Multi-Period MILP Optimization of Utility Plant in a Refinery

by

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This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,

and that any and all revisions required by the final

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ABSTRACT

Energy efficiency is one of the most important factors in refineries which affect the cost and the competitiveness. In order to deal with economical difficulties and compete with other refineries, a refinery must fulfill its energy demand on its own. Moreover securing the continuity of the processes is also another concern. In a refinery processes must be held online whatever the situation is. So it is unreliable to run such huge system only depending on outsources. In this concern we have provided a decision support system for determining the optimum working criteria of equipments in a Tüpraş İzmit Refinery power plant.

Refineries use different sources for fulfill their energy demands. Generally power plants are the main providers. However for electricity demand refineries are usually connected to national grids in order to buy or sell electricity depending on the amount of production and the prices of the electricity in “day ahead” and “daily” electricity market.

We illustrate the efficiency and accuracy of our model on a real example of İzmit Refinery Power Plant and implemented the proposed model into GAMS (General Algebraic Modeling System) optimization package by using “Cplex” solver. The result of 0.45 % of cost reduction can be obtained without any investment.

Finally, we conclude with the sensitivity analysis in order to see the affects of variations in electricity prices in daily electricity market.

ÖZETÇE

Enerji verimliliği rafineriler için maliyeti ve rekabeti etkileyen en önemli faktörlerden biridir. Ekonomik zorluklarla baş edebilmek ve aynı zamanda diğer rafineriler ile yarışabilmek için bir rafineri kendi enerji ihtiyacını karşılayabilmek zorundadır. Bunun yanı sıra rafineri proseslerinin devamlılığını, şartlar ne olursa olsun sağlayabilmelidir. Böyle bir durumda dışa bağımlılık büyük bir güvensizlik yaratmaktadır. Yukarıda belirtilen çekinceler göz önüne alınarak biz TÜPRAŞ İzmit Rafinerisi kapsamında yardımcı servislerin optimum düzeyde çalışmasına yardımcı olacak karar destek sistemi geliştirmiş bulunmaktayız.

Rafineriler değişik kaynaklar kullanarak enerji ihtiyaçlarını gidermektedirler. Genellikle rafineri içinde kurulu olan güç santralleri bu ihtiyaca karşılık vermektedir. Ayrıca rafineriler gerektiğinde elektrik alıp satabilmek için ulusal şebekeye de bağlıdırlar. Gün öncesi ve gün için piyasanın durumuna göre elektrik alımı ve satımı gerçekleştirmektedirler.

Oluşturduğumuz modelin kesinliğini ve etkinliğini İzmit Rafinerisi Güç Santralleri verileri üzerinde, GAMS yazılımı CPlex çözücüsü kullanarak gösterdik. Yaptığımız çalışma sonucunda toplam maliyette, hiç bir yatırıma ihtiyaç duymadan, %0.45'lik bir düşüş sağladık.

Son olarak yaptığımız duyarlılık analizleri sonucunda, elektrik fiyatlarının değişimin etkilerini gördük.

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NOMENCLATURE

$F_s\ (x)$	Steam production of boiler *x*
$F_{fg}(x)$	Fuel gas consumption of boiler *x*
$F_{fo}(x)$	Fuel oil consumption of boiler *x*
p_x	Regression parameters of *x*
F_{VHP}	Flow rate of VHP steam
F_{HP}	Flow rate of HP steam
F_{MP}	Flow rate of MP steam
F_{LP}	Flow rate of LP steam
F_{Cond}	Flow rate of condensate
F_{ng}	Flow rate of natural gas
$cost(s,t)$	Cost of stream *s* at time *t*
$stream\ (s,t)$	Flow rate of stream *s* at time *t*
Mode (asset, m, t)	mode of equipment *asset* at time *t*
pCOST (s, t)	cost of stream *s* at time *t*
pDEMAND (s, t)	demand in stream *s* at time *t*
Pfixed (GRP,ASSET,CONSTANT)	*regression model parameters of equipments*
$stream\ (sDEMAND, t)$	Flow rate of stream *sDEMAND* at time *t*
p$DEMAND(sdemand, t)$	Refinery demand on stream *sdemand* at time *t*

sDemand	set of streams that refinery is demanding
Stin	inlet stream of a steam turbine
STout1	first side draws of steam turbines
STout2	second side draws of steam turbines
STout3	third side draws of steam turbines
PWout	power production of steam turbines
$stream(PWbuy, t)$	amount of electricity bought at time *t*
$stream(PWsell, t)$	amount of electriciy sold at time *t*
$mode(PWGRID, m, t)$	mode of power grid operation at time *t*
$mode(asset, m, t)$	mode *m* of equipment *asset* at time *t*
STout	steam production of a boiler
STinAPH	consumed LP steam in air pre-heater
SToutAPH	condensate leaving the air pre-heater
ATOMin	MP steam consumed for atomizing the fuel oil
stream (Stout, x-HP)	flow rate of *HP* (this can be HP or VHP depending on the boiler) steam from boiler *x*
$p_{FIXED}(x, coef_{FG\text{-}ST})$	fuel gas constant for boiler *x*
stream (x, FGin)	amount of fuel gas to the boiler *x*
$p_{FIXED}(x, coef_{FO\text{-}ST})$	fuel oil constant for boiler *x*
stream (x, FOin)	amount of fuel oil to the boiler *x*
$p_{FIXED}(x, coef_{0\text{-}ST})$	regression constant for boiler *x*
mode (x,m,t)	mode of boiler *x* at time *t*
stream (STinAPH, x-LP)	amount of *LP steam* given to the air pre-heater system

$p_{FIXED}(x, coef_{APH})$	regression constant for air pre-heater system
$stream\ (STout, x)$	amount of produced steam from boiler *x*
$stream\ (Atomin, x\text{-}MP)$	amount of MP steam consumed for atomizing process
$p_{FIXED}\ (x, coef_{FO\text{-}ATOM})$	regression constant
$stream\ (x, FOin)$	amount of fuel oil consumed in boiler *x*
$p_{FIXED}(y, coef_{STout})$	regression constants for side draws
$stream(y, STout)$	flow rates of side draws
$mode(y, m, t)$	on/off mode of steam turbines
$stream(STout, z - VHP)$	flow rate of VHP steam produced
$p_{FIXED}(z, coef_{NG2})$	regression parameter of natural gas for gas turbine
$mode(z, m, t)$	on/off mode of gas turbine
$stream(PWout, x - PW)$	amount of electricity produced from gas turbine
$stream(z, NGin)$	flow rate of natural gas entering the gas turbine

Chapter 1

Introduction

Energy need of the world is getting higher with the increase in population. Although the technologic improvements in all areas, need in oil is still so much. In such a case, refineries have huge role in energy sector. Tupraş is the only refinery in Turkey with a capacity of processing roughly 28 million tons of crude oil .Moreover Tupraş is one of the biggest refineries in Mediterranean area with a Nelson Complexity of 7.25 which indicates, refineries technical capabilities.

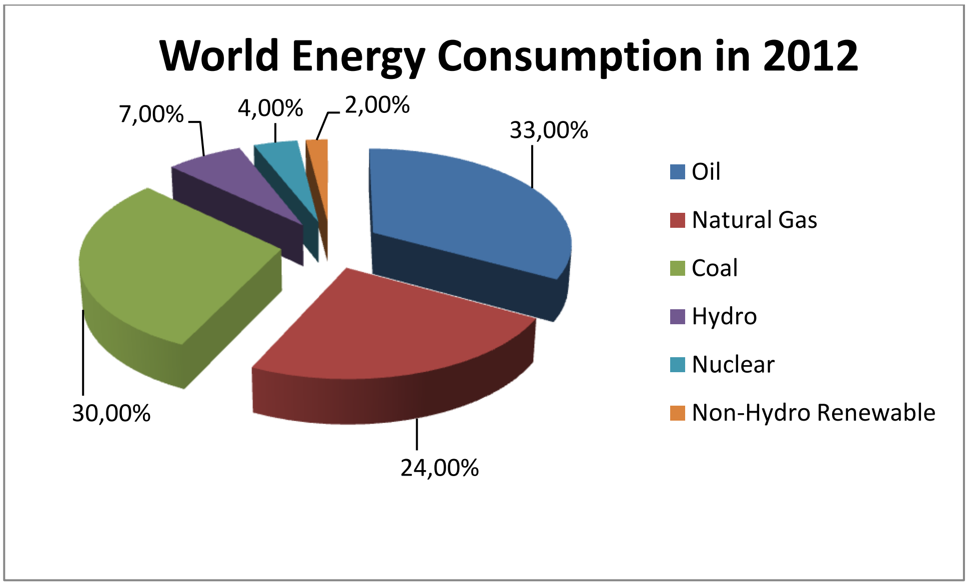

Figure 1 World Energy Consumption in 2012 (Statistical Review of World Energy)

Optimization of utility systems is one of the major interests of refineries because energy costs are usually the biggest part of their expenditures for processes [Papalexandri et al., 1998]. With a deregulated electricity market and importance of process continuity need of determining the optimal strategy for production of energy is obvious. Moreover when refineries are concerned, it gets more important because of the increasing raw material costs. Another need of an optimal strategy is environmental limits and gas emissions which can be achieved by developing an optimal solution.

Refineries and big operating companies use cogeneration system for producing power. Cogeneration can be interpreted as simultaneous production of electricity and heat, which is steam for the case of refineries. [The European Association for the Promotion of Cogeneration]

The purpose of this project is to find an optimal strategy for a cogeneration system in TÜPRAŞ İzmit Refinery which can produce different types of steam for the refining processes and electricity for process continuity, process safety and the economical issues. To do so existing methods to solve a utility system optimization problem will be explored. It will require modeling of the system equipments, thermodynamic approach for discovering the unbalances arise from the errors of flow meters and formulation of optimization to minimize the total cost. Various case studies will be developed to determine a general operating strategy for the utility system to handle variations in different energy demands and electricity prices.

1.1. Tüpraş Izmit Refinery

İzmit Refinery started its production with a capacity of processing 1 million ton of crude oil per year in 1961. With the investments throughout the years the capacity of the refinery is reached to 11.5 million tons of crude oil per year.

İzmit refinery is built in such area that 33 percent of the petroleum consumed in that area. İzmit refinery is one of the most complex refineries of the Mediterranean area with a Nelson Complexity of 7.78.

The main products of the İzmit Refinery are LPG, naphtha, kerosene, diesel, fuel oil and asphalt. Total petroleum products production is about 8.7 million tons with a utilized capacity of 85.2 percent in year 2013.

In order to handle with such huge production İzmit Refinery requires huge amount of energy. In refineries energy is met by electricity and differently pressurized steam. In Izmit Refinery there are 4 different pressurized steam headers which are very high pressurized steam (VHP), high pressurized steam (HP), medium pressurized steam (MP), and low pressurized steam (LP).

