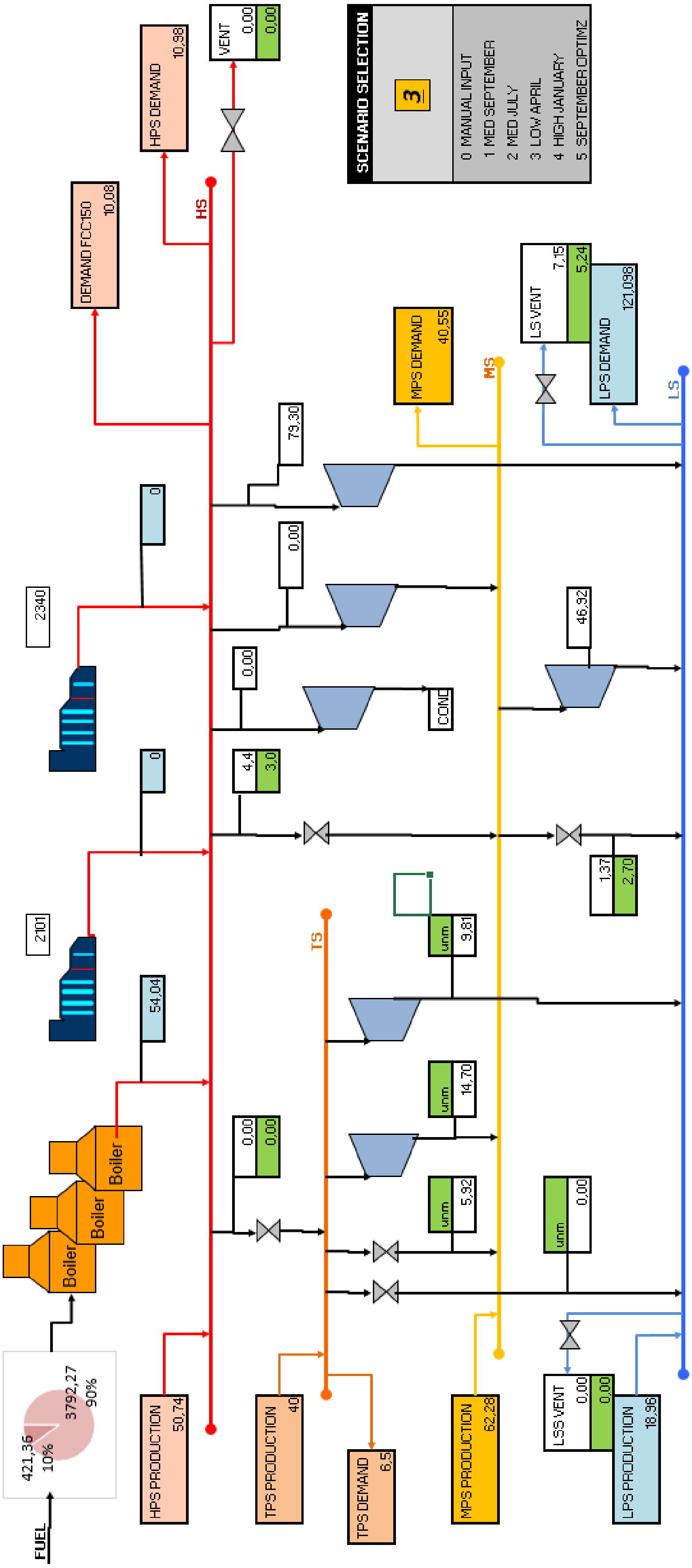


Figure 5.5 Flowsheet built to evaluate the model outputs (Scenario 3).

Table 5.5 Data validation table for Scenario 3. Green underline on a cell indicate a reasonable relative error (Less than 10%).

DATA VALIDATION					
VARIABLE	**UNIT**	**OUTP VALUE**	**MEASUR VALUE**	**ABSOLU ERROR**	**RELAT ERROR**
Utilized Feed Water	Tonne/h	234,61	235,48	0,87	0,37%
Utilized Make up	Tonne/h	107,69	107	0,69	0,64%
LS venting	Tonne/h	7,15	5,24	1,91	36,41%
LSS810 vent	Tonne/h	0,00	0	0,00	0,00%
HS venting	Tonne/h	0,00	0	0,00	0,00%
HS -> MS valve	Tonne/h	4,42	3	1,42	47,48%
HS -> TS valve	Tonne/h	0,00	0	0,00	0,00%
TS -> MSS valve	Tonne/h	5,92	unm	#VALUE!	#VALUE!
MSS -> LSS valve	Tonne/h	0,00	unm	#VALUE!	#VALUE!
MS -> LS valve	Tonne/h	1,37	2,7	1,33	49,43%
Turbine ICR CT8101	Tonne/h	27,17	27,3	0,13	0,46%
Turbine TS -> MSS810	Tonne/h	14,70	unm	#VALUE!	#VALUE!
Turbine TS -> LSS810	Tonne/h	9,81	unm	#VALUE!	#VALUE!
DS 8102 Steam-out	Tonne/h	21,52	25,8	4,28	16,57%
DS 8103 Steam-out	Tonne/h	39,30	37,55	1,75	4,66%
Used Electric Energy	kW	7002,27	unm	#VALUE!	#VALUE!
Used Fuel	Sm3/h	4213,63	3923,53	290,09	7,39%

The data validation tables regarding all the other scenarios are available in Appendix C, were the software retrieved very reasonable results.

In the fourth analysed scenario there are some substantial errors between model outputs and measured data. In this case, even though the estimates for fuel consumption and for the streams related to the rotating equipment are correct, there are quite large errors concerning vented steam and make up water. These type of errors are however connected each other, and indicate a dynamic behaviour of the system that, especially in this particular case, should have been taken into account. In fact, the time frame simulated in the fourth scenario concerns the middle of a day during which the entire hydrocracker unit had been shut down. Dynamic phenomenal, like for example shift in pressure at the different steam pressure levels, could lead to mismatches in the mass balances (a no-more steady state condition and so a no-negligible time derivative would modify the (3.3) and (3.4), written assuming constant pressure). Looking at the flow of make up water shown in Figure 5.6, this dynamic response is evident. The water consumption of the entire network is steadily decreasing duting the time (the shutdown of one unit changed the configuration of the utility network and the steam request downstream) following a sinusoidal function that depends in turn on the control system.

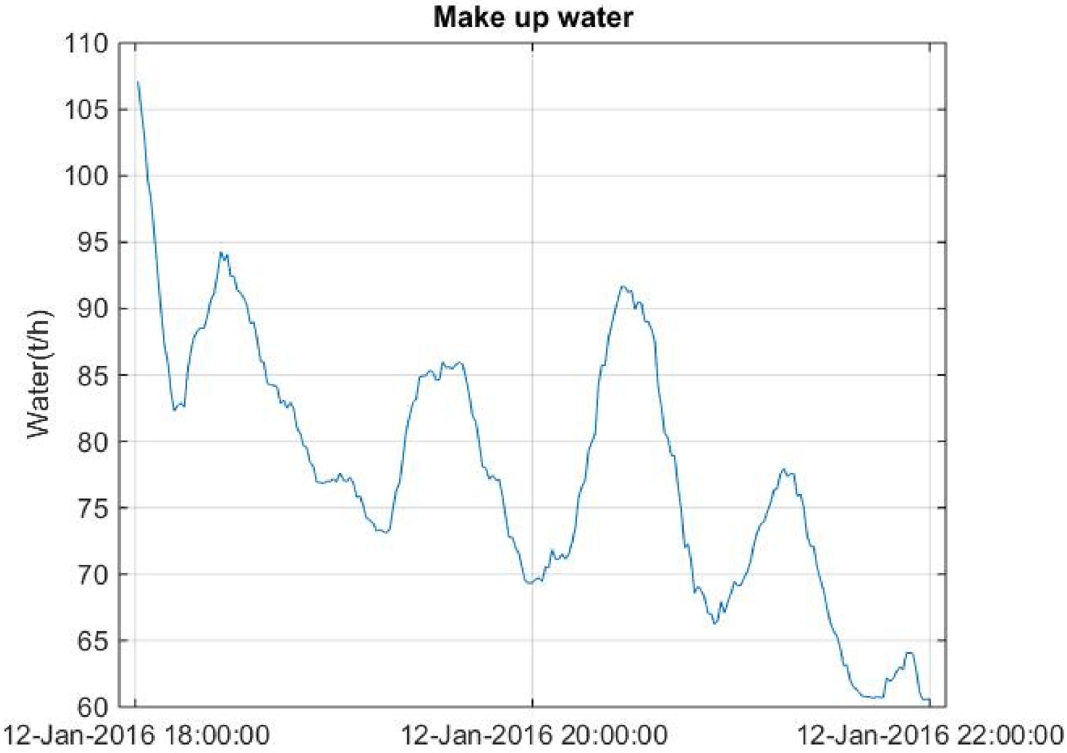


Figure 5.6 Make up water plotted for a four hours interval.

In spite of these considerations, this scenario should not be seen as indicative of flaws in the model, which worked very well for the other cases. Rather it should be seen to illuminate that a steady state model is only accurate when the system is in steady state. For modelling cases with dynamic behavior a dynamic analysis of the system is required, which would take into account pressure variations in the headers. No such errors were identified for the other cases.

