OPTIMUM PLANNING OF AIR COMPRESSORS NETWORK UNDER DIFFERENT ELECTRICITY TARIFFS

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A report submitted
in fulfillment of the requirement for the degree of
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DECLARATION

I declare that this project report entitled "Optimum Planning of Air Compressors Network Under Different Electricity Tariffs" is the result of my work except as cited in the references

Signature :……………………………………

Name :……………………………………

Date :……………………………………

APPROVAL

I hereby declare that I have read this project report and in my opinion, this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :...

Supervisor's Name :...

Date :...

DEDICATION

To my beloved mother and father

ABSTRACT

A compressor is equipment which supplies compressed air to the production lines as production is always a very important prospect for any kind of industry. The compressed air is used as the main power source in various kinds of applications. Some examples of the applications are vacuum packaging, tire inflation, heavy lifting or loading and many more depend on the operation of the industries. This compressor also equipment that consumes huge power and energy as well as the electricity cost. Therefore, the industry needs to have efficient planning to control its power supply, input, and output during the operation. Regarding that, optimum planning of the air compressors network is important as initial preparation for the industry before starting operating.

ABSTRAK

Pemampat adalah peralatan yang membekalkan udara termampat ke lini pengeluaran kerana pengeluaran selalu merupakan prospek yang sangat penting bagi industri jenis apa pun. Udara termampat digunakan sebagai sumber kuasa utama dalam berbagai jenis aplikasi. Beberapa contoh aplikasi adalah pembungkusan vakum, inflasi tayar, pengangkatan atau pemuatan berat dan banyak lagi bergantung pada operasi industri. Pemampat ini juga peralatan yang menggunakan tenaga dan tenaga yang besar serta kos elektrik. Oleh itu, industri perlu mempunyai perancangan yang cekap untuk mengawal bekalan kuasa, input, dan outputnya semasa operasi. Sehubungan itu, perancangan optimum rangkaian pemampat udara adalah penting sebagai persiapan awal untuk industri ini sebelum mula beroperasi.

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I am extremely grateful to my parents for their prayers, love, caring, and sacrifices for educating and preparing me for the future. I also expressed my thanks to my beloved friends that involved with this project. Lastly, thank everyone that always supports me to accomplish this project.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATION

DSM	Demand Side Management
EE	Energy Efficiency
DR	Demand Response
MILP	Mixed Integer Linear Program
GAMS	General Algebraic Modelling System
TNB	Tenaga Nasional Berhad
TOU	Time of Use
ETOU	Enhanced Time of Use
AIMMS	Advanced Interactive Multidimensional Modeling System

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

A compressor is one of the most important mechanisms or equipment that most of the industry used to fulfill the production demand. The compressor unit will have compressed air before the supply air to the production units. The most common types of air compressors are rotary screw compressor, reciprocating air compressor, axial compressor, and centrifugal compressor. In the industry, the connection of the compressors is in the series or parallel based on the purpose of the system. These networks ofcompress can involve several compressor units that may differ in the type of drive and technical specifications (e.g., maximum load capacity, efficiency, and operational range)(Kopanos et al. 2015). The compressor network can be regulated under operational planning, energy scheduling, demand site management, electricity tariff, and resource management.

Every industry needs good operational planning for their compressors where it can achieve minimum power consumption and at the same time meets the demand for the production. The works related to the operational management of air separation systems are limited. Ierapetritou et al.(2002) presented a linear Mixed Integer Programming (MIP) formulation for the operational planning in an air separation plant under the objective to minimize the total operating cost. The operation ofthe plant was described by three different plant operation modes (regular, assisted, shutdown) that vary concerning operational efficiency and energy requirements. Binary variables were used to represent operating modes and switches among the different modes of operation. The model of (Ierapetritou et al. 2002) can generate the schedule of process operation modes and production rates. Along the same lines, (Karwan and Keblis 2007) proposed a MIP model that additionally considers product losses during configuration changes, while (Mitra et al. 2012) presented a MIP formulation that captures the transient behavior between different operating modes.