- **VHP:** the pressure of VHP steam is about $1000^{\#}$ and is only used for production of electricity in steam turbines.
- **HP:** Pressure and the temperature of the HP steam is about $500^{\#}$, 400°C respectively. Used for operating steam driven pumps, compressors and back pressure turbines.
- **MP:** MP steam has a pressure of $150^{\#}$ and used in the heat exchanger as hot source and as stripping steam in columns.
- **LP:** generally used for heating product and crude tanks. And also used for deareation of water.

1.2. Power Plant

In TÜPRAŞ İzmit Refinery, steam and electricity demand is fulfilled by two different power plants which are called Plant A and Plant B.

In Plant A there are 4 very high pressurized steam (VHP) producing boiler which have different efficiencies but same capacities. Produced VHP is only used to produce electricity by 4 different steam turbines which are also located in the same plant and have different draws, efficiencies and capacities. In these steam turbines VHP steam is broken down into different pressure level and electricity is produced. Moreover there is also 1 gas turbine which is producing electricity with using natural gas as a fuel. In addition, gas turbine is connected to a waste heat boiler that produces VHP steam with using the hot exhaust of gas turbine. By this way cogeneration is to be done with a minimum of waste heat which is directly effects the efficiency of cogeneration. The capacities of the equipments will be given later parts of the thesis.

Plant B contributes the steam production by producing high pressure steam. There are also 4 boilers with different efficiencies and capacities. Produced HP steam is used by the back pressure turbines which are allocated in different places in processes. (Steam driven pumps. compressors etc.)

MP and LP steams are the byproduct of steam turbines. VHP steam is broken down to MP and LP steam in order to produce electricity and these by products are used in refining processes. Moreover there are different break down stations where high pressurized steams are broken down into low pressurized ones. However this process is undesired one because while doing this kind of process you are wasting the energy of a high pressurized steam to produce a lower pressurized one.

1.2.1. Boilers

Capacities of boilers in Plant A and Plant B are given in Table 1 and Table 2 respectively.

Table 1 Capacities of boilers in Plant A

Boilers	Capacity (ton/hour)
x1	110
x2	110
x3	110
x4	110
z	70

Table 2 Capacities of Boilers in Plant B

Boilers	Capacity (ton/hour)
x5	100
x6	150
x7	150
x8	80

Boiler processes are investigated in 4 main topics, which are;

- Economizer
- Evaporator
- Steam drum
- Super heater

Boiler feed water is fed to the boilers throughout the boiler feed pumps and reaches to the economizer. Economizer is bunch of pipes which are allocated in the very cold end of the boiler stack gas. The fed water is heated up to its saturation point in this part of the boiler. Then the saturated water is circulating to the evaporator where the water evaporated and steam is produced. In super heater part, steam is further heated up to its superheated point.

1.2.2 Steam Turbines

Tüpraş İzmit Refinery has 4 steam turbines and a gas turbine in Plant A. These steam turbines differ from each other. Two of these steam turbines y1 and y2, are identical, they both have two side-draws which are MP steam and LP steam. Third one is a condensing turbine, y3, which condensate the inlet VHP steam and produce electricity. The last one, y4, has 3 draws which are HP steam, MP steam and condensate. While all the steam turbines producing electricity, they also help the steam balance of the refinery with side draws. Generally y1, y2 and y4 are operating since they also help refinery steam balance with the side draws; y3 is preferred in summer when the steam demand of the refinery is reasonably low. Specifications of the steam turbines are given in table 3, 4 and 5 respectively.

Table 3 Steam Turbine Specifications

Turbine Name	y1 & y2
Max Power	10 MW
rpm	10017
Inlet steam	VHP steam
Side draws	MP & LP steams

Table 4 Steam Turbine Specifications

Turbine Name	y3
Max Power	10 MW
rpm	9421
Inlet steam	VHP steam
Side draws	Condensate

Table 5 Steam Turbine Properties

Turbine Name	y4
Max Power	15 MW
rpm	7552
Inlet steam	VHP steam
Side draws	HP, MP steams & Condensate

1.2.3. Gas Turbine

Generally gas turbines are the biggest electricity producers in most of the cogeneration plants. It is the same in Tüpraş İzmit Refinery. In Plant a there is a gas turbine and a waste heat boiler which are attached to each other. The maximum capacity of the gas turbine is 38 MW/h and attached waste heat boiler has a capacity of producing 70 tons/h VHP steam.

Gas turbines convert the heat energy, which is generated from burning of natural gas, into mechanical energy. In principle it is no different from internal combustion engine. It is composed of 3 parts which are compressor, combustion chamber and a turbine. The combustion cycle follows compression, expansion and exhaust steps.

Air is fed to the compressor throughout the air filters where air is purged. The compressor compresses the air and sends it to the burning chamber. While the compression the air is also heat. In the burning chamber air is met with the natural gas and combustion occurs. Here the continuity of air flow and natural gas spray is really important. Since disturbances in those will result a trip which prevent generation of electricity. Moreover 25% of the air flow is used to cool down the burning chamber walls.

Heated air coming out from the burning chamber is send to the turbine and met with the turbine blades, where its heat energy is converted into mechanical energy with the movement of turbine blades.

The movement of the turbines blades inverted to electricity in the generator. By this way gas turbine z can produce 38 MW/h of electricity.

The exhaust of the gas turbine is still hot and can be used to produce steam. In this part of the cogeneration, waste heat boilers have an important role. The efficiency of the whole system is kind of depends on the waste heat boilers performances. In İzmit Refinery there is one waste heat boiler attached to the gas turbine and can produce 70 tons of VHP steam in hour. Working principle of a waste heat boiler is same as the heat exchangers. Heat exchange is done throughout the finned tubes. Exhaust of the gas turbine met with the finned tubes in the waste heat boiler and releases its energy.

1.3. Description of the Utility System

TÜPRAŞ İzmit Refinery supply the power and steam demands of refining processes with its utility plants which are Plant A and Plant B .

Figure 1 presents the simplified flowchart of the utility system of TÜPRAŞ Izmit Refinery in which each unit connected to a utility header depending on the inlets and outlets of the equipment. Equipments are represented as rectangle and arrows indicate the connections between equipments and to the headers. This configuration considers only the systems that are subject to optimization.

In the figures Plant A and Plant B are shown together in order to understand the working mechanism of the total Utility system.

For the first figure, black lines represent the fuels of the boilers and the gas turbine which are natural gas, fuel gas and fuel oil. Red lines are the steam headers (VHP, HP, MP, LP & Condensate). Blue lines are the connection between headers and the equipments. Last yellow line indicates the electricity.

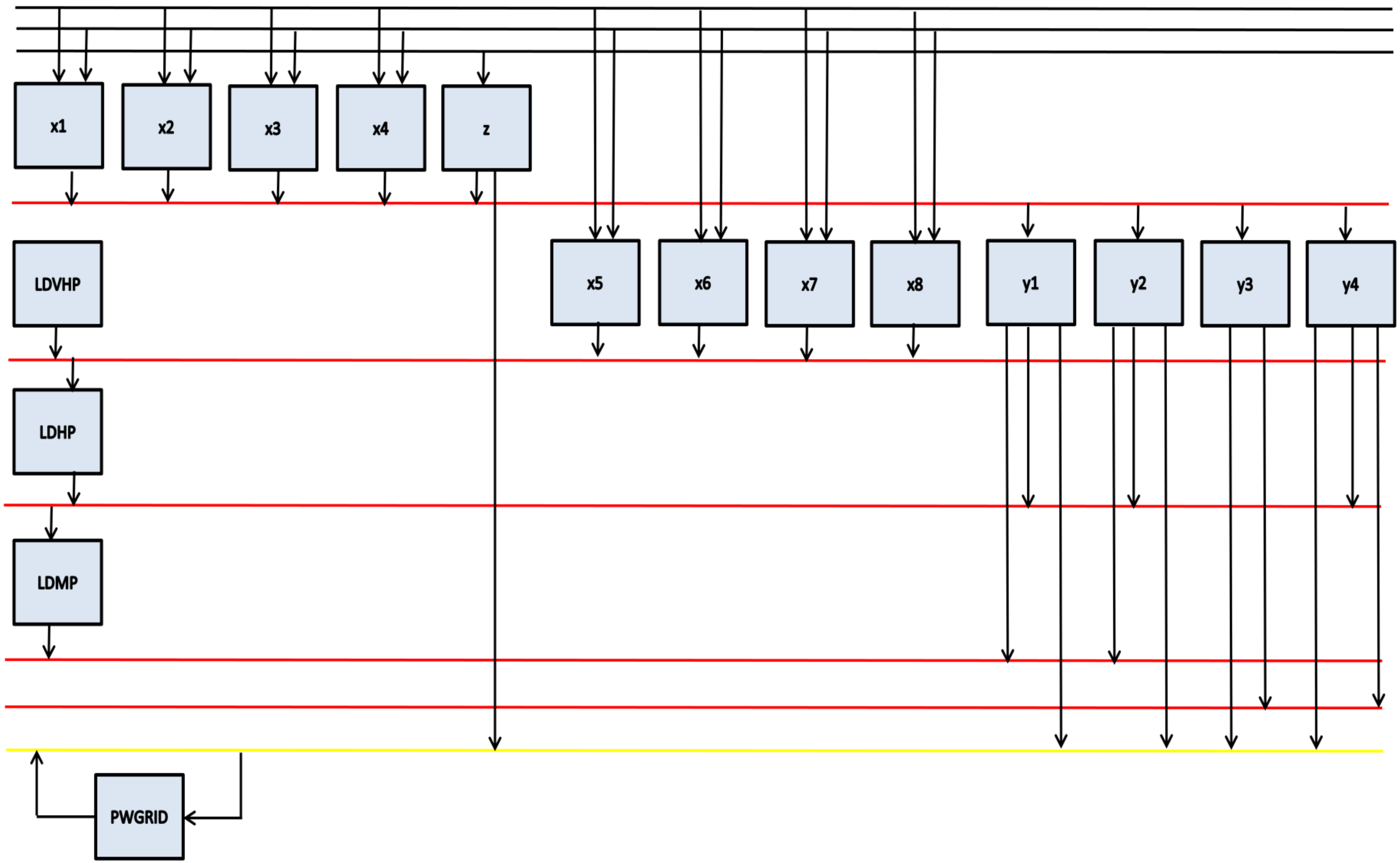

Figure 2 Utility System in Izmit Refinery

1.3. Objective of the Study

Electricity and steam pose significant challenges in the daily operation of oil refineries due to the fact that they cannot be inventoried for later use. Therefore, production planning to fulfill the steam and electricity demand, considering fluctuations in the price of electricity within a day, is one of the primary objectives. In this work, we present an industrial scale decision support system for the rational analysis of operational decisions. We present our MILP modeling approach and summarize the findings on an industrial case study.