Chapter 6

USE OF THE MODEL FOR PREDICTIVE PURPOSE

A model of the steam system has been tested and validated with real steady state data in Chapter 5. The main purpose and use of this model is to be able to analyse the change in flows after a modification imposed on the steam balances. To do so, a “manual INPUT” scenario has been added to the interface described previously, in turn connected to a spreadsheet for model inputs management. By selecting “0” in the scenario menu (the tag for the manual input), the values in the right part of the spreadsheet will be ignored and it will be possible to define a complete steady state simulation with a new set of values which does not even have to respect the equipment configuration in the refinery, but show for example the effect of a retrofit.

6.1 Example of a retrofit analysis

One of the retrofits proposed during the studies about the refinery concerned a reduction of the steam production in the exchanger E-8107 by 7,5 MW and a 8 MW thermic power saved in process furnaces. These changes will be inserted into the model in terms of mass flow and volumetric flow.

Analysing the E-8107, which has an annual average flow rate of 36 Tonne/h (Solomon Study) and works with a constant enthalpy drop of around 2300 kJ/kg, in every possible scenario the proposed retrofit will reduce the total duty by approximately 33% and the flow rate by 12 Tonne/h. The energy balance for the heat exchanger is in fact:

$$\dot{m}(\Delta h) = \dot{Q} = 7{,}5\ MW \tag{6.1}$$

Regarding the steam boilers, instead, the effect of the retrofit will depend on the refinery gas production:

Overproduction of refinery gas

During an overproduction period, in which no LNG is imported and the HRSG are bypassed, a saving of 8MW in other heaters at the plant will lead to increase the availability of the usable fuel gas in the boilers. Using the efficiency of the boilers (88%) and the enthalpy difference over the boilers of 2450 kJ/kg, the potential change affecting the steam production due to the fuel gas saving is calculated to be:

$$\frac{8000\ kW * \eta_{Boiler}}{2450\ kJ/Kg} * 3{,}6 \approx 10\ Tonne/h \tag{6.2}$$

This amount of steam is close to what is lost from the production in E-8107, which is the only steam producer of the TS header. Using the let-down valve between the HS and the TS level, it is possible to supply the same amount of steam, keeping the working configuration for the rest of the system largely unaffected. This situation is the same even if the quantity of fuel that has to be fired in the boilers is large, since the boilers at the refinery present an overdesigned capacity. During these periods, then, the retrofit effect is to move part of the consumption of fuel gas from the process unit to the steam system, reducing production of steam in the TS pressure level.

Low or medium production of refinery gas

During the other refinery-gas production regimes, the entire mixture of fuel will have an amount of LNG decreased of the 8MW concerning the retrofit. Using the Lower-Heating-Value previously defined, the mass flow of LNG which could be saved is:

$$\frac{8\ MW}{43\ MJ/Kg} * 3{,}6 = 0{,}67\ Tonne/h \tag{6.3}$$

The model of the steam network in this case will be useful to investigate what happen to the stem network if the high pressure steam production does not increase to face the lack of production in the E-8107, imposed by the retrofit.

The following picture compares the results of a pre-retrofit simulation with those of a post-retrofit simulation.

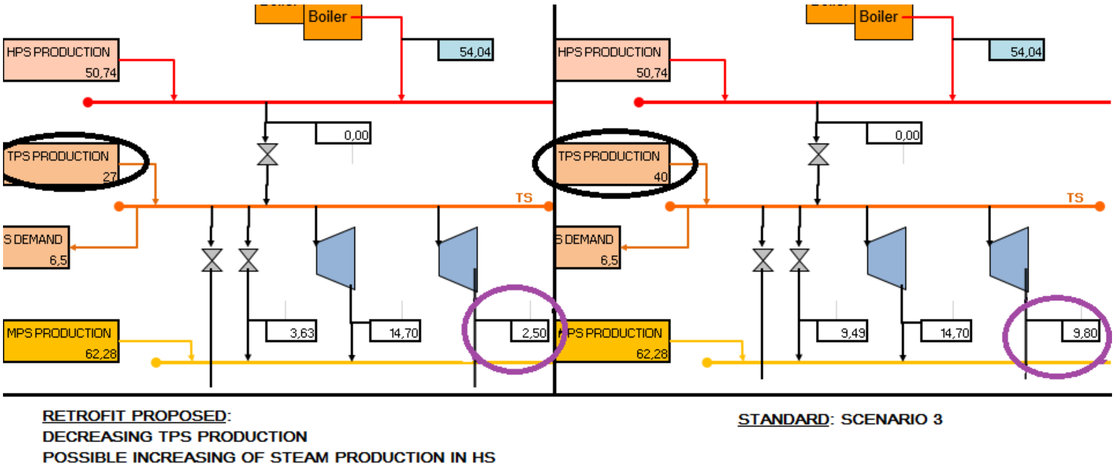


Figure 6.1 Effects of the proposed retrofit within the steam network.

The post-retrofit results show a production of steam which is not sufficient to satisfy the turbine requests downstream. In fact, as can be checked by looking in Figure 6.1, one of the turbines downstream fed by the TS pressure steam must be turned off because of the lack of steam in the header. To verify how important this loss is, further analysis about electric energy costs would be necessary.

However, the total turbine request downstream (assuming all the turbines in operation) is more than 40 Tonne/h: a reduction in the production of the E-8107 implies higher make-up from high pressure header all over the year, or an intensive reduction of the turbine utilization in the ICR section at the refinery, accompanied by a large consumption of electric energy for the motors in such area. The production of steam in the high pressure level could increase, importing make up gas of vaporizing sellable products. The choice, once again, is strongly related to the market prices of electricity, LNG and sold products.

Chapter 7

OPTIMIZATION OF THE STEAM NETWORK OPERATION

The global steam request within the units of the refinery is relatively stable compared to the gas-phase fuel production within the distillation towers, which can vary a lot according to the weather, the crude formula, and to the efficiencies of other processes. The steam production in the boilers, in turn, depends strongly on the amount of this fuel gas coming from refinery processes, as well as on the demand of steam coming from the switchable pumps (if they are powered either by electric motors or steam turbines). Figure 7.1 summarizes the described situation:

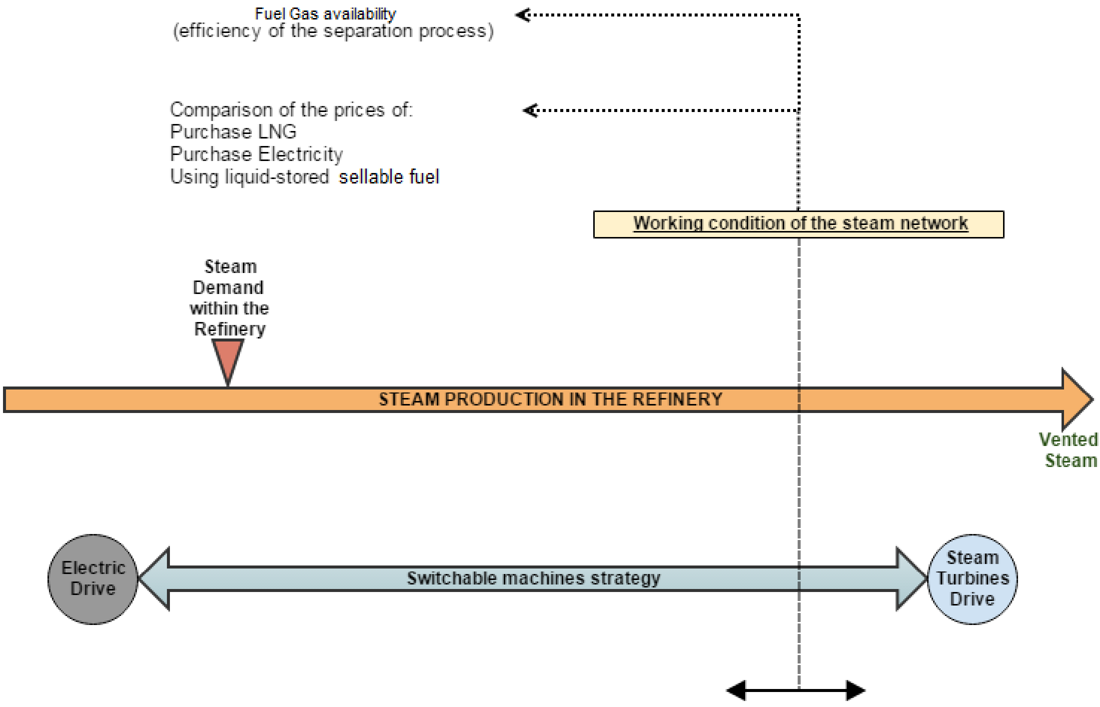


Figure 7.1 Switchable machines strategy summary

The working condition, indicated by the dashed vertical line, is not mathematically optimized nowadays to achieve the best economic target. The market prices of imported fuel and electric power are not constant over time, and this situation leads to a trade-off:

- An intense use of electric motors to move the pumps means less demand of steam, thus less amount of vented steam and less imported fuel consumption in the boilers. A lot of electricity is imported though.
- A high level of imported fuel, on the other side, leads to an elevated use of the direct-drive steam turbines to move the pumps, and to a higher amount of vented steam downstream: in this condition a large amount of electric energy is saved.

When the steam demands and the production from heat exchangers in the network are known, and by evaluating the different market prices for imported fuel and electric power, it is possible to use the steam network model to find an optimized operating condition, which can also include the possibility to shut down one or more boilers and thereby changing considerably the steam production upstream. In order to be able to identify an optimal solution some constraints (consisting in limits and production/consumption inputs) have to be fixed.