Moreover, multiple compressors in parallel connection are used to increase the total available capacity. The more compressors used the more power consumption need to run the compressors. The initiatives to reduce energy consumption or encourage consumers to achieve optimization are referred to as Demand Side Management (DSM). The most industrial goal is to perform and gain maximum profit with low energy consumption. However, what makes the DSM of industrial consumers challenging is rather the complexity of their underlying processes which demands a deep domain knowledge (Ramin, Spinelli, & Brusaferri, 2018). According to the TNB (Tenaga Nasional Berhad) official website stated that the Time of Use (TOU) scheme offers different times of the day. During the off-peak period, for example, tariff rates will be lower than the peak period. Figure 1.1.1 shows TNB's TOU time zone.

TOU Time Zones	
Time Zone	Hours
Peak	08:00 – 22:00 hours
Off-peak	22:00 – 08:00 hours

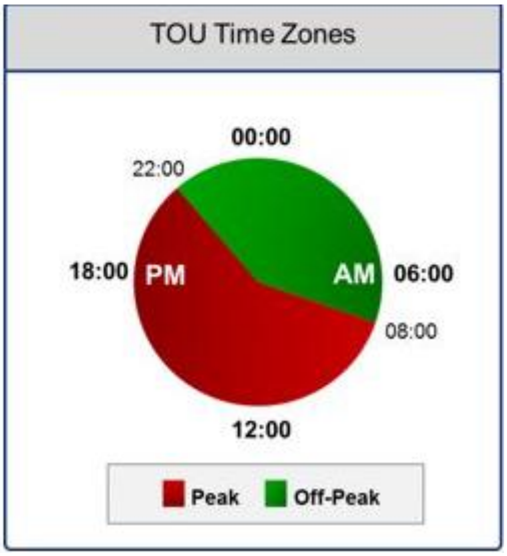

Figure 1.1.1 Time of Use (TOU) from TNB

1.2 PROBLEM STATEMENT

Industries world deals with a huge amount of energy consumption which comes from energy-intensive mechanical equipment for example compressor.The energy consumption will increase due to the high production demand.Regarding this issue, most industries will invest more costs to meet the production requirement. Besides, engineers nowadays use a spreadsheet to manage the plant. This traditional planning only can be handled by experienced engineers. It also not very systematic for the operational.

Moreover, mostindustriesdid not implement a modern planning system that will reach the maximum operational efficiency and minimize the cost of operation. In this study, mainly focus to achieve the optimization of the operation of the compressors by developing optimum planning of air compressors network under different electricity tariffs.

1.3 OBJECTIVE

The objectives of this project are as follows:

1. To investigate the current relation of energy consumption on the operational condition of the air compressors network
2. To formulate an optimization model that integrates with the planning of energy-intensive compressors network with different electricity tariffs
3. To demonstrate the capability of the proposed optimization model in terms of energy and cost minimization for optimum planning of industrial air compressors network

1.4 SCOPE OF PROJECT

The scopes of this project are:

1. Consists of eleven compressors connected in parallel that supply compressed air to three processing units through three headers.
2. Parameter variables:
   i) Constraints related to start-up and shutdown actions.
   ii) Constraints related to the operational status and production level of the processing units.
   iii) Demands for final products.
   iv) Constraints related to the assignment of utility units to connecting lines.
3. The result for optimum planning is performed by using GAMS's software.
4. The demand for optimum planning is regulated electricity tariff for the E3 category.