The proposed model in this work considers the normal operation requirements for cogeneration in refineries. Upset scenarios are left beyond of the scope of this work. Moreover demands of the refinery are taken from PHD (process historian database) which collects and store the data within a given time period that can vary from 1 second to a monthly average. This paper presents multi-period, multiple choices of equipments with different efficiencies and multiple scenarios, regarding different electricity prices within a day, optimization and decision model. Electricity price fluctuations are also not considered as a part of the work. The model will be formulated as MILP and be implemented into GAMS solver. Cplex Solvers is used according to objective and constraints of the model.

Chapter2

Literature Review

2.1. Existing Methods

There have been significant research efforts and progress in the optimization of utility systems in the last three decades. Various optimization methods for cogeneration planning were reviewed by [Hobbs, 1995]. Optimizations of the systems are formulated using mixed integer programming framework where some of the variables are restricted to be integers, and equipments are modeled using linear and non-linear approaches depending on the precision of the study. Papoulinas and Grossman [1983] proposed a mixed integer linear programming (MILP) approach as Kalitventzeff [1991] do for solving the utility control strategy problem.

As the mixed integer programming offers a solution for utility systems which need discrete decisions such as an on/off switch. For longer period optimization of these systems, Hui and Natori [1996] suggested formulating the optimization problem using multi period mixed integer programming. The multiple periods can be developed depending on the nature of the system or based on periodical variations such as daily or hourly.

For the uncertainties in mixed integer programming some further improvements are made by [Papalexandri et al., 1996] and [Papalexandri et al., 1998] which use the past variations to identify uncertainties in the energy demand of normal operating conditions. In addition [Velasco-Garcia et al., 2001] suggested successive mixed integer linear programming to consider the shut-downs and start-ups of the utility systems equipments and to get a good amount of saving. You may have serious difficulties in using these methods if the variations of the processes are too great to distinguish in discrete time periods.

There are also other methods which can be used to determine the optimal control or operating strategies for utility systems. Heuristic rule-based expert system can be used to minimize the net cost of energy provided to the plant by Yi et al. [1998]. Steady-state modeling and steam generation models, where the steam generation allocated different common headers, were used to develop the expert system. Steam generation models use Newton's iteration method and linear programming algorithms in order to get the optimal result. The study done by [Kim and Han, 2001] included switching cost of operation determined using dynamic programming to improve short-term heuristic optimal planning model. Decision mapping method, which is similar to Kim and Hans, was proposed by [Halasz et al., 2002].

Moreover, for the optimal control strategy for the utility systems, other applications have also used similar framework to minimize the operational cost. Maréchal and Kalitventzeff [1998] proposed a model which uses the combination of mixed integer optimization and an expert system to determine optimal configuration of the utility system for satisfying minimum energy requirements at minimum cost. Kim et al. [2002] discussed the preventative optimization framework which was considered as emergency situations in the optimization models by using quantitative constraints while working with system failures. For dealing with the prediction errors in energy demand Yi and Han [2001] and [Yi et al., 2003] integrated re-planning and rule-based optimal operation. The modeling of a nonlinear planning and scheduling problem for refinery operation using large scale mixed integer programming was discussed by [Pinto et al., 2000]. Pinto had shown how objective function and constraints in optimization models could be formulated for refinery production. Both discrete and continuous time representations approaches were tested by Pinto for optimization results using mixed integer framework and the work has focused on the development of nonlinear models. Zhang et al. [2001] and Micheletto et al. [2008] discussed the overall refinery optimization through the integration of different process units in a mixed integer optimization model.

1.4. Issues and Problems

Since every utility system has its own specialties it is difficult to integrate one of the suggested approaches explained above to the utility system of TÜPRAŞ İzmit Refinery. In most of the existing techniques focusing on mixed integer problem framework are not taking into account of constraints interactions. The constraints are generally formulated for a single purpose such as maximizing electricity production or minimum flow rates. In general those constraints should be affected by each other because alteration of a constraint can have an impact on the other one. To sum in those studies, the effect on the optimal solution due to constraints interactions are generally ignored.

Since the utility system in İzmit Refinery is a unique one. Specific constraints and mixed integer linear programming is required. In order to determine the equipments on/off states mixed integer programming is a must for this study. Moreover the optimization results will be used for the real case the run time of the optimization is also one of the main concerns. In order to achieve this mixed integer linear programming is used.

Chapter 3

Optimization of the Utility System

3.1. Introduction

To propose a quick and reliable optimization model for optimizing the utility system in İzmit Refinery, equipments regression models are done. Depending on the thermodynamic knowledge and the historical data, regression models of the equipments are formed.

Next step is to propose and optimization model which ensures the mass and energy balances around the utility system. For this purpose we had to determine the decision variables and create the regression models based on those variables.

3.2. Regression Models

3.2.1. Boilers Regression Models

In TÜPRAŞ İzmit Refinery there are two types of boilers which are grouped as VHP producers and HP producers. VHP producing boilers are located in Plant A and the HP producing in Plant B.

For the regression models of the boilers fuel flows and the boiler feed waters are considered. For an example regression models of boilers x6 and x1 are given below.

General regression models of the boilers are respectively;

$$F_s\,(x) = p0 + p01 * F_{fg}(x) + p02 * \; F_{fo}(x) \qquad (3.1)$$

Where, $F_s\ (x)$ represents the steam production of the boiler x. $F_{fg}(x)$, $F_{fo}(x)$ are the fuel gas and fuel oil inlet flows of boiler x, and finally p's are the constants.

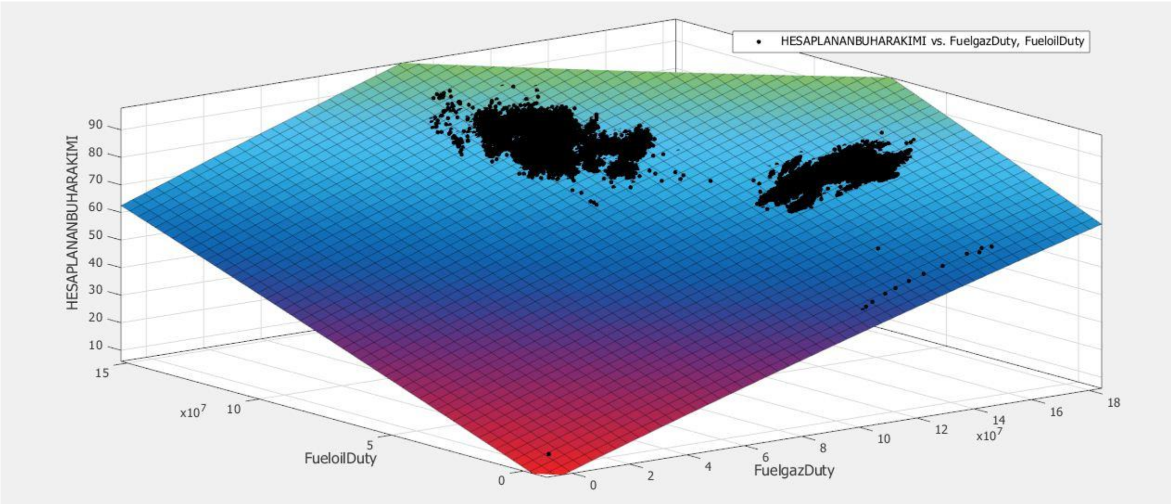

Figure 3 Regression model of boiler x6

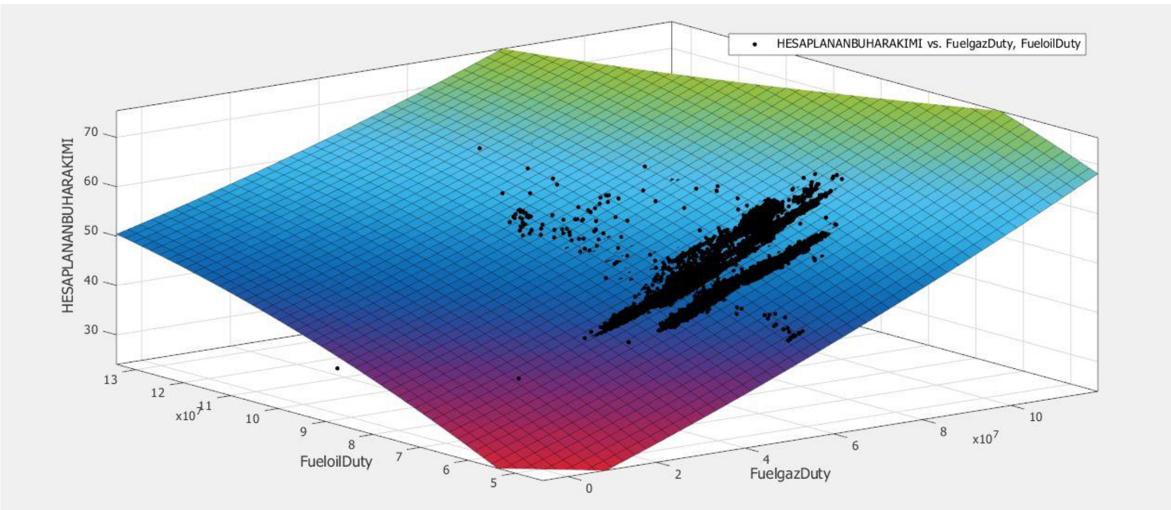

Figure 4 Regression model of boiler x1

These regression models are done for every boiler and used in the optimization model to determine the steam production and fuel consumptions of the boilers.

3.2.2. Regression Models of Steam Turbines

There are 4 steam turbines in the utility system of İzmit Refinery. All of these steam turbines consume VHP in order to produce electricity. Two of these steam turbines are identical and has 2 side draws MP and LP. Third one is a condensing unit which has only condensate outlet. The fourth one has three side draws (HP, MP and condensate) and has the biggest capacity.