7.1 Creation of data profiles in Aspen editor

The first step to enable running the steam model in optimization mode is to create “weak” constraints that define the limits between which the optimizer will operate. The number of constant parameters in this optimization problem will be less than the number of fixed variables used in the steady state simulation: the system will be free to move between an infinite set of working condition and hopefully will be able to achieve the best solution according to an economic saving criteria.

The large set of variables will also present a geographical information for each stream or component, according to the dials described in 2.2.1. This distinction is important because it adds another useful constraint for the flow variables. For instance, if steam is produced in the West dial of the refinery and the optimizer has evaluated the possibility to change one of the drivers to one of the steam turbines, it will first choose a turbine located in the same dial, minimizing the flow losses (for a certain flow rate).

Three different types of database have been created in the Aspen’s flowsheet environment, to handle three different types of constraints:

- **Demand database:** constant parameters that the optimizer have to keep.
- **Availability database:** flow limits of pipes and components as well as switchable drivers control.
- **Tariffs database:** set of tariffs for the importation of electric energy and LNG.

All these profiles are related to each other through a Microsoft Excel interface, with the structure presented in Figure 7.2: The Profile Editor (which is the editor for the Demand, the Availability and the Tariffs databases) can operate between several periods. Multiple periods can be part of the same scenario, with same inputs but variable utility costs. The optimizer has been configured to operate with any scenarios, in an interface made only for this network. The following schemes and table, however, will show only the results concerning one scenario, precisely the stable condition of the 13th of September, and without using multiple periods. All the profiles and tariffs data are stored in Microsoft Access files. When an optimization run, all the fixed and free variables specified in the Aspen flowsheet will be overwritten by the pieces of information present in the optimizer editors. Any specification present in the flowsheet, then, will not be taken into account.

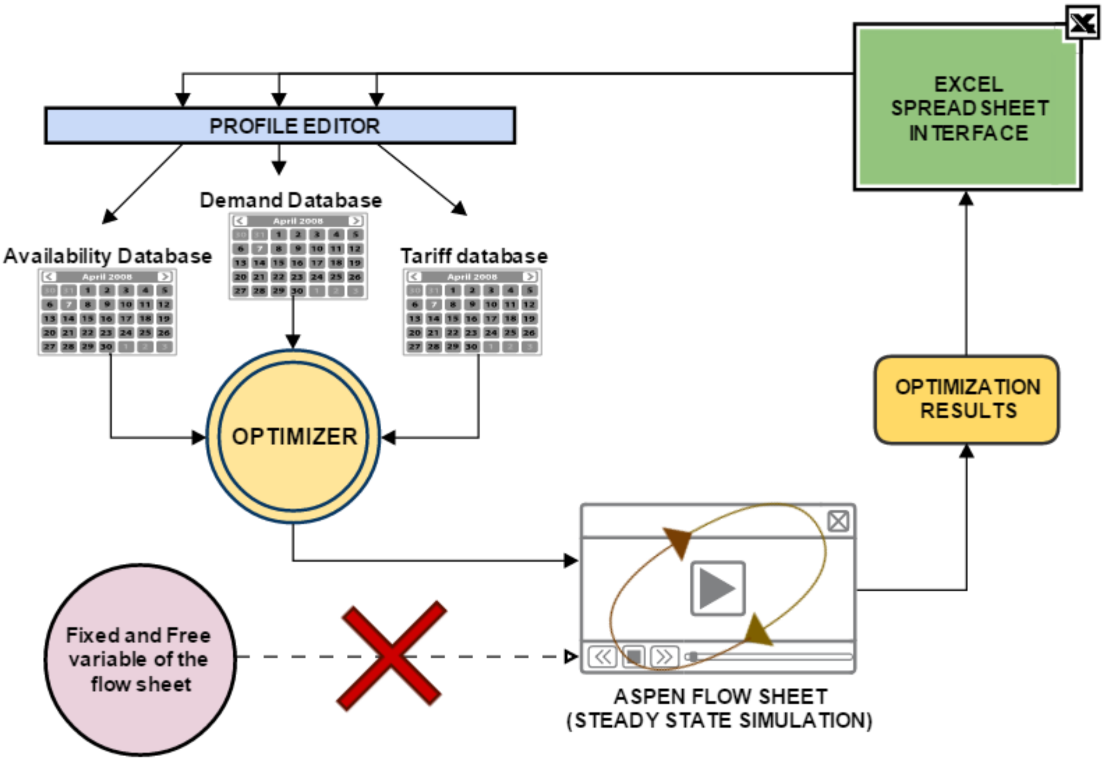


Figure 7.2 Optimizer structure in Aspen Utilities Planner.

7.1.1 Demand profile

The demand profile editor is the “Input list” of the optimizer, and it includes all the fixed variables of the simulation model that have to be kept as fixed parameters also during the optimization process. They are all listed starting from the top left-hand corner of Table 7.1 and, as can been seen, they are defined by a single value.

Indeed, this profile editor represent only the parameters that do not change even if the optimizer generates a different configuration (for a specified time-instant): for example all the consumptions and the production directly related to the refinery units at the analysed instant are included here. In this profile editor the power required from all the turbines at the refinery has been specified (Both switchable and non-switchable machines). If a valve had been closed for some reason, it would also have been specified in this editor. Steam production from waste heat recovers (related to the specific instant analysed) is also specified in this editor.

7.1.2 Availability profile

The second profile editor is the one used to define all the limits in which the optimizer has to operate, as applied constraints. The right-hand side of the Table 7.1 shows this profile editor. Valves and desuperheaters are listed according to the range of flow rate they can handle. Boilers and HRSGs are presented with their production limits (the upper limits for the HRSG are not fixed for every condition but it is a function of the recoverable heat) and in addiction a parameter called “availability” defines the possibility to completely exclude them. If the optimizer decides to shut down either a boiler or a HRSG equipment, the flows through this equipment are set to zero and the component will be categorized as “Shutdown”. As a result, the related equipment design equations are excluded from the model and related variables are changed to Fixed to keep the model Square. Also, to fix a position for those types of turbines which are not switchable and must be either always in operation or shut down because of maintenance, every element of the “PumpList” model has be defined as:

- **Available:** the optimizer is allowed to switch its driver between “steam” and “electric” driver.
- **Must be ON:** the optimizer is not allowed to switch the driver, fixed on “steam” driver.
- **Not in Operation:** the optimizer is not allowed to switch the driver, fixed on “electric” driver.

The boilers availability limit (the maximum and minimum production for each of them) has been modified compared to the one provided in the datasheet, according to the measurements of the production, since the real production present a quite different limit.

The valves and desuperheaters have been defined according to the datasheets and the maximum amount of flow they can handle.

7.1.3 Tariffs profile

Aiming at minimization of the total utility cost, it is necessary to define the prices of each purchased or sold utility. The tariff profile editor is used to enter this information. The tariff structure defined contains two components, the “contracts” and the “tiers”. In the profile editor contracts and relative tiers have been created. Multiple tiers can be used to handle those types of contracts in which purchasing prices vary non-continually with usage or usage rate. Since this optimization is intended as a test for showing what could be realized in the future, a simple mono-tier structure will be kept, with a fixed price for every energy unit. To make the problem simpler, only two main contracts have been created, regarding the imported LNG and the imported electric energy. Make up water cost has been considered as negligible, while the gas produced within the plant does not have to be purchased. In the bottom left-hand corner of the Table 7.1 the links to the tariffs editor are shown.

Both the contracts have only a fixed value of purchasing unit, and they have been assumed to be “Rate of energy” type contracts (different from a “usage” type, in which the user pays a fixed amount for a given energy). Personalized equations and time series could be put within the contracts, supported by several variables like marginal costs, load shedding and start/stop costs of the components. These functions are further explained in Appendix D.

Table 7.1 Profile and Tariff editors of the optimizer.

OPTIMIZER INPUTS (DEMAND)