Table 1.4.2: Industrial tariff for E3 categories

TARIFF E3 – HIGH VOLTAGE PEAK/OFF-PEAK INDUSTRIAL TARIFF	
For each kilowatt of maximum demand per month during the peak period	35.50 RM/kW
For all kWh during the peak period	33.70 sen/kWh
For all kWh during the off-peak period	20.20 sen/kWh
The minimum monthly charge is RM600.00	

CHAPTER 2

LITERATURE REVIEW

2.1 Compressor Network in Industry

A compressor is a primary function in the operation of natural gas pipelines. In the process industries, compressed air is needed to move their production system. The main duty for a compressor is to supply compressed air through pipelines either the connection is in series or parallel. Multiple compressors that connect in parallel will increase the total capacity for the industry. However, the more compressor operated at the same time will generate huge power consumption which means the cost will be increasing as well. Therefore, the ideal optimization of the compressor network should be implemented in the industry. As a result, power consumption costswill be minimized but still meets the demands required from the production units.

An optimal decision usage of the compressor will significantly impact the operating cost. The topic of utility system optimization has been studied well. As an example, Kopanos et al., (2015) and Xenos et. al,(2016) proposed an optimization model to improve the performance of the compressors. The model consists of the start-up and shutdown cost, operating status, and the power consumption of the compressor.Nguyen et. al,(2008)conduct a study on a comparison of three alternative approaches of mixed-integer linear programming(MILP), genetic algorithms (GA), and expert systems (ES) for optimization of compressor selection in a natural gas pipeline system. According to their research mixed-integer, linear programming (MILP) is mathematical programming unique in which the objective function and problem constraints are linearly defined and as a result, MILP solves problems using a simple linear branch-and-bound algorithm to minimize the overall operating cost. For the genetic algorithm (GA), it works well in time-constrained problems because theoptimal solution improves in every generation instead of being the result of a lengthy solution process. Next,the expert system approach uses primarily captured human heuristics for providing the basis for building automation solutions.

2.2 Operational Planning

Operational planning describes the plan made to meets the demands while scheduling can provide a clear view of the system. Planning and scheduling both need to accomplish the system efficiently. The main purpose of this operational planning is to achieved optimization in the production system. Operational planning takes several months and has an objective in determining production profile. A mathematical programming model that considers the operating constraints for compressors and performance degradation for compressors is implemented in this study. The planning consists of the operating status, the power consumption, the start-up and the shutdown costs for compressors, the compressor connectsto the header, the timing and the type of necessary maintenance tasks as well as the outlet mass flow rates for compressed air. Operational planning can be conducted either in a single production site or multisite production. Verderame & Floudas, (2009) maderesearch on the operational planning framework for multisite production and distribution networks and stated that multisite production produces efficient production utilization compared to a single production site.

Scheduling in an industry environment is very important to give a clear view process undergo for the plants or industries. In this study, scheduling focussed on the compressor network. Some industries used the traditional method for their scheduling which data collected from a spreadsheet while not many industries used modern scheduling which more systematic. By using scheduling, important data will be collected especially the operating cost. The optimum scheduling can be minimizing the supply air from the compressors to the production line and at the same time, the operating cost also will be minimized. Effective scheduling also will improve the productivity, resource utilization, and profitability of the plant or industry. The topic of scheduling is well studied and implemented in many kinds of equipment and for an example (Li, Huang, Zhao, & Liu, 2017) made a research about operation scheduling of multi-hydraulic press system for energy consumption reduction and developed scheduling formulation for grouped hydraulic presses as shown in Figure 2.2.1

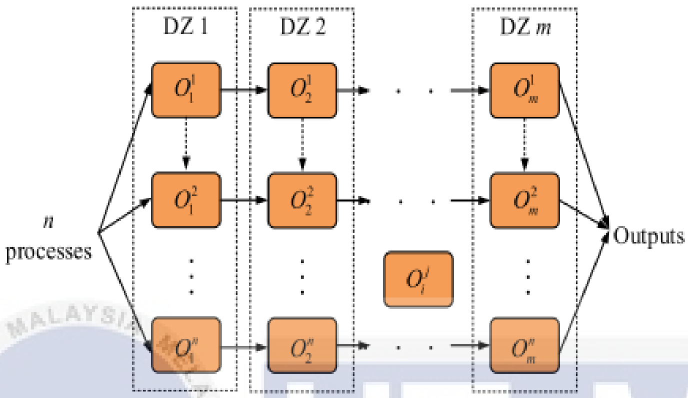

Figure 2.2.1: Operation procedures of each process in the grouped system

The other example of scheduling is from (Xenos et al., 2016)which provides an optimal schedule for the compressor to give the best decisions for their washing process.