The general regression model for the steam turbines is;

$$Power\ generation = a * F_{HP} + b * F_{MP} + c * F_{LP} + d * F_{Cond} + e \qquad (3.2)$$

$$Steam\ Consumption = F_{HP} + F_{MP} + F_{LP} + F_{Cond} \qquad (3.3)$$

Where *F*'s are the side draws of the steam turbine these draws can be HP, MP, LP or condensate. Moreover a, b, c, d and e are the representation of the constants. This formula differs for each steam turbine depending on the number and the properties of the side draws. As an example regression model of steam turbine y1 is given in the *Figure 5.*

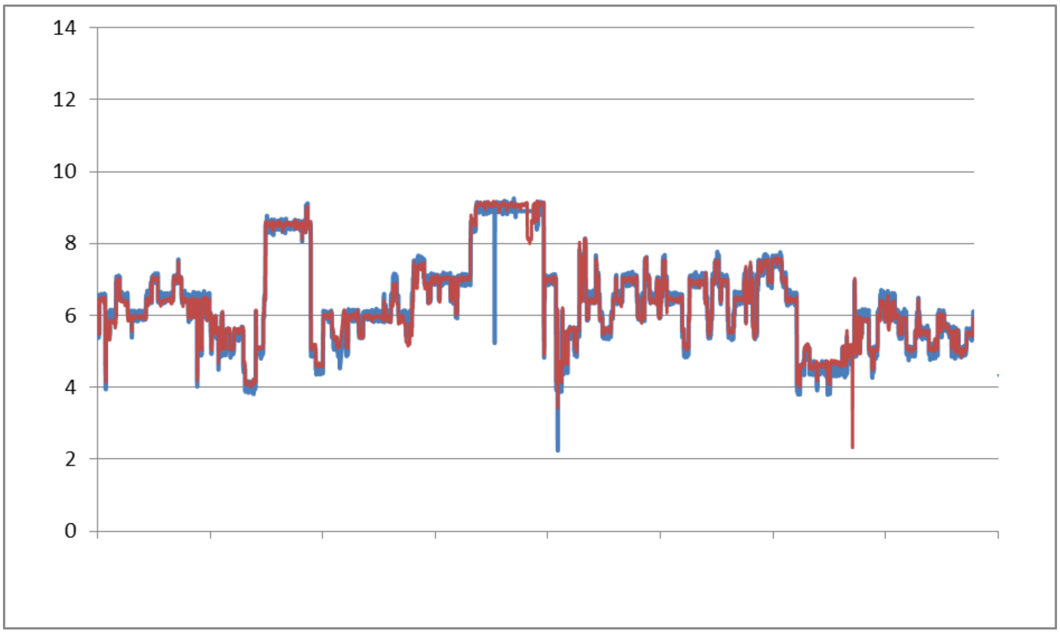

Figure 5 Regression Model of Steam Turbine y1

3.2.3. Regression Model of Gas Turbine

TÜPRAŞ İzmit Refinery utility plants have a gas turbine and a HRSG attached to it. The maximum electricity generation capacity of the gas turbine is 38 MW/hour and the maximum VHP steam production capacity of the HRSG is 70 ton/hour. The regression models for both gas turbine and HRSG are depending on the natural gas consumption of the gas turbine. This is valid since the HRSG produces VHP steam by using the exhaust or the gas turbine and the amount and the temperature of the exhaust is directly proportional with the amount of natural gas used.

The general regression models for electricity production and VHP steam production are;

$$Power\ production = p_1 * F_{ng} + p_0 \qquad (3.4)$$

$$Steam\ Production = p_2 * F_{ng} + p_3 \qquad (3.5)$$

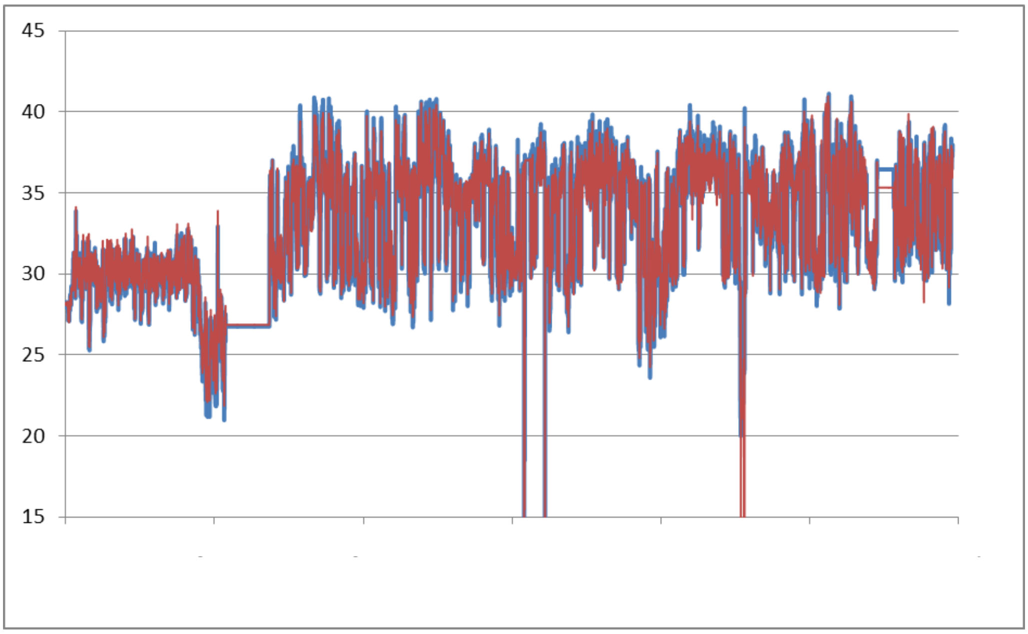

Figure 6 Regression Model of the Gas Turbine z

3.3. Optimization Model

In this section of the work, optimization model of the utility system of the TÜPRAŞ İzmit Refinery will be investigated in details.

We start with objective function and then continue with decision variables, parameters and constraints.

3.3.1. Objective Function

The main aim of the optimization is cost deduction of energy production process. In this manner the objective function the optimization system is about cost minimization. The objective function of the system is

$$\min z = \sum cost(s,t) * stream\ (s,t) \tag{3.6}$$

For the given objective function,

- z is the total cost,
- cost (s,t) represents the cost of stream *s* at time *t*
- stream (s,t) represents the amount of the flow of stream *s* at time *t*

To sum up consumed fuels and bought electricity from the grid are taken as cost where the sold electricity is deducted from the overall cost.

3.3.2. Decision Variables

In the decision step of the decision variables, utility system needs are taken into consideration. Since the optimization model should determine the on/off switch of the equipments there should be integer variables and for the continuous flows it is need to have continuous variables. Both of the variables are given below

Table 6 Decision Variables

Continious Variables	Flows	Stream (s,t)	Amount of stream s at time t
Integer Variables	Modes	Mode (asset,m,t)	mode m of equipment asset at time t

3.3.3. Parameters

Optimization model has parameters that cannot be changed by the model. These parameters can be static which never change or dynamic which can vary throughout the day.

Static parameters are the equipments regression model parameters which can also updated by the users depending on the behavior of the equipments. These parameters should be updated with time since the equipment efficiencies generally decreases with time due to the dirt accumulated in them.

On the other hand dynamic parameters consist of fuel prices, energy demand of the refinery and the steam demand of the refinery. These parameters can be changing in each hour and are given to the model.

Table 7 Dynamic and Static Parameters

Dynamic parameters	pCOST(s,t)	cost of stream s at time t
	pDEMAND(s,t)	demand in stream s at time t
Static parameters	Pfixed (GRP,ASSET,CONSTANT)	regression model parameters of equipments

3.3.4. Constraints

As all the refinery processes, utility system has constraints that you cannot change even you are able to find a better solution, safety constraints. The optimization model is created around these constraints. The optimum solution should not violate the safety of the workers or the refinery.

There are also other constraints, which are,

- **Refinery demand**, refinery demand should be met.
- **Equipment constraints**, Maximum and minimum limits of the equipments.
- **Electricity buy/sell constraints**, It s not possible to buy all the electricity from the grid because the failure in the grid will end up with a black out in the refinery or you cannot produce too much in order to sell it to the grid. This is not a electricity supplier.

- **Equipment models,** Natural behavior of the equipments. These can also be taken as constraint.

Refinery Demand

The main aim of the utility system is to ensure that refining processes demands are to be met. The general formulation of the supply demand is as follows,

$$stream(sDEMAND, t) = \mathrm{p}DEMAND(sdemand, t) \;\; \forall t \tag{3.7}$$

Where

- pDemand (sdemand, t) represents refinery demand on stream *sdemand* at time *t*
- stream (sDemand, t) represents amount of stream *sDemand* at time *t*
- *sDemand* represents the set of streams that refinery is demanding

Equipment Constraints

Equipments maximum and minimum limits are given in *Table 8* and *Table 9*. In both tables productions and consumption are given for both steam producers and electricity producers.

Table 8 Steam Producers constraints

	Consumptions				Production
	FG(m3/h)		FO (ton/h)		ST(ton/h)
	min	max	min	max	max
X1	2566	9309	1,5	8,5	110
X2	2566	9303	1,5	8,5	110

X3	2566	9303	1,5	8,5	110
X4	2566	9309	1,5	8,5	110
X5	1840	4480	1,4	8	100
X6	3200	9120	2	10,5	150
X7	3200	9120	2	10,5	150
X8	304	965	0,53	8,7	80

For the steam producers, consumption constraints taken as fuel consumption which are fuel gas and fuel oil. On the other hand production constraints include VHP steam production for Plant A boilers and HP steam Production for Plant B boilers.

Table 9 Steam Turbines Constraints

	Stin (ton/h)		STout1 (ton/h)		STout2 (ton/h)		STout3(ton/h)		PW (MWh)	
	min	max	min	max	min	max	min	max	min	max
Y1	0	100	0	50	20	65	0	0	2,25	9,25
Y2	0	100	0	50	20	65	0	0	2,25	9,25
Y3	0	44	0	44	0	0	0	0	2,25	9,25
Y4	0	120	0	40	0	70	15	60	2,5	14

Steam Turbines and gas turbine can be called as electricity producers for the case of İzmit Refinery. For steam turbines inlet is always VHP steam where gas turbine uses natural gas to produce electricity.

Since VHP steam is break down into lower pressurized steams in the steam turbines the constraints also includes the amount limitations on the side draws as well as amount of VHP steam.

For the gas turbine natural gas consumption and electricity production are taken as constraints.

Electricity buy/sell Constraints

The main concern for producing electricity in refineries is to sustain refining processes and safety. Exporting electricity from the grid can be seen as an option; however any failure in the national grid will lead black out, which is dangerous and loss of huge money. For this purposes as most of the refineries Tüpraş İzmit Refinery can produce its own electricity in the utility plants. But this does not mean that refinery has no connection with the national grid. There is a connection but this buy/sell electricity issues are done depending on strict constraints. If there is no emergency situation then the buy and sell limits of electricity are 10 MWh.

$$stream(PWbuy, t) \leq 10 \ \ \forall t \qquad (3.8)$$

$$stream(PWsell, t) \leq 10 \ \ \forall t \qquad (3.9)$$

It is also forbidden to make buying and selling operations at the same time.

$$\sum mode(PWGRID, m, t) = 1 \ \ \forall t \qquad (3.10)$$

Where; *mode* represents the operation type.

Safety Constraints

Safety constrain is needed in order to sustain the refining operations. Here the safety constraint includes the substitute policy of the boilers. If there is an upset in one of the boilers the others should burden the load of the upset boiler.