Variable	Section	Description	Demand	Unit
FLOW RATE	HS	HRSG2101	14,6	Tonne/Hr
		HRSG2340	8,8	Tonne/Hr
		E1512 for HPS	25,1	Tonne/Hr
		V8203 for HPS	32,5	Tonne/Hr
	TS	E8107 for TS level	46,1	Tonne/Hr
	MS	Production MPS	130,4	Tonne/Hr
	LS	Production LPS	12,7	Tonne/Hr
SHAFT POWER	HS -> Cond	Load Factor CCR Turbine	85%	
	HS -> LSS810	Load Factor ICR Turbine	90%	
	HS -> LSS320	BT-3201	298	kW
		BT-3202	166	kW
		BT-3203	166	kW
		CT-3402	423	kW
		PT-3801 A	181	kW
		PT-3802 A	113	kW
	HS -> LSS230	PT-2310 A	324	kW
		PT-2307 A	363	kW
		PT-2307 B	363	kW
		PT-2305 B	209	kW
	HS -> LSS210	PT-2102 B	664	kW
		PT-2102 C	664	kW
		PT-2103 B	207	kW
		PT-2104 A	265	kW
		PT-2107 A	304	kW
		PT-2110 A	266	kW
		PT-2110 B	266	kW
		PT-2112	233	kW
		PT-2201 B	207	kW
		PT-2202 B	204	kW
		PT-2203 A	347	kW
	HS -> LSS	PT-2903	614	kW
	HS -> LS	CT-1525 B	265	kW
		PT-1534 B	15	kW
	HS -> MSS320	PT-3202 A	671	kW
		PT-3202 B	671	kW
		PT-3203 A	80	kW
		PT-3203 B	80	kW
	TS -> MSS810	PT-8122 B	82	kW
		PT-8126 B	251	kW
		PT-8127 B	244	kW
	TS -> LSS810	PT-8110 A	100	kW
		CT-8340 A	282	kW
		CT-8350	100	kW
	MS -> LSS320	PT-3201 B	84	kW
		PT-3204 B	82	kW
		PT-3205 B	84	kW
		PT-3206 B	32	kW
		PT-3301 A	92	kW
	MS -> LSS	PT-2306 B	19	kW
		PT-8112 B	16,33	kW
	MS -> LS	PT-2905 B	380	kW
		PT-2906 B	240	kW
		PT-3701 A	6	kW
		PT-3701 B	6	kW
		PT-1511 A	127	kW
		PT-1511 B	127	kW
		PT-1524 B	97	kW
		PT-1901 B	22,3	kW
		PT-2412 B	15	kW
		PT-2413 B	15	kW
		PT-2314 B	45	kW
		PT-2343 B	114	kW
FLOW RATE	HS	Consumption at FCC150	9,8	Tonne/Hr
		Consumption HPS - HEX	0,9	Tonne/Hr
		Consumption HPS	9,8	Tonne/Hr
	TS	Consumption TPS	7,0	Tonne/Hr
	MS	Consumption MPS - HEX	58,0	Tonne/Hr
		Consumption MPS	47,0	Tonne/Hr
	LS	Consumption LPS - HEX	110,0	Tonne/Hr
		Consumption LPS	35,8	Tonne/Hr

TARIFFS AND PRICES

	Energy type	SEK/Unit	Unit
PRIMARY ENERGY	ELECTRIC ENERGY	0,01	kWh
	NATURAL GAS (LNG)	1	MJ

OPTIMIZER CONSTRAINTS (AVAILABILITY)

	Description	Availability	Min	Max
PRDCTN	SG 3201	Must Be On	0	50
	SG 3202	Available	0	50
	SG 3203	Available	0	50
	HRSG2101	Must Be On		
	HRSG2340	Must Be On		
SWITCHABILITY PROFILE	CT-2301	Must Be On		
	CT-8101	Must Be On		
	BT-3201	Must Be On		
	BT-3202	Must Be On		
	BT-3203	Must Be On		
	CT-3402	Available		
	PT-3801 A	Available		
	PT-3802 A	Available		
	PT-2310 A	Available		
	PT-2307 A	Must Be On		
	PT-2307 B	Not Available		
	PT-2305 B	Available		
	PT-2102 B	Available		
	PT-2102 C	Available		
	PT-2103 B	Available		
	PT-2104 A	Available		
	PT-2107 A	Available		
	PT-2110 A	Must Be On		
	PT-2110 B	Not Available		
	PT-2112	Must Be On		
	PT-2201 B	Available		
	PT-2202 B	Available		
	PT-2203 A	Available		
	PT-2903	Available		
	CT-1525 B	Available		
	PT-1534 B	Must Be On		
	PT-3202 A	Available		
	PT-3202 B	Available		
	PT-3203 A	Available		
	PT-3203 B	Available		
	PT-8122 B	Available		
	PT-8126 B	Available		
	PT-8127 B	Available		
	PT-8110 A	Must Be On		
	CT-8340 A	Available		
	CT-8350	Available		
	PT-3201 B	Available		
	PT-3204 B	Available		
	PT-3205 B	Available		
	PT-3206 B	Available		
	PT-3301 A	Must Be On		
	PT-2306 B	Available		
	PT-8112 B	Must Be On		
	PT-2905 B	Available		
	PT-2906 B	Available		
	PT-3701 A	Not Available		
	PT-3701 B	Must Be On		
	PT-1511 A	Must Be On		
	PT-1511 B	Must Be On		
	PT-1524 B	Available		
	PT-1901 B	Must Be On		
	PT-2412 B	Must Be On		
	PT-2413 B	Must Be On		
	PT-2314 B	Must Be On		
	PT-2343 B	Available		
VALVES AND DESUPERHEATERS	HS->MS (32PC8)		0	140
	MS->LS (32PC9)		0	73,5
	HS->TSS (PC241)		0	50
	TS->MSS810 (81PC260)		0	31
	MSS810->LSS810 (81PC261)		0	12
	DS 1501		0	75
	DS 2201		0	75
	DS 2302		0	75
	DS 2901		0	75
	DS 3203		0	75
	DS 3801		0	75
	DS 8101		0	75
	DS 8102		0	50
	DS 8103		0	45
	VENT HS (32PC6)		0	60
	LSS810 VENT (81PC262)		0	60
	LS VENT (32PC9B)		0	60

7.2 Optimization results: minimization of the utility system working cost

Once all the profile editors are ready to be compiled, the optimizer has been set-up and checked as described in Appendix D. The Aspen Utilities optimizer uses a mature integer linear programming technique do the optimization (MILP).

This kind of optimization could be thought of as a simple problem with only two solutions: either minimized steam production with all drives in electric motor configuration or maximized steam production with turbine-driven pumps, depending on the prices of LNG and electricity. However, obtaining a good solution is not so simple. In fact, the optimal operating configuration can sometimes can be somewhere between these two extremes. At every pressure level of the system, steam production in process heat exchangers and steam consumption take place (these as modelled as input parameters). A deficit in the steam production, for example, driven by a low price of electric power, could lead to a situation in which some constraints are not completely satisfied. Moreover, for every value of steam production, infinite distributions of flows are possible within the network, through plenty of interconnections with pipes, valves and turbines downstream. The optimized solution takes into account all these variables, showing the best operating configuration that could have been used at the refinery (during an analysed time frame) to achieve the best economic profit.

Summarizing, for a given percentage of LNG in the mixture, given prices of electric energy and LNG, a given steam production from process-recovery-heat exchangers and a given constant process-steam demand, the best configuration will be estimated. Even though the interface could retrieve an optimized configuration for every possible scenario, the results that will be shown in this part are only the one concerning the first scenario analysed: the 13th September 2015 at 3:10am. The Table 7.2, in fact, compare three types of solutions: the first one is the real situation measured at the plant, while the second and the third one represent two different configuration related to two different relative prices of LNG and electricity.

Table 7.2 Optimization results for the first scenario.

VARIABLE	UNIT	13 SEPT (3:10) REAL CONDITION	ELECTRICITY CHEAPER THAN LNG	LNG CHEAPER THAN ELECTRICITY
Electric Energy used to move dual-driver pumps	[MW]	5,8	7,1	1,33
Total Fuel fired within the boilers	[Tonne/h]	6,68	4,52	12,37
Steam production from the Boilers	[Tonne/h]	70,6	57,45	142
Number of switchable pump with "Turbine-driver"	/	15/33	13/33	32/33
Total Vented Steam into the atmosphere	[Tonne/h]	19	2,8	94
Make-Up Water for steam network	[Tonne/h]	130	119,3	197
Total Water Used for steam network	[Tonne/h]	352,2	339,6	432
Percentage of MakeUp	/	36,9%	35,1%	45,6%

Examining the retrieved configurations, the optimized scenario for a cheaper price of electric energy is quite close to the real configuration at the plant. The production of steam is almost the minimum necessary to guarantee feeding downstream to the consumers. The optimizer in this case use only thirteen of the turbine drivers: to use more than thirteen turbines, the production should otherwise be increased. A big difference with the real situation lies in the vented steam: the real situation presents an excessive production of steam at the high pressure level, which must be released into the atmosphere downstream. The last column is quite interesting, because it is the configuration optimized for a cheaper price of LNG, and could also be associated to a moment of greater production of refinery-fuel. The steam production in this case is twice the one of the real condition. The same happens with the fired fuel. A lot of steam is vented, since the amount of consumption downstream does not change, and almost all the switchable pumps are moved by steam turbines. In this case the working point of the steam system would be individuated by a vertical dash line, passing as far to the right as possible, in the Figure 7.1.

Chapter 8

COMMENTS AND DISCUSSIONS

A complete database of steam streams and a complete layout of the steam network have been obtained. The reliability of the data has been confirmed by measurements at the plant and employees' experience. Regarding the steam model, which has been built based on both empirical and analytical concepts, some assumptions have been made, especially regarding dynamic behaviour of process units. In order to have a completely reliable model, some of these points should be analysed more deeply and some parts of the system integrated with a model of the entire plant.

To give an example, the boiler models are quite close to reality, however, the fuel network has been simplified a lot since the main purpose of this thesis was the steam network. The real fuel used in the boilers is a mixture made upstream, with a fairly variable concentration, and a variable specific heat, molecular weight, etc. This variability has in the model been simulated only by using two different fuels with constant properties. It is easy to understand that such assumptions will sometimes bring hardly acceptable results at the fuel side. Without any doubts it could be interesting to model the fuel network upstream the steam generation, linking the composition of the mixed fuel gas and its properties to the boilers as an input for the model. This step could allow to forecast a fuel consumption for a given production of steam and so improve the developed steam model from the economic point of view.

Reaching a completely reliable model that reflects what actually happens within the steam system could indeed be useful for both economic and energy-saving purposes. The model could in fact identify the real cost of several kinds of steady-state operating scenarios and aid the evaluation of different investment options. It will essentially operate as a simulator to reflect the behaviour of the system as it is presently configured [22].