2.3 Demand Side Management (DSM)

Demand-side management (DSM) refers to the management in reducing peak electricity demand. DSM has many beneficial effects, including preventing emergencies in the electrical system, reducing blackouts, and increasing the reliability of the network. DSM usually been applied to electricity load but is also used for changes that can be made to demands for all types of energy. Most of the literature and case studies on DSM are linked to electrical demands as a result of the programs set up by utilities and governments as an example (Y. Wang et al., 2019) studied on demand-side management of plug-in electric vehicles and organized unit commitment: a novel parallel competitive swarm optimization approach. The main reason industry implemented DSM is to achieve environmental and social objectives by reducing energy use and reducing greenhouse gas emissions.

For energy consumers, there may have many reasons to choose a certain DSM operation. These would usually be financial, environmental, advertising, or regulatory. The examples benefits of DSM to the consumer are a reduction in customer energy bills, reduction in the need for the new plant, transmission and distribution networks, and reduction in peak power prices for electricity. The motive behind the application of the DSM is clearly different for the various parties concerned.Therefore, for utility companies, increasing or changing the energy demand of the consumer may mean avoiding or delaying the installation of additional generating capacity.

Palensky et. al, (2011) stated DSM can be categorized into Energy Efficiency (EE), Time of Use (TOU), Demand Response (DR), Spinning Reserve (SR) as shown in Figure 2.3.1. In addition, demand-side management is an important function in the energy management of the future smart grid and provides support for smart grid applications in various areas such as electricity market regulation and management, infrastructure construction, and the management of distributed energy resources and electric vehicles.Controlling and managing energy demand will reduce overall peak load demand, reshape the demand curve and improve grid efficiency by reducing overall costs and carbon emissions(Logenthiran, Member, Srinivasan, Member, & Shun, 2012).