Equipments Models

In this section the equipments models that are going to be used if the equipments are on. These models are divided into three groups, which are;

- Boilers,
- Steam Turbines,
- Gas Turbine

In order to decide whether the equipment is on running or which fuel is used in the boilers, modes of operations are identified. For the boilers modes represent the fuel type whereas for the gas and steam turbines these modes used for on/off status. Moreover these modes are also used to decide the interaction between national grid and the refinery.

Table 10 Modes of Equipments

	MODE 1	MODE 2	MODE 3
Boilers	Fuel Gas	Fuel Oil	Fuel Gas + Fuel Oil
Steam Turbines	on		
Gas Turbine	on		
National Grid	Electricity buy	Electricity sell	

Inlet streams of the equipments are formulated as *(PLT, GRP, ASSET, INNER, S)*. By this way equipments in different plant can be differ from each other and streams in and out of an equipment are classified.

Moreover modes of equipments are formulated as *(GRP, ASSET, MODE).*

Since equipment cannot work in two modes at the same time a constraint is needed to prevent such a situation. The answer is given such as;

$$\sum mode(asset, m, t) \leq 1 \tag{3.11}$$

Maximum and minimum limits of equipments are multiplied by the on/off mode of equipment so that constraints are valid if the equipment is on running. Otherwise the constraints forced to be zero.

$$STREAM(\mathrm{PLT, GRP, ASSET, INNER, S}) \leq \mathrm{mode}(\mathrm{GRP, ASSET, MODE}) * \max_{\mathrm{STREAM}} \quad \forall t \tag{3.12}$$

$$STREAM(\mathrm{PLT, GRP, ASSET, INNER, S}) \geq \mathrm{mode}(\mathrm{GRP, ASSET, MODE}) * \min_{\mathrm{STREAM}} \quad \forall t \tag{3.13}$$

$$STREAM(\mathrm{PLT, GRP, ASSET, INNER, S}) = STREAM(\mathrm{PLT, GRP, ASSET, INNER, S}) + \mathrm{SUM}(\mathrm{mode}(GRP, \mathrm{ASSET, MODE})) * \mathrm{constant} \quad \forall t \tag{3.14}$$

3.3.5. Boilers

The regression models of the boilers are dependent on the fuel that is consumed by that boiler. From consumed fuel gas and fuel oil, amount of steam produced is calculated.

In order to use fuel oil as a fuel in the boilers, *atomized steam* must be used to atomize the fuel oil. For the atomization process MP steam is injected to the fuel oil in the entrance of the boiler. This situation is also considered while constructing the model.

Pre-heaters are also another concern here. The air that is given to the burners should be pre-heated in order to provide efficient burning. For pre-heating process LP steam is used. The amount of LP steam is also modeled in the optimization process.

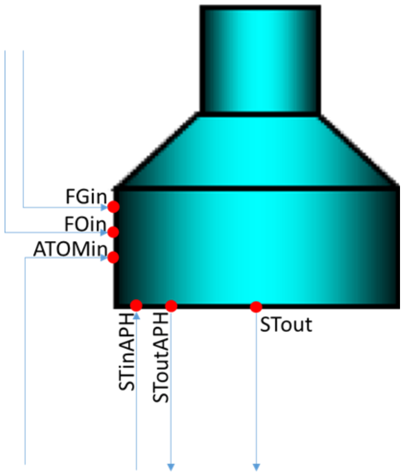

Figure 7 Flow Diagram of a Boiler

Where;

- *Stout* is representation of produced steam,
- *STinAPH* is the representation of the LP consumed in the air pre-heater system
- *SToutAPH* is the representation of the condensate flow leaving the air pre-heater
- *ATOMin* is the representation of the amount of MP steam given to the atomization system

So the general formulations for boilers, atomization system and air pre-heater system are given as;

$$stream(STout, x - HP) = p_{FIXED}(x, coef_{FG-ST}) * stream(x, FGin) + p_{FIXED}(x, coef_{FO-ST}) * stream(x, FOin) + p_{FIXED}(x, coef_{0-\mathrm{ST}}) * SUM(mode(x, m, t)) \tag{3.15}$$

Where,

- x : Boiler name
- *stream (Stout, x-HP) :* flow rate of *HP* (this can be HP or VHP depending on the boiler) steam from boiler *x*
- $p_{FIXED}(x,coef_{FG-ST})$: fuel gas constant for boiler *x*
- *stream(x, FGin)* : amount of fuel gas to the boiler *x*
- $p_{FIXED}(x,coef_{FO-ST})$: fuel oil constant for boiler *x*
- *stream(x, FOin)* : amount of fuel oil to the boiler *x*
- $p_{FIXED}(x,coef_{0-ST})$: regression constant for boiler *x*
- *mode(x,m,t)*: mode of boiler *x* at time *t*

Air Pre-heater System is modeled as follows;

$$stream(STinAPH, x-LP) = p_{FİXED}(x, coef_{ATOMin}) * stream(STout, x) \tag{3.16}$$

- *stream (STinAPH, x-LP)* : amount of *LP steam* given to the air pre-heater system
- $p_{FIXED}(x, coef_{APH})$: regression constant for air pre-heater system
- *stream (STout, x)* : amount of produced steam from boiler *x*

Atomizing steam consumption depends on the fuel type used. If boiler consumes fuel oil then amazing is required.

$$stream(ATOMin, x-MP) = +p_{FIXED}(x, coef_{FO-ATOM}) * stream(x, FOin) \tag{3.17}$$

- *stream (Atomin,x-MP)* : amount of MP steam consumed for atomizing process
- p_{FIXED} $(x, coef_{FO\text{-}ATOM})$: regression constant
- *stream(x,FOin)*: Amount of fuel oil consumed in boiler *x*

3.3.6. Steam Turbines

The regression model for the steam turbines considers the relationship between produced electricity and the flow rates of the side draws of the steam turbines. Finally in order to sustain the mass balance, sum of the flow rates of the side draws are equalized to the inlet VHP steam amount.

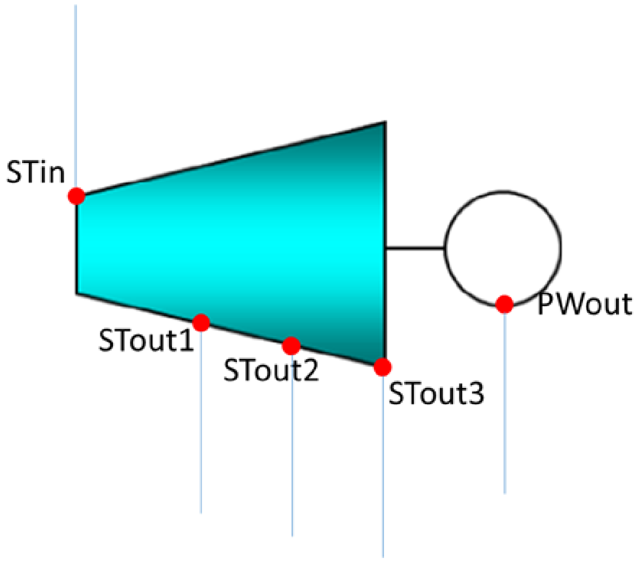

Figure 8 Steam Turbine Flow Diagram

Where,

- *STin* represents the amount of VHP steam entering the steam turbine
- *Stout*s represent the side draws of the steam turbine
- *PWout* represents the power production of the steam turbine

The general formulations of the steam turbines as follow;

$$stream(STin, y) = stream(y, STout1) + stream(y, STout2) + stream(y, STout3) \tag{3.18}$$

$$\begin{aligned} stream(PWout, y) \\ = p_{FiXED}(y, coef_{STout-1}) * stream(y, STout1) + p_{FiXED}(y, coef_{STout-2}) \\ * stream(y, STout2) + p_{FiXED}(y, coef_{STout-3}) * stream(y, STout3) \\ + p_{FiXED}(y, coef_{STout-4}) * stream(y, STou4) + p_b(y, coef_0) \\ * (SUM(\mathrm{mode}(\mathrm{y}, \mathrm{m}, \mathrm{t})) \end{aligned} \tag{3.19}$$

Where,

- $p_{FiXED}(y, coef_{STout})$: represents the regression constant for side draws
- $stream(y, STout)$: represents the flow rate of side draws
- $\mathrm{mode}(\mathrm{y}, \mathrm{m}, \mathrm{t}))$: represents the on/off mode of the steam turbine

The first equation is for the mass balance and the second one is the regression model represents the relationship between side draws and the electricity production.

3.3.7. Gas Turbine

In this section we will investigate the optimization model of the gas turbine. Here gas turbine and the attached HRSG are taken as one unit. Electricity production from gas turbine and the VHP steam production from HRSG are related to the natural gas consumption of the gas turbine.

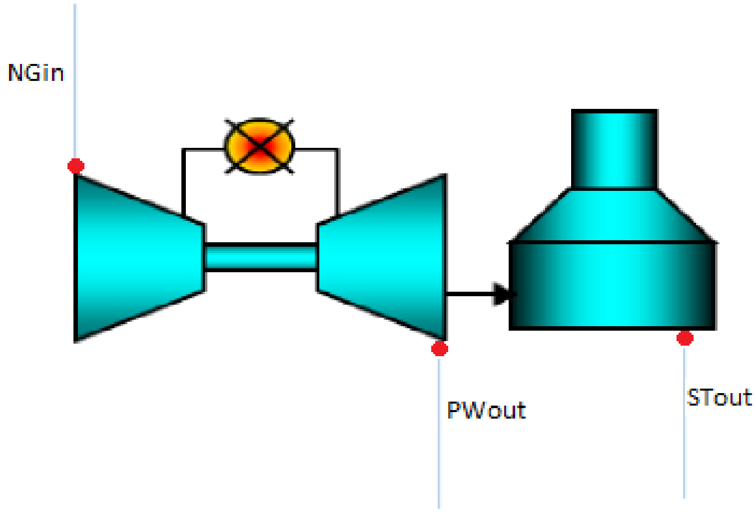

Figure 9 Gas turbine and HRSG flow diagram

Here *NGin* represents the flow rate of the natural gas entering the gas turbine, whereas *PWout* and *STout* represent electricity production and the VHP steam production respectively.

VHP steam production from HRSG is formulated as follows,

$$stream(STout, z-VHP) = p_{FIXED}(z, coef_{NG2}) * stream(z, NGin) + p_{FIXED}(z, coef_{02}) * (SUM(mode(z,m,t)) \qquad (3.20)$$

Where,

- $stream(STout, z-VHP)$ represents the flow rate of VHP steam produced
- $p_{FIXED}(z, coef_{NG2})$ and $p_{FIXED}(z, coef_{02})$ are the regression constants

- $mode(z, m, t)$ represents the on/off mode of gas turbine

Electricity production of the gas turbine represented as,

$$stream(PWout, z - PW) = p_{FIXED}(z, coef_{NG1}) * stream(z, NGin) + p_b(z, coef_{01}) \tag{3.21}$$

Where,

- $stream(PWout, z - PW)$ represents electricity production of gas turbine
- $p_{FIXED}(z, coef_{NG1})$ and $p_b(\mathrm{z}, coef_{01})$ are the regression parameters
- $stream(z, NGin)$ is the natural gas flow rate entering the gas turbine

3.3.8. Piece-Wise Linearization

Piece-wise linearization is a must in this study due to on/off modes of equipments and different behaviors in different inlet and working conditions. In order to have linear model there should not be a multiplication of any variable in any of the equations.