8.1 Further developments of the model

The model of the refinery's steam network will help to realize some already started projects, like:

- An investigation of the effect of a possible retrofit aimed to reach a better heat integration between the chemical processes and the steam network.
- A control system analysis and a dynamic analysis of the steam network. Looking at how any retrofit proposal could affect the controllability of the system.

Moreover, the model of the steam network could be useful for many future analysis purposes such as:

- An integration of the steam model with the process units and the fuel network of the refinery, including consumption of fuel within the process furnaces.
- *A dynamic* model of the steam network.
- A realization of a real time control system, with forecasting possibilities and long-term optimization for every kind of working scenario.

Chapter 9

CONCLUSION

In this Master's Thesis project a complete model of a refinery steam network has been created, and is available in Aspen custom modeller file. The model has been validated against a database, in which four main steady state scenarios at the refinery has been included. Measurements within the plant, energy and mass balances, assumptions regarding unmeasured variables, component datasheets and interviews with the company employees has been necessary to reach this purpose.

The boilers fuel consumption, the electric power used for the electric-driven pumps, the vented steam and the make-up water have been included and connected to each other in the model. These variables are the main variables with which the steam network interacts towards the rest of the system and the environment. To optimize these variables leads to a better energy management at the refinery. This thesis presents such an optimization of the steam model operation, taking into account the different steam consumptions and prices of primary energy at the plant (as far as the steam network is concerned).

The steam network model can be useful for evaluating important choices connected to the economic balances of the refinery, as for instance retrofits, refinery's sections shut-down periods and changes of switchable pump and compressor driver configurations. In every mentioned case, the model, handling mass and energy balances, can be used to simulate how changes of steam production/consumption at different pressure levels affect the overall balances (including fuel and electricity consumption).

APPENDIX

APPENDIX A
Turbine Efficiencies at Partial Load

Energy saving measures and different demands in the refinery processes lead to reduction of the amount of required mechanical drive power for compressors and pumps, driven by steam turbines. For reaction types turbines (with pressure drop across the wheels), work output from the turbine is usually accomplished by operating a control throttle at the turbine inlet, as shown in Figure A.1.

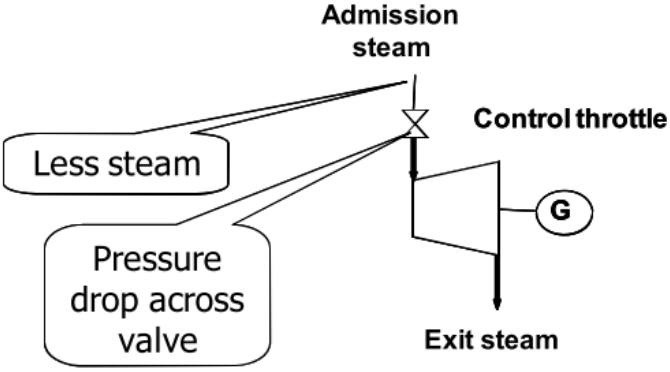


Figure A.1 Throttle control for partial load operation of a steam turbine.

By the definition of isentropic efficiency provided in (2.1), the shaft power output of a steam turbine can be calculated using the following equation, where the subscripts 1 and 2 indicate respectively inlet and outlet conditions:

$$\dot{W}_{st} = \dot{m}_{st} \cdot (h_1 - h_2) = \dot{m}_{st} \cdot \eta_{is,T} \cdot \Delta h_{is} [kW] \qquad \text{(A.1)}$$

Equation (A.1) relates the shaft power output with the mass flow within the turbine, for a given isentropic efficiency. The isentropic efficiency can be assumed to be constant for small variations of the flow rate, but for greater variations, it is important to account for variation of the efficiency. The throttling before the turbine nozzles leads to chokes flow and to a partial reduction of the mass flow entering in the machine.

For a given turbine, practical experience and theoretical considerations show that mass flow rate and turbine inlet/outlet pressures are related through the following equation where C_T is the so-called turbine constant, and v_1 the specific volume at inlet condition.

$$\dot{m}_{st} = C_T \cdot \sqrt{\frac{p_i^2 - p_2^2}{p_i \cdot v_i}} \tag{A.2}$$

The value of the turbine constant C_T remains unchanged if the flow path of steam through the turbine is unchanged for off design operation. This condition is fulfilled for throttle control of incoming steam. For steam turbines with a bleed valve, instead, modifications of steam bleed conditions will result in a modified turbine constant [23].

However, with known new inlet steam data (the inlet pressure), the isentropic efficiency of the turbine will change. Once again, according to practical experience and theoretical considerations it can be found out the isentropic efficiency varies according to the following expression, which has been used in the model:

$$\eta_{is,T} = a \cdot \chi^2 + b \cdot \chi - 0{,}2 \tag{A.3}$$

Where χ is the same dimensional parameter already mentioned in 3.1.3, defined by (3.5) and related to the constant C_T. a and b can be easily determined since one of the point of this curve is known (the nominal design condition) and this is also the maximum one on the curve (i.e. the derivative at this point is known).

Applying the constraints to the function $\eta_{is,T}(\chi)$ for the turbines at the refinery, the equation (A.4) for the turbine CT-2301 and the (A.5) for the CT-8101 have been obtained. Design conditions have been taken directly from the datasheet of the machines. The two curves obtained are shown together in the Figure A.2.

Table A.1 Constraints applied at design condition.

$\eta_{is,T} = a \cdot \chi^2 + b \cdot \chi - 0{,}2$	
$\chi = design\ dimentional\ ratio$	$\eta_{is,T} = maximum\ efficiency$
$\eta'_{is,T} = 2 \cdot a \cdot \chi + b$	
$\chi = design\ dimentional\ ratio$	$\eta'_{is,T} = 0$

$$\eta_{is,T\_2301} = -0{,}00012\ \chi^2 + 0{,}022\ \chi - 0{,}2 \tag{A.4}$$

$$\eta_{is,T\_8101} = -0{,}0000725\ \chi^2 + 0{,}0166\ \chi - 0{,}2 \tag{A.5}$$

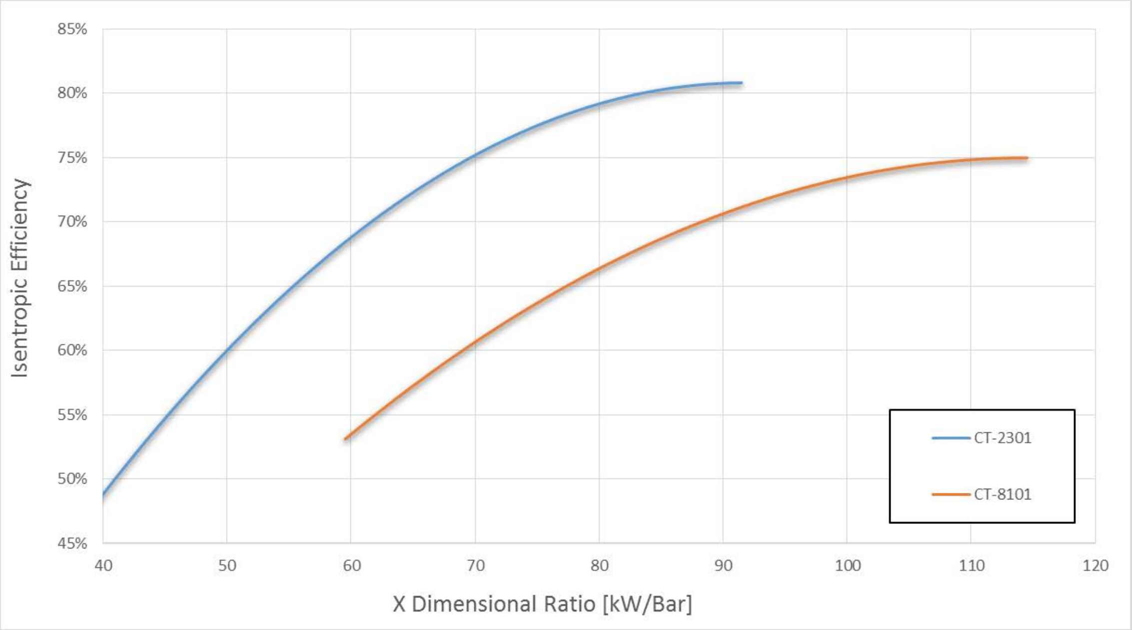


Figure A.2 Isentropic efficiency curves obtained using the dimensional ratio X.

These curves have been used directly in the model, interpolating a set of point in a table.

APPENDIX B

Custom Constraints and Equations

Once a flowsheet structure is completed in Aspen Utilities Planner, every component is treated like a block, with its proper equations and variables. The entire system formed by all the flowsheet's blocks together is a large system of equation in which a square condition is required to solve a steady state problem. The script language used by the OOMF kernel (the engine behind the Equation Oriented strategy in products such as Aspen Plus) Microsoft Visual Basic [24]. These script commands are automatically generated by the software for basic calculation about block relationships, but also they can be typed using the command line or other script files. In the Lysekil refinery's flowsheet this possibility has definitely concretized since it has been necessary to manually add some constraints which could not be handled by the software itself.

A simplified example of one of the problems met in the flowsheet could be the one shown in Figure B.1, where three different flows are leaving a header: one of them is a fixed flow measured within an heat exchanger; the two flows to the left are instead going to the atmosphere (the venting-valve) and downstream (where there might be other headers), respectively. Since the two latter mass flows are not fixed, the model cannot be squared because it cannot find a solution for the branching of the flows.