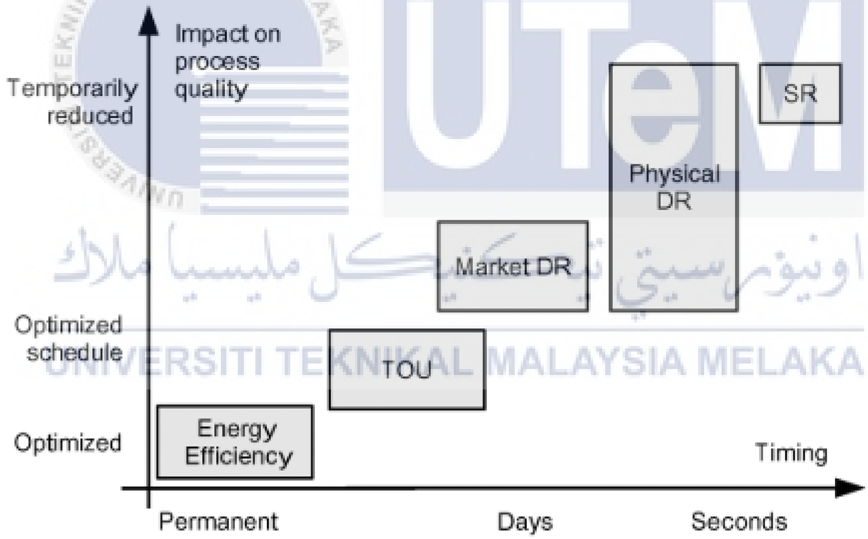

Figure 2.3.1: Category of DSM

Power consumption refers to the energy supplied to mechanical equipment and then operate the industry. As stated, this study is focussed on the compressor. The compressor produces compressed air to supply to the production system. The compressor consumes huge power consumption depends on the output capacity of a compressor and compressed air demand. The operation of a compressor is restricted due to the minimum and maximum power provided by its driver. Besides, the number ofcompressors in the industry also will affect the value of the power consumption. The energy efficiency of a compressor can be defined as the ratio of compressed air output to the input power. For the criteria of the optimization design, the use of the engine power of the compressors indirectly acknowledges the output of the compressors (Xenos et al., 2015). The topic of power consumption is well studied and presented for different applications by several authors.For example, Liu, Zhang, & Lu, (2015) empirically studied the correlation between the total power used by the machine tool and the slicing force at the blade end, and the SEC template was collected accordingly.

Demand-side management is related to power consumption. Industries with huge power consumption required great demand-side management achieved better energy efficiency. Besides, better demand-side management will reduce energy costs without affecting the production demand.

2.4 Energy Efficiency

Energy efficiency (EE) is one of the important programs under DSM. Energy efficiency can be defined as a long-term conservation strategy that aimed to save energy and reduce demand through energy-efficient processes. In the industry, energy efficiency can be achieved by running the system at maximum runtime at its most energy-efficient processes. The other action to have energy efficiency is from good operational scheduling. By implementing energy efficiency in the industry, the demand for peak times can be reduced and at the same time, the average power cost also reduced. According to (Tronchin, Manfren, & Nastasi, 2018) stated the actions need to improve energy efficiency in multiple sectors of the economy are appropriate legislation, successful market strategies, and collaboration between private and public sectors. The topic of energy efficiency is well studied. For example (H. Wang et al., 2019) selected Standard for Exchange of Product model data-Numerical Control (STEP-NC) as the enabling technology to aim energy efficient in machining. In manufacturing, energy efficiency not only benefits manufacturing industries, but at the same helps alleviate the worldwide pollution problem in the long run (Liu, Zhang, & Lu, 2015).

Table 2.1: Summary for Literature Review

Article	Operational Planning	Energy Scheduling	Demand-side Management	Electricity Tariff	Power Consumption	Utility System
Artigues et.al, (2013)		✓			✓	
Li et. al, (2017)	✓	✓			✓	
Xenos et. al, (2016)	✓	✓	✓	✓	✓	✓
Kopanos et al, (2015)	✓		✓		✓	✓
Y. Wang et al, (2019)			✓	✓		✓
Palensky et. al (2011)	✓		✓		✓	
Logenthiran et. al (2012)		✓	✓		✓	
Ahmad et. al, (2019)		✓		✓	✓	
Desta et.al, (2018)	✓			✓	✓	
Adamson et. al, 2017)	✓	✓			✓	
Verderame & Floudas, (2009)	✓	✓	✓	✓		✓
(Zulkafli & Kopanos, 2016)	✓	✓	✓	✓	✓	✓

Table 2.1 shows a summary of the research paper for the literature review. The reviewed papers are focused on operational planning, energy scheduling, demand-side management, electricity tariff, power consumption, and utility system. The pattern shows most of the research for operational planning will be related to the power consumption which the objective is to minimize power consumption.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology used in this project to create a scheduling tool for a compressor network under industrial regulated electricity tariffs. The flow chart of the project is shown in Figure 3.1.1. The project starts by studying the journals, articles, or any materials regarding the compressor network such as the mathematical model for optimization operational, scheduling and planning method, and power consumption from the compressor. The study continues with research on the recent traditional scheduling system. Next, the optimization model is written as Mixed Integer Linear Programming (MILP) in General Algebraic Modelling System (GAMS). GAMS will run the simulation. After that, several data and results will be obtained. After that, the data and results will be analyzed which the main focus is power consumption, energy, electricity price cost.