To prevent this kind of multiplications multiple choice method, which is a type of piece-wise linearization, is selected and used in the models.

For this purpose the constants of the regression models are multiplied by the mode of the equipment. By this way when the mode of the equipment is “0”the whole equation becomes zero.

$$STREAM(\mathrm{PLT, GRP, ASSET, INNER, S}) \leq \mathrm{SUM}(\mathrm{mode}(\mathrm{GRP, ASSET, MODE})) * \mathrm{max}_{\mathrm{STREAM}} \ \forall t \tag{3.22}$$

$$STREAM(\mathrm{PLT, GRP, ASSET, INNER, S}) \geq \mathrm{SUM}(\mathrm{mode}(\mathrm{GRP, ASSET, MODE})) * \mathrm{min}_{\mathrm{STREAM}} \ \forall t \quad (3.23)$$

$$STREAM(\mathrm{PLT, GRP, ASSET, INNER, S}) = STREAM(\mathrm{PLT, GRP, ASSET, INNER, S}) + \mathrm{SUM}(\mathrm{mode}(GRP, \mathrm{ASSET, MODE})) * \mathrm{constant} \ \forall t \quad (3.24)$$

3.4. Computational Results

3.4.1. Evaluation of Optimization Model

The created optimization model is used on different cases and the results are investigated with the Tüpraş Energy Management Department and the results are found to be reliable. When the results are compared with the past data and operational data it is seen that the results are satisfactory.

3.4.2. Optimization Results

In general with the optimization model that is created, offline optimization studies can be done depending on the day ahead prices of electricity or the daily electricity prices.

The evaluation of the optimization results are made by the Energy Management Department of Tüpraş and these results are found to be feasible when the past data are considered. For the case studies September 2013 and December 2013 data are taken from the process historian database and steam and electricity productions and the total cost of the utility system are compared with the results of the optimization. Case selection decisions are made upon the times when there is no upset occurred. The energy required for the refining processes are gathered from the hourly data of electricity and steam productions of the utility system.

The prices of the natural gas, fuel oil and fuel gas are also taken from the Energy Management Department of Tüpraş and total cost of the utility system is calculated upon those prices.

The day ahead electricity offers are taken from the PMUM which is a website run by government where all the offers from suppliers and customers are collected. These data are gathered as hourly bases and given into the optimization model as an input.

The results of the case studies are given below with the actual data for each day

Table 11 Actual Process Data

	Electricity	VHP steam	HP steam	MP steam	LP steam	Fuel gas	Fuel Oil	Natural gas
	MW	ton/hour	ton/hour	ton/hour	ton/hour	m3/hour	ton/hour	lbm/sec
05.09.2013 00:00	49,31	164,68	143,93	62,18	52,21	16889,93	1,86	5,27
05.09.2013 01:00	49,1	166,17	146,21	62,18	55,28	17437,77	1,91	5,24
05.09.2013 02:00	49,11	164,98	150,29	60,42	55,91	18037,53	2	5,22
05.09.2013 03:00	48,96	164,22	153,37	59,13	56,07	18235,13	2,07	5,24
05.09.2013 04:00	49	161,49	152,87	58,81	53,33	18119,92	2,05	5,23
05.09.2013 05:00	49,12	160,8	153,72	58,96	52,7	18070,06	2,07	5,21
05.09.2013 06:00	48,99	162,13	151,86	59,33	52,37	18007,58	2,02	5,23
05.09.2013 07:00	48,6	161,52	151,22	60,18	52,65	17830,04	2,04	5,37
05.09.2013 08:00	48,24	161,35	150,5	59,99	52,67	17741,21	2	5,39
05.09.2013 09:00	48,75	161,33	150,51	59,77	53,49	18055,81	1,89	5,38
05.09.2013 10:00	49,13	161,88	150,76	59,65	55,99	18118,18	1,92	5,35
05.09.2013 11:00	49,09	148,81	153,07	57,78	55,43	17873,12	1,91	5,33

05.09.2013 12:00	48,76	126,36	159,93	56,38	49,81	17227,35	1,97	5,32
05.09.2013 13:00	48,42	114,01	160,45	56,56	49,2	17056,73	1,95	5,34
05.09.2013 14:00	48,2	126,9	159,5	57,73	49,13	16994,06	1,92	5,34
05.09.2013 15:00	48,44	157,44	158,21	55,89	50,63	16857,48	1,91	5,36
05.09.2013 16:00	48,49	159,56	164,11	55,7	51,58	17373,16	1,96	5,36
05.09.2013 17:00	49,11	157,68	166,63	55,46	45,44	16824,54	1,91	5,3
05.09.2013 18:00	49,63	156,75	162,92	50,36	48,68	14681,13	1,8	5,28
05.09.2013 20:00	52,92	154,04	181,3	37,41	39,22	16039,14	1,92	5,18
05.09.2013 21:00	53,51	156,6	183,75	37,22	39,19	16518,44	1,93	5,29
05.09.2013 22:00	53,39	158,68	169,5	40,37	40,59	15446,25	1,77	5,3
05.09.2013 23:00	53,67	158,77	166,55	45,59	44,42	15927,94	1,79	5,35
Average	**49,72**	**154,99**	**159,07**	**54,48**	**49,95**	**17114,06**	**1,94**	**5,29**
Total	**1193,24**	**3719,76**	**3817,71**	**1307,46**	**1198,87**	**410737,5**	**46,51**	**127,08**

The prices of the natural gas, fuel oil and fuel gas for the same time are given in *Table 12.*

Table 12 Prices of Fuels

Natural gas	0,459033056	TL/lbm
Fuel oil	1202,8	TL/ton
Fuel gas	0,659736	TL/m^3

The cost of used fuels and the total cost for the same time are given in the *Table 13*.

Table 13 Cost of Fuel used in Utilities

	Cost of Fuel oil	Cost of Fuel gas	Cost of Natural gas	Total Cost
	TL	TL	TL	TL
05.09.2013 00:00	2105,4	11142,9	8702,37	21950,7
05.09.2013 01:00	2168,4	11504,3	8654,95	22327,7
05.09.2013 02:00	2265,7	11900	8632,67	22798,4
05.09.2013 03:00	2353,1	12030,4	8662,59	23046,1
05.09.2013 04:00	2326,6	11954,4	8646,11	22927,1
05.09.2013 05:00	2343,4	11921,5	8616,74	22881,6
05.09.2013 06:00	2293,8	11880,3	8635,26	22809,3
05.09.2013 07:00	2313,1	11763,1	8880,5	22956,7
05.09.2013 08:00	2267,7	11704,5	8904,88	22877,1
05.09.2013 09:00	2140,6	11912,1	8894,97	22947,7
05.09.2013 10:00	2174,5	11953,2	8835,55	22963,3
05.09.2013 11:00	2161,8	11791,5	8809,5	22762,9
05.09.2013 12:00	2237,1	11365,5	8790,66	22393,3
05.09.2013 13:00	2208,5	11252,9	8822,36	22283,8
05.09.2013 14:00	2184,2	11211,6	8832,4	22228,2
05.09.2013 15:00	2167,5	11121,5	8850,36	22139,3
05.09.2013 16:00	2225,1	11461,7	8856	22542,8
05.09.2013 17:00	2172,7	11099,8	8765,13	22037,6

05.09.2013 18:00	2038	9685,67	8729,55	20453,3
05.09.2013 19:00	2216,4	10143,4	8569,22	20929
05.09.2013 20:00	2178,4	10581,6	8563,17	21323,2
05.09.2013 21:00	2193,6	10897,8	8744,19	21835,6
05.09.2013 22:00	2008,6	10190,5	8757,54	20956,6
05.09.2013 23:00	2032,1	10508,2	8845,26	21385,6
Average	**2199**	**11290,8**	**8750,08**	**22239,9**
Total	**52776**	**270978**	**210002**	**533757**

In the same day refinery not only produce its own need of electricity but also sell electricity to the national grid due. The price of electricity and the amounts that are sold or bought are given in *Table 14.* These data are also collected from PHD.

Table 14 Cost of Electricity Market Movements

	Bought Electricity		Sold Electricity		Net Amount	Price of Electricity	Total Cost
	MW		MW		MW	TL	TL
05.09.2013 00:00	0	0	1,37	1,15	-2,51	165	-414,67
05.09.2013 01:00	0	0	1,32	1,11	-2,43	154,95	-377,25
05.09.2013 02:00	0	0	1,23	1,05	-2,29	144,83	-331,13
05.09.2013 03:00	0	0	1,43	1,16	-2,59	130,01	-336,62
05.09.2013 04:00	0	0	1,14	0,92	-2,06	128	-263,27
05.09.2013 05:00	0	0	0,93	0,79	-1,72	127,99	-220,49

05.09.2013 06:00	0	0	1,04	0,92	-1,96	124,98	-244,77
05.09.2013 07:00	0	0	2,01	1,71	-3,72	129,99	-483,82
05.09.2013 08:00	0	0	2,26	1,91	-4,17	180,01	-750,22
05.09.2013 09:00	0	0	1,94	1,64	-3,58	201	-720,07
05.09.2013 10:00	0	0	1,67	1,4	-3,07	202	-620,01
05.09.2013 11:00	0	0	1,45	1,28	-2,73	203	-554,62
05.09.2013 12:00	0	0	0,93	0,87	-1,8	202	-364,23
05.09.2013 13:00	0	0	1,19	1,04	-2,23	203	-452,53
05.09.2013 14:00	0	0	1,37	1,13	-2,5	203	-506,94
05.09.2013 15:00	0	0	1,39	1,17	-2,56	203	-519,64
05.09.2013 16:00	0	0	1,37	1,14	-2,51	202,99	-510,42
05.09.2013 17:00	0,01	0,01	0,5	0,41	-0,89	200,99	-179,82
05.09.2013 18:00	0	0,01	0,57	0,42	-0,98	190	-186,09
05.09.2013 19:00	0,59	0,6	0,02	0,01	1,16	180,01	208,3
05.09.2013 20:00	1,93	1,72	0	0	3,65	194,99	712,08
05.09.2013 21:00	1,29	1,24	0	0	2,53	184,83	467,44
05.09.2013 22:00	1,01	0,99	0	0	2	199,99	399,56
05.09.2013 23:00	0,96	0,98	0	0	1,94	180,01	349,1
Average	**0,24**	**0,23**	**1,05**	**0,88**	**-1,46**	**176,52**	**-245,84**
Total	**5,79**	**5,54**	**25,13**	**21,23**	**-35,04**	**4236,57**	**-5900,1**