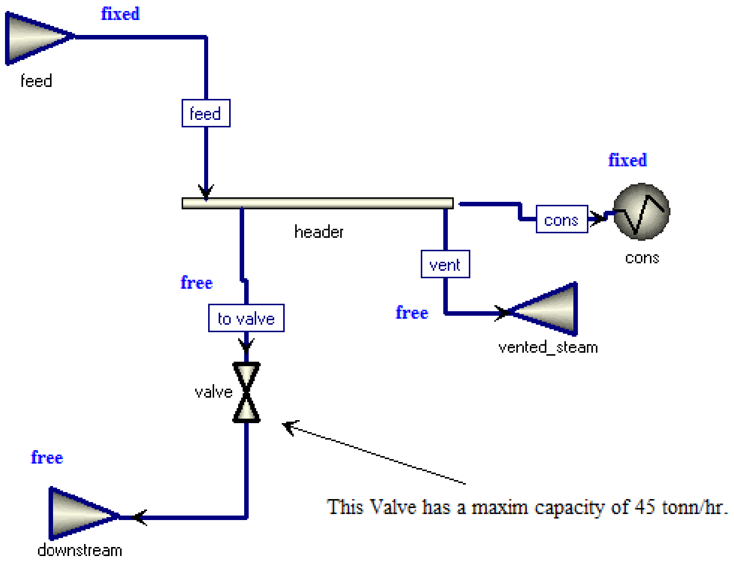
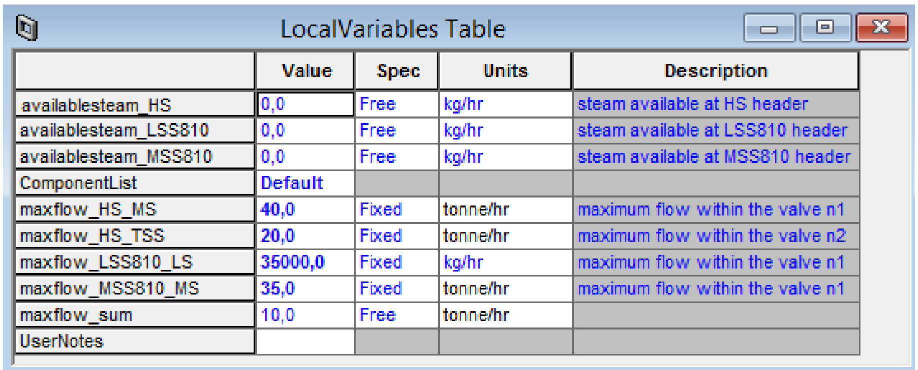


Figure B.1 Constraint leak example.

The script language is very effective for this kind of problem, because it has many features of an advanced programming language (such as mathematical and string functions, if-then-else logic, and for-do loops), that can help introducing some useful constraints [25]. In this case a hierarchical propagation of the flows downstream is needed, and to do so an "if-clause" can be used: keeping the example of the Figure B.1, the if-clause would be "if the available steam is greater of the consumption downstream, then 45 Tonne/h in this case will flow through the valve, while the other part will be vented; if not (else), the vented steam will be set equal to zero".

Moreover, adding some scripts besides the default ones could be useful regarding the introduction of new "local variables", which are not present in the program. This feature has been used for some consideration about the steam network, with the introduction of fixed valve capacities and a variable called "availablesteam", indicating a measure of the excess of steam within the header. The Figure B.2 shows these new variables.



	Value	Spec	Units	Description
availablesteam_HS	0,0	Free	kg/hr	steam available at HS header
availablesteam_LSS810	0,0	Free	kg/hr	steam available at LSS810 header
availablesteam_MSS810	0,0	Free	kg/hr	steam available at MSS810 header
ComponentList	Default			
maxflow_HS_MS	40,0	Fixed	tonne/hr	maximum flow within the valve n1
maxflow_HS_TSS	20,0	Fixed	tonne/hr	maximum flow within the valve n2
maxflow_LSS810_LS	35000,0	Fixed	kg/hr	maximum flow within the valve n1
maxflow_MSS810_MS	35,0	Fixed	tonne/hr	maximum flow within the valve n1
maxflow_sum	10,0	Free	tonne/hr	
UserNotes				

Figure B.2 Local variables introduced to the flowsheet with a script.

Other scripts have been added to the model in order to handle the LNG contained into the mixture, as well as the load factor of the big turbines, defined as it follows:

$$\text{Load Factor} = \frac{Power\ demand\ (Compressor\ shaft)}{Nominal\ Power\ of\ the\ turbine} \qquad \text{(C.1)}$$

Visual Basic script added to the model

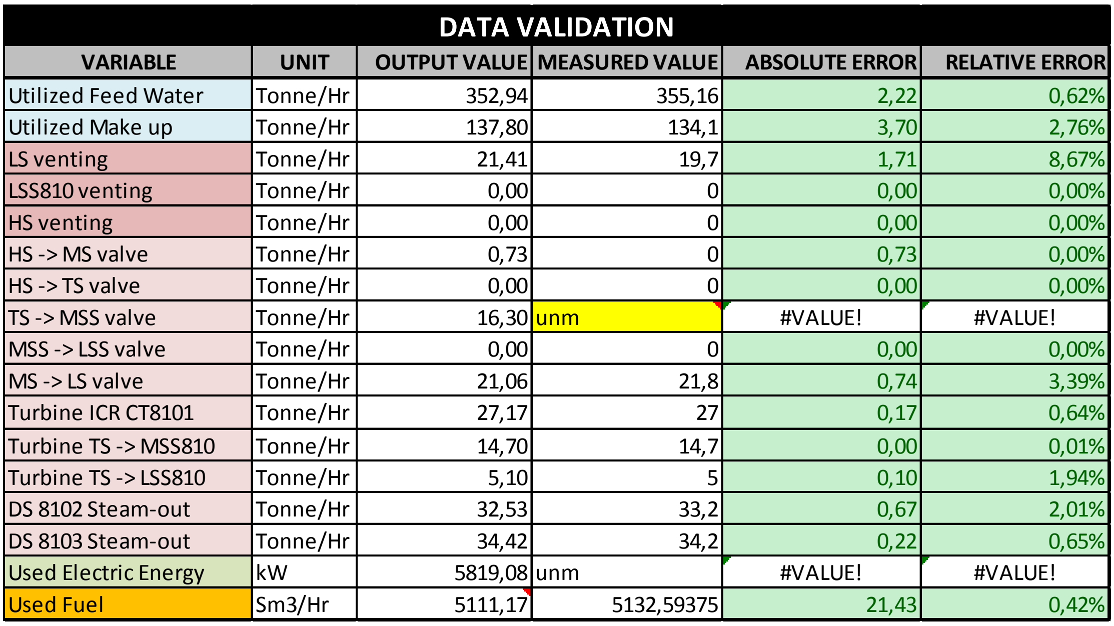
```
CONSTRAINTS
// Aspen Utilities Planner - Loading flowsheet equations and integrated constraints: Done;
//
//*********************************************************FUELS RELATIONS
LNG_percentage as realvariable(0.082, fixed, description: "LNG make-up in the fuel network");
LNG.Fmol_out = LNG_percentage * (LNG.Fmol_out + FuelGas.Fmol_out);
//
//****************************************************PARTIAL LOAD TURBINES
LoadFactor_T_CT2301 as realvariable(0.9, fixed, description: "Load factor of condenser Turbine");
T_CT2301.PowerOut("PowerOut1"). Power = 2.9 * LoadFactor_T_CT2301; //nominal Power = 2,9 MW
//
LoadFactor_T_CT8101 as realvariable(0.5, fixed, description: "Load factor of Hydrocracker Turbine");
T_CT8101.PowerOut("PowerOut1"). Power = 2.75 * LoadFactor_T_CT8101; //nominal Power = 2,75 MW
//
//*********************************************************VALVES HIERARCHY
```

```
// ******************* HS header hierarchy **********************
availablesteam_HS as flow_mass(0, free, description: "steam available at
HS header"); //steam available downstream
availablesteam_HS = H_HS.SteamInTotal - (H_HS.SteamOut("SteamOut1").
Connection("HSout_C"). F +
H_HS.SteamOut("SteamOut1"). Connection("HSout_C_HEX"). F +
H_HS.SteamOut("SteamOut1"). Connection(
"HSout_FCC150"). F + H_HS.SteamOut("SteamOut1").
Connection("HSout_T_CT2301"). F + H_HS.SteamOut(
"SteamOut1"). Connection("HSout_T_CT8101"). F + H_HS.SteamOut("SteamOut1").
Connection("HSout_T_LS"). F +
H_HS.SteamOut("SteamOut1"). Connection("HSout_T_LSS210"). F +
H_HS.SteamOut("SteamOut1"). Connection(
"HSout_T_LSS230"). F + H_HS.SteamOut("SteamOut1").
Connection("HSout_T_LSS320"). F + H_HS.SteamOut(
"SteamOut1"). Connection("HSout_T_MSS320"). F + H_HS.SteamOut("SteamOut1").
Connection("MSout_T_PT2903"
). F);
//Setting up valve limits
maxflow_HS_MS as flow_mass(140, fixed, description: "maximum flow within
the valve n1");
maxflow_HS_TSS as flow_mass(50, fixed, description: "maximum flow within
the valve n2");
maxflow_sum as flow_mass; maxflow_sum = maxflow_HS_MS + maxflow_HS_TSS;
//if clause (2 equations mus be specified for each condition)
if availablesteam_HS <= maxflow_HS_MS then // CONSTRAINTS ON:
H_HS.SteamOut("SteamOut1"). Connection("HSout_V_TSS810"). F = 0; //2valve
H_HS.BlowSteam("BlowSteam1"). F = 0; //3valve
elseif (availablesteam_HS > maxflow_HS_MS and availablesteam_HS <=
maxflow_sum) then
H_HS.SteamOut("SteamOut1"). Connection("HSout_V_MS_DS3202"). F =
maxflow_HS_MS; //1valve
H_HS.BlowSteam("BlowSteam1"). F = 0; //3valve
else
H_HS.SteamOut("SteamOut1"). Connection("HSout_V_MS_DS3202"). F =
maxflow_HS_MS; //1valve
H_HS.SteamOut("SteamOut1"). Connection("HSout_V_TSS810"). F =
maxflow_HS_TSS; //2valve
endif
//
// ******************* MSS810 header hierarchy **********************
availablesteam_MSS810 as flow_mass(0, free, description: "steam available
at MSS810 header"); //steam
available downstream
availablesteam_MSS810 = H_MSS_810.SteamInTotal;
//setting up valve limits
maxflow_MSS810_MS as flow_mass(40, fixed, description: "maximum flow
within the valve n1");
//if clause (2 equations mus be specified for each condition)
if availablesteam_MSS810 <= maxflow_MSS810_MS then
H_MSS_810.SteamOut("SteamOut1"). Connection("MSS810out_V_LSS810"). F = 0;
else
H_MSS_810.SteamOut("SteamOut1"). Connection("MSS810out_DS8102"). F =
maxflow_MSS810_MS;
endif
//
// ******************* LSS810 header hierarchy **********************
availablesteam_LSS810 as flow_mass(0, free, description: "steam available
at LSS810 header"); //steam
available downstream
availablesteam_LSS810 = H_LSS_810.SteamInTotal;
//setting up valve limits
```

```
maxflow_LSS810_LS as flow_mass(45, fixed, description: "maximum flow within the valve n1");
//if clause (2 equations mus be specified for each condition)
if availablesteam_LSS810 <= maxflow_LSS810_LS then
H_LSS_810.BlowSteam("BlowSteam1"). F = 0;
else
H_LSS_810.SteamOut("SteamOut1"). Connection("LSS810out_DS8103"). F = maxflow_LSS810_LS;
endif
//
END
```