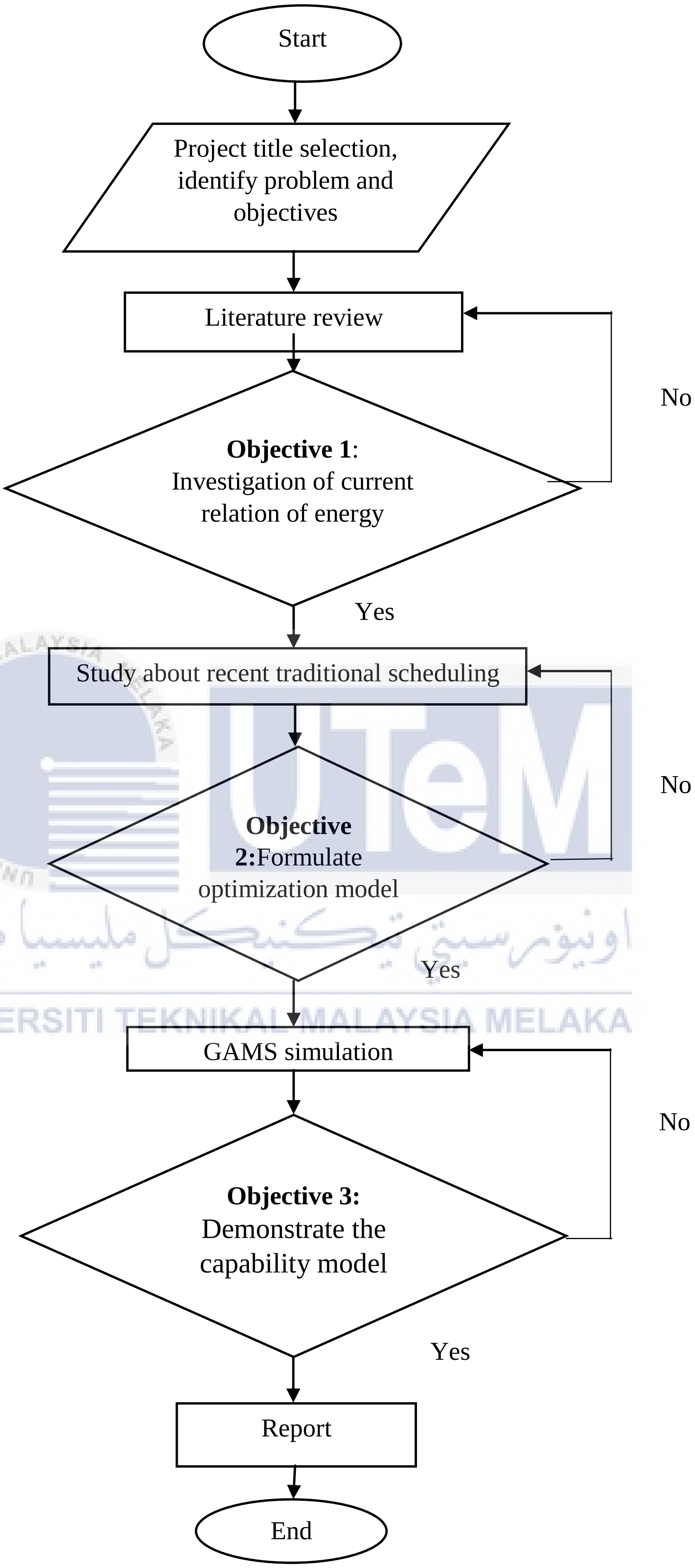

Figure 3.1.1: Flow chart the methodology

3.2 Optimization Framework

A mixed-integer linear programming (MILP) model is proposed for the optimal operation of the production system. There are three main parts of the optimization framework which(i) the utility system, (ii) the production system, and (iii) the objective function.