When all the costs and data are considered total cost of utility system is given in *Table 15.*

Table 15 Total Utility Cost

	Cost of Electricity	Cost of Fuels	Total Cost
	TL	TL	TL
05.09.2013 00:00	-414,67	21950,7	21536,03
05.09.2013 01:00	-377,25	22327,7	21950,4
05.09.2013 02:00	-331,13	22798,4	22467,27
05.09.2013 03:00	-336,62	23046,1	22709,49
05.09.2013 04:00	-263,27	22927,1	22663,78
05.09.2013 05:00	-220,49	22881,6	22661,1
05.09.2013 06:00	-244,77	22809,3	22564,54
05.09.2013 07:00	-483,82	22956,7	22472,9
05.09.2013 08:00	-750,22	22877,1	22126,89
05.09.2013 09:00	-720,07	22947,7	22227,59
05.09.2013 10:00	-620,01	22963,3	22343,29
05.09.2013 11:00	-554,62	22762,9	22208,24
05.09.2013 12:00	-364,23	22393,3	22029,03
05.09.2013 13:00	-452,53	22283,8	21831,3
05.09.2013 14:00	-506,94	22228,2	21721,23
05.09.2013 15:00	-519,64	22139,3	21619,66
05.09.2013 16:00	-510,42	22542,8	22032,42

05.09.2013 17:00	-179,82	22037,6	21857,77
05.09.2013 18:00	-186,09	20453,3	20267,16
05.09.2013 19:00	208,3	20929	21137,34
05.09.2013 20:00	712,08	21323,2	22035,25
05.09.2013 21:00	467,44	21835,6	22303,04
05.09.2013 22:00	399,56	20956,6	21356,11
05.09.2013 23:00	349,1	21385,6	21734,67
Average	**-245,84**	**22239,9**	**21994,02**
Total	**-5900,1**	**533757**	**527856,52**

All these data shows the actual utility plant working conditions. The results of the optimization are given in *Table16* and the difference between actual and the optimized results are compared.

Table 16 Optimized Results for Utility System

	Fuel Oil flow rate	Cost of Fuel Oil	Fuel gas flow rate	Cost of Fuel gas	Natural gas flow rate	Cost of Natural gas	Sold Electricity	Bought Electricity	Cost of Electricity	Optimized Cost
	ton/hour	TL	m3/hour	TL	lbm/sec	TL	TL	TL	TL	TL
05.09.2013 00:00	1,4	1588,72	16607,62	10956,65	5,16	8533,19	0	1,99	328	21405,96
05.09.2013 01:00	1,4	1588,72	16690,14	11011,09	5,16	8533,19	0	2,39	369,76	21502,15
05.09.2013 02:00	1,4	1588,72	16937,43	11174,23	5,16	8533,19	0	2,34	338,62	21634,15
05.09.2013 03:00	1,4	1588,72	17100,36	11281,73	5,16	8533,19	0	2,19	284,08	21687,11
05.09.2013 04:00	1,4	1588,72	16786,06	11074,37	5,16	8533,19	0	2,73	349,15	21544,83

05.09.2013 05:00	1,4	1588,72	16815,41	11093,73	5,16	8533,19	0	2,92	373,78	21588,82
05.09.2013 06:00	1,4	1588,72	16661,06	10991,9	5,16	8533,19	0	2,86	357,94	21471,15
05.09.2013 07:00	1,4	1588,72	16706,01	11021,56	5,16	8533,19	0	2,36	306,98	21449,85
05.09.2013 08:00	1,4	1588,72	16629,85	10971,31	5,16	8533,19	0	2,04	367,98	21460,6
05.09.2013 09:00	1,4	1588,72	16685,02	11007,71	5,16	8533,19	0	2,43	488,27	21617,3
05.09.2013 10:00	1,4	1588,72	16917,39	11161,01	5,16	8533,19	0	2,4	484,83	21767,14
05.09.2013 11:00	1,4	1588,72	16899,9	11149,48	5,16	8533,19	0	2,56	519,57	21790,35
05.09.2013 12:00	1,4	1588,72	16853,4	11118,8	5,16	8533,19	0	3,25	655,71	21895,81
05.09.2013 13:00	1,4	1588,72	16858,9	11122,42	5,16	8533,19	0	2,98	605,37	21849,1
05.09.2013 14:00	1,4	1588,72	16874,21	11132,52	5,16	8533,19	0	2,68	543,04	21796,87
05.09.2013 15:00	1,4	1588,72	16739,89	11043,91	5,16	8533,19	0	2,85	578,21	21743,42
05.09.2013 16:00	1,4	1588,72	17295,3	11410,33	5,16	8533,19	0	2,72	551,85	22083,47
05.09.2013 17:00	1,4	1588,72	16947,69	11181	5,16	8533,19	0	4,37	878,18	22180,48
05.09.2013 18:00	1,4	1588,72	16607,62	10956,65	5,16	8533,19	0	4,45	846	21923,97
05.09.2013 19:00	1,4	1588,72	16097,3	10619,97	5,16	8533,19	0	8,89	1600,29	22341,59
05.09.2013 20:00	1,4	1588,72	16248,09	10719,45	5,16	8533,19	0	10	1949,9	22790,68
05.09.2013 21:00	1,4	1588,72	16607,62	10956,65	5,16	8533,19	0	9,91	1831,96	22909,92
05.09.2013 22:00	1,4	1588,72	15706,47	10362,12	5,16	8533,19	0	10	1999,9	22483,37
05.09.2013 23:00	1,4	1588,72	16607,62	10956,65	5,16	8533,19	0	8,12	1461,13	22539,09
Average	**1,4**	**1588,72**	**16703,35**	**11019,8**	**5,16**	**8533,19**	**0**	**4,14**	**752,94**	**21894,05**
Total	**33,6**	**38129,3**	**400880,4**	**264475,22**	**123,93**	**204796,5**	**0**	**99,41**	**18070,49**	**525457,2**

When the results are compared with the actual data;

Total actual cost of utility system = 527.856,52 TL

Whereas total optimized cost = 525.457,20 TL

The percent deduction of total cost is calculated as;

$$\frac{527856{,}52 - 525457{,}20}{527856{,}52} = 0{,}4545\%$$

The other case scenarios results are given in *Table17.*

Table 17 Case Studies

Date	Cost of Fuel gas	Cost of Fuel oil	Cost of Natural gas	Cost of Electricity	Total of Actual Cost	Optimized Total Cost	Percent Improvement in Total Cost
	TL	TL	TL	TL	TL	TL	
01.09.2013	207730,13	54387,68	201630,09	-295,08	463452,83	461202,22	0,49%
05.09.2013	270978,28	52776,41	210001,93	-5900,10	527856,52	525457,20	0,45%
19.09.2013	181860,24	88315,02	208035,98	10216,86	488428,10	486608,49	0,37%
06.12.2013	207703,83	89797,40	191857,47	-13844,14	475514,55	473462,40	0,43%
15.12.2013	157831,35	108614,49	191361,71	322,45	458130,00	455746,74	0,52%

The result of the optimization offers average of 0,45 % cost deduction.

Model Results are given in *Table 18.*

Table 18 Model Results

Execution time(sec)	245,6
Average Total Cost (TL)	525457,2
# of Constraints	327

# of Variables	# of Binary Variables	45
	# of Continuous Variables	57
	Total # of Variables	102
# of Iterations with Cplex		14675