APPENDIX C
Data Validation Tables for every Scenario

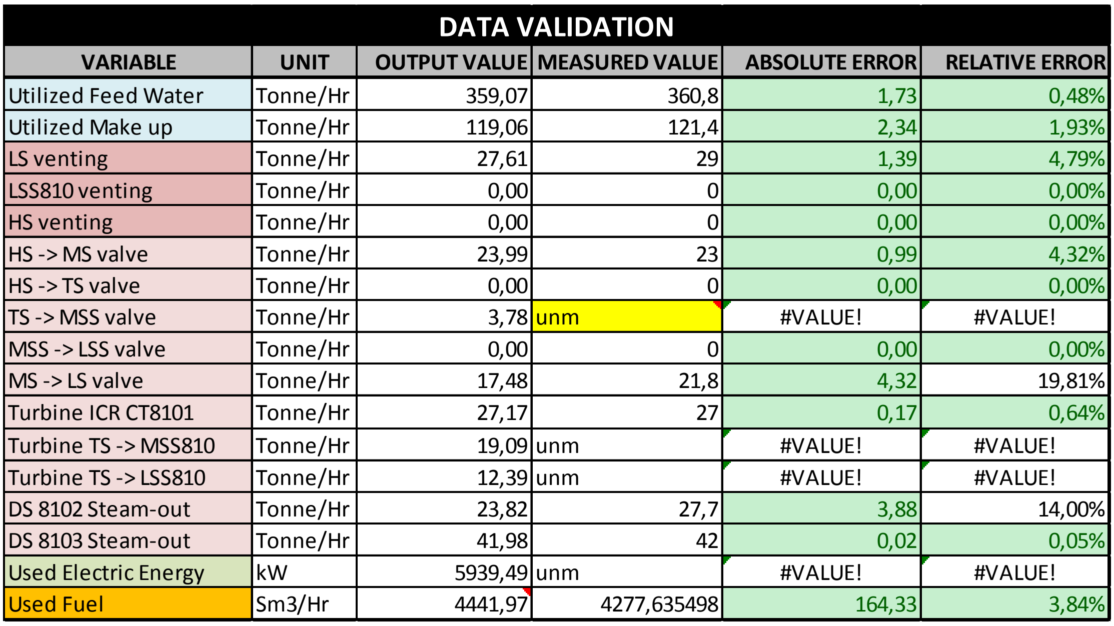
Table C.1 Data validation table for Scenario 1.



DATA VALIDATION

VARIABLE	UNIT	OUTPUT VALUE	MEASURED VALUE	ABSOLUTE ERROR	RELATIVE ERROR
Utilized Feed Water	Tonne/Hr	352,94	355,16	2,22	0,62%
Utilized Make up	Tonne/Hr	137,80	134,1	3,70	2,76%
LS venting	Tonne/Hr	21,41	19,7	1,71	8,67%
LSS810 venting	Tonne/Hr	0,00	0	0,00	0,00%
HS venting	Tonne/Hr	0,00	0	0,00	0,00%
HS -> MS valve	Tonne/Hr	0,73	0	0,73	0,00%
HS -> TS valve	Tonne/Hr	0,00	0	0,00	0,00%
TS -> MSS valve	Tonne/Hr	16,30	unm	#VALUE!	#VALUE!
MSS -> LSS valve	Tonne/Hr	0,00	0	0,00	0,00%
MS -> LS valve	Tonne/Hr	21,06	21,8	0,74	3,39%
Turbine ICR CT8101	Tonne/Hr	27,17	27	0,17	0,64%
Turbine TS -> MSS810	Tonne/Hr	14,70	14,7	0,00	0,01%
Turbine TS -> LSS810	Tonne/Hr	5,10	5	0,10	1,94%
DS 8102 Steam-out	Tonne/Hr	32,53	33,2	0,67	2,01%
DS 8103 Steam-out	Tonne/Hr	34,42	34,2	0,22	0,65%
Used Electric Energy	kW	5819,08	unm	#VALUE!	#VALUE!
Used Fuel	Sm3/Hr	5111,17	5132,59375	21,43	0,42%

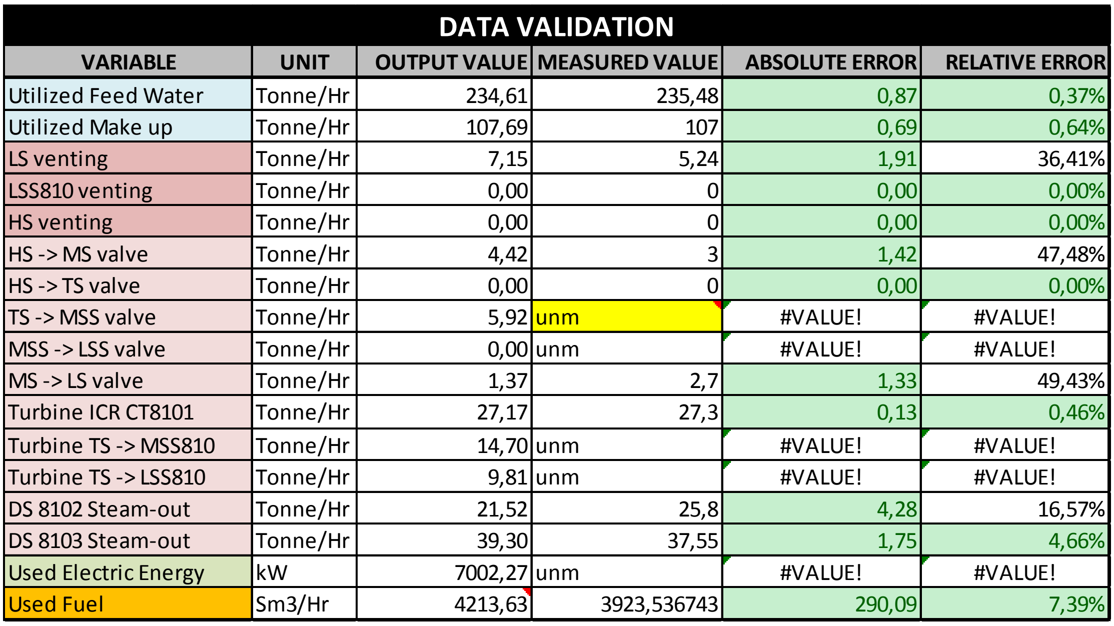
Table C.2 Data validation table for Scenario 2.