3.2.1 The Compressor Network

3.2.1.1 Constraints related to start-up and shutdown actions

The binary variables need to be introduced first in order to model the main operational aspects of the utility units. Below are the binary variables:

$$X_{(i,t)} = \begin{cases} 1 & if\ utility\ unit\ i\ is\ operating\ during\ time\ period\ t, \\ 0 & otherwise. \end{cases}$$

$$S_{(i,t)} = \begin{cases} 1 & if\ utility\ unit\ i\ starts\ up\ at\ the\ beginning\ of\ time\ period\ t, \\ 0 & otherwise. \end{cases}$$

$$F_{(i,t)} = \begin{cases} 1 & if\ utility\ unit\ i\ shut\ down\ at\ the\ beginning\ of\ time\ period\ t, \\ 0 & otherwise. \end{cases}$$

Constraints (1) and (2) represents model start-up and shutdown actions through the operating status of the utility unit.

$$S_{(i,t)} - F_{(i,t)} = X_{(i,t)} - \tilde{\chi}_i \qquad \forall i \in K, t \in PH : t = 1$$
$$S_{(i,t)} - F_{(i,t)} = X_{(i,t)} - X_{(i,t-1)} \forall i \in K, t \in PH : t > 1 \qquad (1)$$

$$S_{(i,t)} + F_{(i,t)} \leq 1 \qquad \forall i \in K, t \in PH \qquad (2)$$

Based on constraints (1), the start-up will take place if a compressor unit has not been operating in the previous time period but operates in the current time period (i.e., $S_{(i,t)}$ = 1 and $F_{(i,t)}$ = 0). Parameter $\tilde{X}_i$ represents the operating status of the compressor unit *i* just before the start of the planning horizon. Parameter $\tilde{X}_i$ will equal to 1 if the compressor unit *i* has been operating just before the start of the planning horizon and but will be zero if it is otherwise. For constraints (2), it excludes the simultaneous realization of a start-up and a shutdown action. Hence, these constraints (2) could be excluded from the optimization model if start-up and shutdown cost is included in the objective function.

3.2.1.2 Constraints related to minimum runtime and minimum shutdown

The symbol for minimum runtime is ω_i.

The symbol for minimum runtime is ω_i. The function proposed constraints (3) is to ensure that if compressor units start-up at a given time period *t*, it will operate at least $\omega_i$time period.

$$X_{(i,t)} \geq \sum_{t'=\max\{1,t-\omega_i+1\}}^{t} S_{(i,t')} \; \forall i, t \in PH : \omega_i > 1$$

$$X_{(i,t)} = 1 \qquad \forall i \in PH, t = 1, \ldots., (\omega_i - \widetilde{\omega}_i) : 0 < 1\, \widetilde{\omega}_i < \omega_i \tag{3}$$

Parameter $\widetilde{\omega}_i$ represents the initial state of each compressor unit with respect to its minimum runtime. As a conclusion, this parameter is about the total time period compressor unit *i* has operating at the beginning of the scheduling horizon.

$$1 - X_{(i,t)} \geq \sum_{t'=max\{1,t-\psi_i+1\}}^{t} F_{(i,t')} \quad \forall i, t \in PH: \psi_i > 1$$

(4)

$$X_{(i,t)} = 1 \forall i \in I, t = 1, \dots, (\omega_i - \widetilde{\omega}_i): 0 < \widetilde{\omega}_i < \omega_i$$

$$X_{(i,t)} = 0 \forall i \in I, t = 1, \dots, (\psi_i - \tilde{\psi}_i): 0 < \tilde{\psi}_i < \psi_i$$

Constraints (4) show that each compressor unit *i* will have minimum shutdown time (ψ_i). Once a compressor unit *i* begin to shutdown, it will offline for a while depend on the minimum shutdown time (ψ_i) before it can operate back.