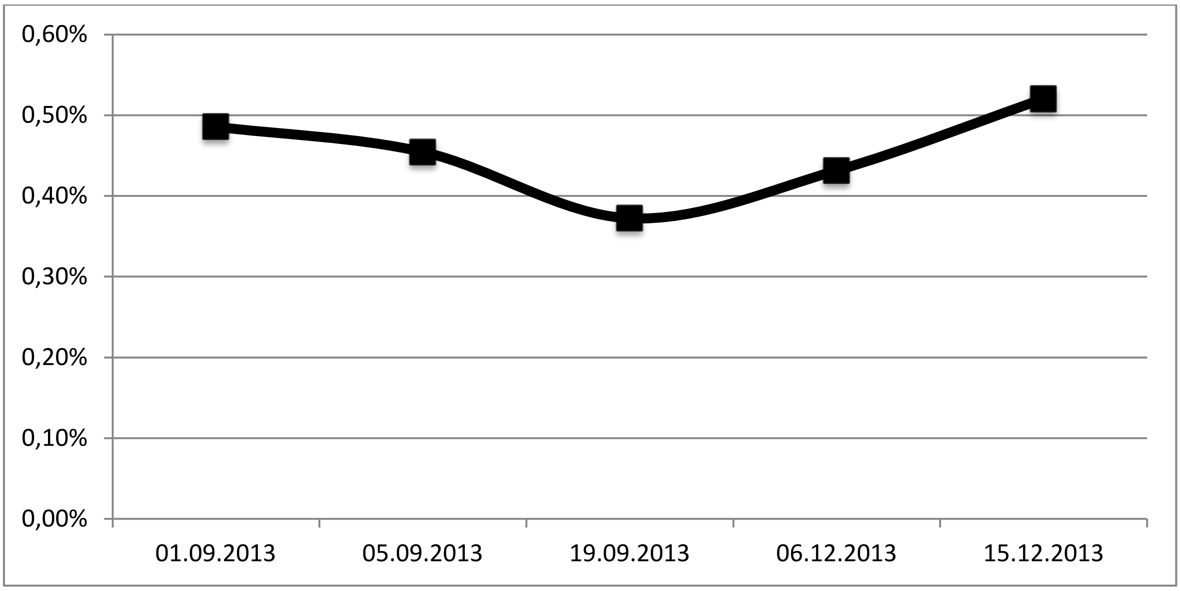

Figure 10 Percent Deduction in Total Cost

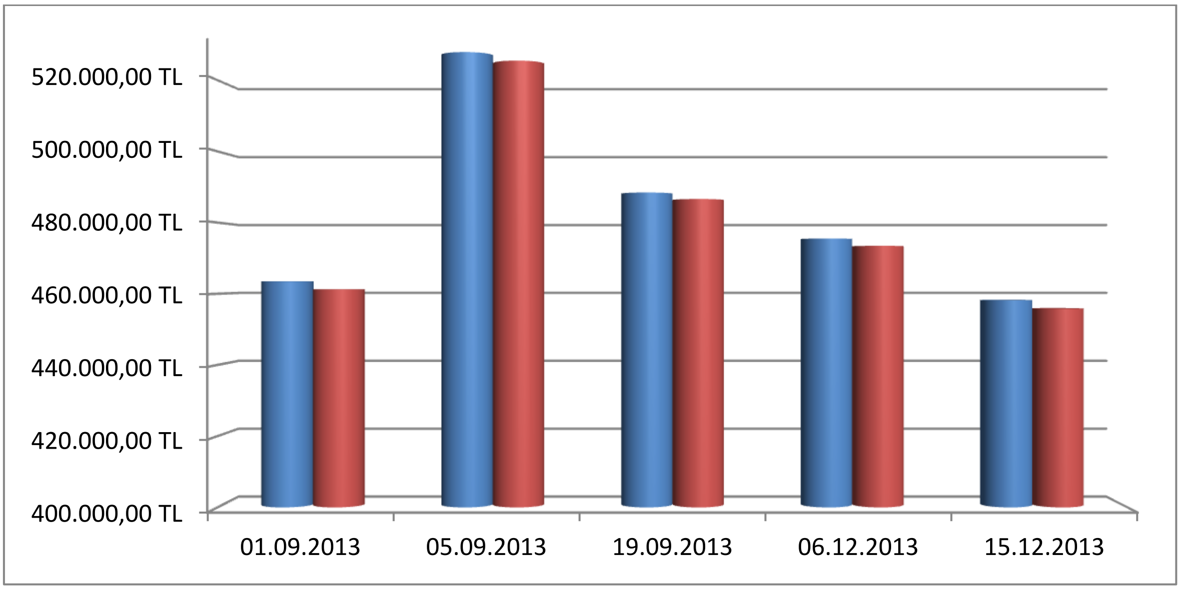

Figure 11 Comparison Between Actual (blue) and Optimized Cost (red)

3.4.3. Sensitivity Analysis

In order to determine the impacts of the electricity price upon the utility system working conditions, we performed sensitivity analysis.

The electricity price changed between 0 and 500 TL/MW and the data of 05.09.2013 00:00 – 01:00 is used. At that time refinery demands are given in *Table 18.*

Table 19 Refinery Demands in 05.09.2013

PW-REF	(MW)	44,31
HP-REF	(ton)	143,93
MP-REF	(ton)	62,18
LP-REF	(ton)	52,21

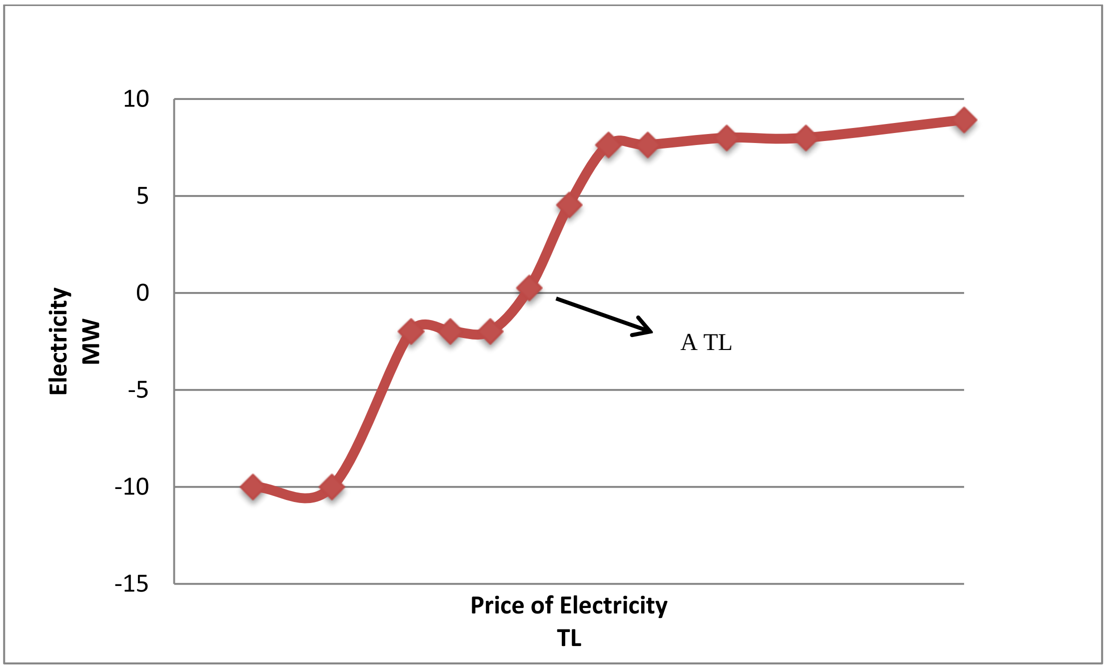

Figure 12 Electricity Price vs. Net Electricity

When the price of electricity is below “A” TL/MW, system decides to buy electricity from the national grid. However when the price of electricity exceeds “A” TL/MW that optimization decides to sell Electricity to the national grid.

4. Discussion

4.1. Main Observations of Wind Energy Investment Model

We present a multi-period mixed integer linear programming model to optimize utility system of the TÜPRAŞ İzmit Refinery. The decision variables included in the optimization process are streams and the equipments modes which are continuous and integer variables respectively. Multiple choice piece-wise linearization method is also used in order to minimize the run time of the optimization which is required due to the hourly optimization need or utility operation. The purposed model is tested using the actual data taken from process historian database that is already installed in the Tüpraş. For the optimization GAMS software is used and the Cplex solver is selected to solve the optimization. All the computational work has been executed on a personal computer (32-bit operating system, 2.50 GHz CPU, and 4.00 GB). The hourly scenarios are solved in run time of approximately 4 minutes which is met the requirements of the Tüpraş.

Moreover sensitivity analysis depending on the electricity prices is done in order to decide break-even point for electricity market movements.

Result of in average 0.45% of deduction in the total operational cost of utility system is achieved in daily basis which is a huge amount when the amounts of expenses are considered.

4.2. Future Work

Since the formulations that are used in the optimization are generic formulas this optimization can be applied to the other refineries too by only changing the regression parameters of the equipments.

Another addition can be introducing the refining processes to the optimization. By this way consumption side can also be optimized and maybe additional cost deductions can be achieved.

Also future investments can be introduced to the optimization which can enable the user to investigate the advantages and disadvantages of the new investments. This can also helpful while deciding investment plans.

BIBLIOGRAPHY

Benjamin F. Hobbs. Optimization methods for electric utility resource planning. European Journal of Operational Research, 83(1):1 – 20, 1995. ISSN 03772217.

B. Kalitventzeff. Mixed integer non-linear programming and its application to the management of utility networks. Engineering Optimization, 18(1-3):183, 1991. ISSN 0305215X.

K. P. Papalexandri, E.N. Pistikopoulos, B. Kalitventzeff, M.N. Dumont, K. Urmann, and J. Gorschluter. Operation of a steam production network with variable demands modelling and optimization under uncertainty. Computers & Chemical Engineering, 20(European Symposium on Computer Aided Process Engineering- 6):S763 – S768, 1996. ISSN 0098-1354.

Katerina P. Papalexandri, Efstratios N. Pistikopoulos, and B. Kalitventzeff. Modelling and optimization aspects in energy management and plant operation with variable energy demands-application to industrial problems. Computers & Chemical Engineering, 22(9):1319 – 1333, 1998. ISSN 00981354.

Soterios A. Papoulias and Ignacio E. Grossmann. A structural optimization approach in process synthesis—i. utility systems. Computers and Chemical Engineering, 7: 695 – 706, 1983. ISSN 0098-1354.

Patricia Velasco-Garcia, Petar Sabev Varbanov, Harvey Arellano-Garcia, and Günter Wozny. Utility systems operation: Optimisation-based decision making. Applied Thermal Engineering, 2011. ISSN 1359-4311.

Chi-Wai Hui and Yukikazu Natori. An industrial application using mixed-integer programming technique: A multi-period utility system model. Computers & Chemical Engineering, 20:S1577 – S1582, 1996. ISSN 00981354.

Jeong Hwan Kim and Chonghun Han. Short-term multiperiod optimal planning of utility systems using heuristics and dynamic programming. Industrial & Engineeering Chemistry Research, 40(8):1928 – 1938, 2001. ISSN 08885885.

Jeong Hwan Kim, Sangjun Ju, Heui-Seok Yi, In-Su Han, and Chonghun Han. Preventive optimization framework for unexpected equipment failures in the utility system with quantitative emergency handling constraints. Industrial & Engineeering Chemistry Research, 41(24):6070 – 6081, 2002. ISSN 08885885.

J.M. Pinto, M. Joly, and L.F.L. Moro. Planning and scheduling models for refinery operations. Computers & Chemical Engineering, 24:2259 – 2276, 2000. ISSN 0098-1354.

Heui-Seok Yi and Chonghun Han. The integration of complete replanning and rulebased repairing for optimal operation of utility plants. Korean Journal of Chemical Engineering, 18(4):442 – 450, 2001. ISSN 02561115.

Heui-Seok Yi, Yeong-Koo Yeo, and Jin-Kuk Kim. A rule-based steam distribution system for petrochemical plant operation. Industrial & Engineeering Chemistry Research, 37(3):1051 – 1062, 1998. ISSN 08885885.

L. Halasz, A.B. Nagy, T. Ivicz, F. Friedler, and L.T. Fan. Optimal retrofit design and operation of the steam-supply system of a chemical complex. Applied Thermal Engineering, 22:939 – 947, 2002. ISSN 1359-4311.

François Maréchal and Boris Kalitventzeff. Process integration: Selection of the optimal utility system. Computers & Chemical Engineering, 1998.

Sandra R. Micheletto, Maria C.A. Carvalho, and José M. Pinto. Operational optimization of the utility system of an oil refinery. Computers & Chemical Engineering, 32(Process Systems Engineering: Contributions on the State-of-the-Art Selected extended Papers from ESCAPE '16/PSE 2006.):170 – 185, 2008. ISSN 0098-1354.

R.R. Iyer and I.E. Grossmann, Synthesis and operational planning of utility system for multi-period operation. Computers Chem. Engng. Vol. 22. No.7-8. 0098-1354/98

J.C. Bruno, F. Fernandez, F. Castells and I.E. Grossmann, A rigorous MINLP model fort he optimal synthesis and operation of utility plants, Trans IChemE, Vol. 76, Part A. 0263-8762/98

B.J. Zhang and B. Hua, Effective MILP model for oil refinery-wide production planning and beter energy utilization, Journal of Cleaner Production 15, (2007) 439-448

J. Manninen and X.X. Zhu, Optimal gas turbine integration to the process industries. *Industrial & Engineering Chemical Research*, 38(11):4317–4329, 1999.

C C Chou and Y S Shih. A thermodynamic approach to the design and synthesis of plant utility systems. I*ndustrial and Engineering Chemistry Research*, 26(6):1100–1108, 1987.

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