DATA VALIDATION

VARIABLE	UNIT	OUTPUT VALUE	MEASURED VALUE	ABSOLUTE ERROR	RELATIVE ERROR
Utilized Feed Water	Tonne/Hr	359,07	360,8	1,73	0,48%
Utilized Make up	Tonne/Hr	119,06	121,4	2,34	1,93%
LS venting	Tonne/Hr	27,61	29	1,39	4,79%
LSS810 venting	Tonne/Hr	0,00	0	0,00	0,00%
HS venting	Tonne/Hr	0,00	0	0,00	0,00%
HS -> MS valve	Tonne/Hr	23,99	23	0,99	4,32%
HS -> TS valve	Tonne/Hr	0,00	0	0,00	0,00%
TS -> MSS valve	Tonne/Hr	3,78	unm	#VALUE!	#VALUE!
MSS -> LSS valve	Tonne/Hr	0,00	0	0,00	0,00%
MS -> LS valve	Tonne/Hr	17,48	21,8	4,32	19,81%
Turbine ICR CT8101	Tonne/Hr	27,17	27	0,17	0,64%
Turbine TS -> MSS810	Tonne/Hr	19,09	unm	#VALUE!	#VALUE!
Turbine TS -> LSS810	Tonne/Hr	12,39	unm	#VALUE!	#VALUE!
DS 8102 Steam-out	Tonne/Hr	23,82	27,7	3,88	14,00%
DS 8103 Steam-out	Tonne/Hr	41,98	42	0,02	0,05%
Used Electric Energy	kW	5939,49	unm	#VALUE!	#VALUE!
Used Fuel	Sm3/Hr	4441,97	4277,635498	164,33	3,84%

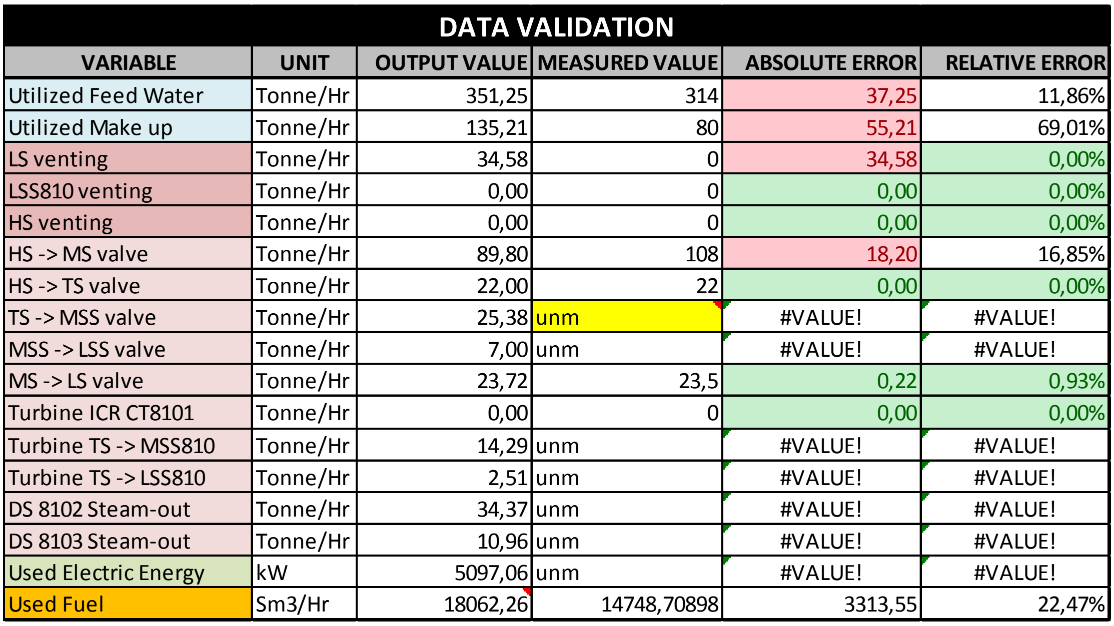
Table C.3 Data validation table for Scenario 3.



DATA VALIDATION

VARIABLE	UNIT	OUTPUT VALUE	MEASURED VALUE	ABSOLUTE ERROR	RELATIVE ERROR
Utilized Feed Water	Tonne/Hr	234,61	235,48	0,87	0,37%
Utilized Make up	Tonne/Hr	107,69	107	0,69	0,64%
LS venting	Tonne/Hr	7,15	5,24	1,91	36,41%
LSS810 venting	Tonne/Hr	0,00	0	0,00	0,00%
HS venting	Tonne/Hr	0,00	0	0,00	0,00%
HS -> MS valve	Tonne/Hr	4,42	3	1,42	47,48%
HS -> TS valve	Tonne/Hr	0,00	0	0,00	0,00%
TS -> MSS valve	Tonne/Hr	5,92	unm	#VALUE!	#VALUE!
MSS -> LSS valve	Tonne/Hr	0,00	unm	#VALUE!	#VALUE!
MS -> LS valve	Tonne/Hr	1,37	2,7	1,33	49,43%
Turbine ICR CT8101	Tonne/Hr	27,17	27,3	0,13	0,46%
Turbine TS -> MSS810	Tonne/Hr	14,70	unm	#VALUE!	#VALUE!
Turbine TS -> LSS810	Tonne/Hr	9,81	unm	#VALUE!	#VALUE!
DS 8102 Steam-out	Tonne/Hr	21,52	25,8	4,28	16,57%
DS 8103 Steam-out	Tonne/Hr	39,30	37,55	1,75	4,66%
Used Electric Energy	kW	7002,27	unm	#VALUE!	#VALUE!
Used Fuel	Sm3/Hr	4213,63	3923,536743	290,09	7,39%

Table_Appendix C.4 Data validation table for Scenario 4.



DATA VALIDATION

VARIABLE	UNIT	OUTPUT VALUE	MEASURED VALUE	ABSOLUTE ERROR	RELATIVE ERROR
Utilized Feed Water	Tonne/Hr	351,25	314	37,25	11,86%
Utilized Make up	Tonne/Hr	135,21	80	55,21	69,01%
LS venting	Tonne/Hr	34,58	0	34,58	0,00%
LSS810 venting	Tonne/Hr	0,00	0	0,00	0,00%
HS venting	Tonne/Hr	0,00	0	0,00	0,00%
HS -> MS valve	Tonne/Hr	89,80	108	18,20	16,85%
HS -> TS valve	Tonne/Hr	22,00	22	0,00	0,00%
TS -> MSS valve	Tonne/Hr	25,38	unm	#VALUE!	#VALUE!
MSS -> LSS valve	Tonne/Hr	7,00	unm	#VALUE!	#VALUE!
MS -> LS valve	Tonne/Hr	23,72	23,5	0,22	0,93%
Turbine ICR CT8101	Tonne/Hr	0,00	0	0,00	0,00%
Turbine TS -> MSS810	Tonne/Hr	14,29	unm	#VALUE!	#VALUE!
Turbine TS -> LSS810	Tonne/Hr	2,51	unm	#VALUE!	#VALUE!
DS 8102 Steam-out	Tonne/Hr	34,37	unm	#VALUE!	#VALUE!
DS 8103 Steam-out	Tonne/Hr	10,96	unm	#VALUE!	#VALUE!
Used Electric Energy	kW	5097,06	unm	#VALUE!	#VALUE!
Used Fuel	Sm3/Hr	18062,26	14748,70898	3313,55	22,47%

APPENDIX D
Optimizer Configuration and Settings

Optimizer Features

Besides the ordinary constraints presented implicitly within the flowsheet, the optimizer allow to set some desired characteristics of the system before carrying on an optimization. This topics, which allows to achieve specific types of optimization, are:

- **Enforcing hot standby requirements:** Allow the optimizer to take into account some standby capacities. Every steam generator could be used for this purpose and the hot standby capacity needs to be specified.
- **Configuring start-up/shutdown constraints:** This feature, which allow to set start-up and shut-down times and costs, is very important when carrying out a multi-period optimization. These values are taken into account to determine the economic profile for utility generation and/or purchase over the entire optimization timeframe.
- **Configuring load shedding:** determine the optimum load shedding scheme, according to load shedding costs inserted in every block. This function could be very useful in overproduction periods, since it would take into account lost production in the plant.
- **Obtaining marginal utility costs:** Fixing the marginal cost of a component, a production-unit cost is fixed. This variable let the optimizer evaluate when an increase of production for a particular unit is worth. If the cost of the production is lower than the useful effect, then the optimizer will let the production increase.

The optimization that has been carried on for the steam network did not cover all these features, although useful, since other system characteristics should have been analysed properly. The only feature which has been taken into account is the "Start-up/Shutdown": setting the times to variable and the costs to zero, the optimizer has handled the scenario as if it was an optimized steady state configuration, leaving the dependence on time apart.

Mixed integer linear solver configuration

The Aspen Utilities optimizer is linear and uses a mature integer linear programming technique do the optimization (MILP), in which the objective function and the constraints (other than the integer constraints) are linear. Data input errors can sometimes cause optimization failures (infeasibilities). To avoid so two error diagnostic mechanisms has been used to detect optimization errors: presolve checking and error tracking. In the first one a pre-simulation of the entire network has been made, with the aim to correct (if present) main errors caused by bad-posed bounds between simulation variables (for example, a minimum bound which is greater than a maximum bound on a variable). The second one, instead, is carried out by introducing a balance variable on each mass balance equation which is minimized in the objective function. When the first optimization of the model has been completed, the problematic balance equations had a non-zero value of the balance variable, which allowed to localize the error source within the system. The “cut strategy” (number of cuts generated in each branch and bound solution) of the solver has been chosen as “moderate” (in a five levels scale this is the second most aggressive) according to the complexity of the problem: even though the flowsheet is quite large in the studied case, the optimization aim is a function only of two different prices and the problem is quite simple, being some complex constraints not included.

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