3.2.1.3 Constraints related to assignment of compressor to connecting lines.

For the constraint that relates to the connecting line, the binary variable below is introduced to activate the connection between the compressor and the connecting lines.

$$Y_{(i,j,t)} = \begin{cases} 1 \; if \; utility \; unit \; i \; serves \; connecting \; line \; j \; during \; time \; period \; t \; , \\ 0 \; otherwise \end{cases}$$

$$\sum_{j \in J_i} Y_{(i,j,t)} = X_{(i,t)} \qquad \forall i \in K, t \in PH$$

(5)

Constraint (5) helps to select which compressor unit is connected to which line. The compressor unit will serve one connecting line during operation at one time, as the constraint is given.

3.2.1.4 Constraints related to assignment changes related to compressor units to connecting lines

Binary variable $D_{(i,t)}$ is introduced to represent the constraint that relates to assignment changes of the connecting line. This limitation is important in order to ensure that there is no unnecessary exchange of connection between the compressor unit and the connecting lines.

$$D_{(i,t)} \begin{cases} 1 \text{ if utility unit } i \text{ changes connecting line at the beginning of time period } t \\ 0 \text{ otherwise} \end{cases}$$

$$D_{(i,t)} = Y_{(i,j,t)} - \tilde{\varphi}_{(i,j)} - S_{(i,t)} \forall i \in K, t \in PH: t = 1$$

$$D_{(i,t)} = Y_{(i,j,t)} - Y_{(i,j,t-1)} - S_{(i,t)} \forall i \in K, t \in PH: t > 1 \quad (6)$$

Parameter $\tilde{\varphi}_{(i,j)}$ is the active connection of compressor units and connecting lines before scheduling horizon

3.2.1.5 Constraints related to the maximum runtime

Constraint (7) represents the maximum runtimeo_i for the compressor unit after it has been started. These constraints ensure that the compressor unit operates for a maximum run time as soon as it starts up.As informed, each compressor units have their reliability and it is important to have maximum runtime to avoid any damage on the units.

$$\sum_{t'=\max\{1,t-o_i\}}^{t} X_{(i,t')} \leq o_i \qquad \forall i \in K, t \in PH$$

$$\sum_{t'=\max\{1,t-(o_i-\widetilde{\omega}_i)\}}^{t} X_{(i,t')} \leq (o_i - \widetilde{\omega}_i) \quad \forall i \in K, t = (o_i - \widetilde{\omega}_i + 1) : \widetilde{\omega} > 1 \qquad (7)$$

3.2.1.6 Constraints related to inventory tank

Constraints (8) represent the inventory tank in the compressor network.

$$B_{(z,t)} = \sum_{i \in K} \sum_{j \in JI} \sum_{j \epsilon JZ} M_{(i,j,t)} \qquad z \in ZE, t \in PH$$

$$B_{(z,t)} \geq g_z^{min}\, z \in ZE, t \in PH$$

$$B_{(z,t)} \leq g_z^{max}\, z \in ZE, t \in PH \qquad (8)$$

3.2.2 Outlet Pressure for Compressor

Constraints (9) represent the outlet pressure for the compressor that serves header j Parameters (α_i) and (β_i) denote the load curve coefficient for the header$j$. Parameter ($\lambda_{(j,t)}$) is a problem-specific large number that could represent the header$j$ of the capacity. The total compressed air mass flow rate supplied to the header is shown in constraint (10).

$$P_{(i,j,t)} = \alpha_j MB_{(i,j,t)} + \beta_j Y_{(I,j,t)} \forall i \in K, j \in JI, t \in PH \quad (9)$$

$$MB_{(i,j,t)} \geq \sum_{i \in K} \sum_{j \in K} M_{(i,j,t)} - \lambda_{(j,t)} \left(1 - Y_{(i,j,t)}\right) \qquad \forall i \in K, j \in JI, t \in PH$$

$$MB_{(i,j,t)} \leq \sum_{i \in K} \sum_{j \in K} M_{(i,j,t)} - \lambda_{(j,t)} \left(1 - Y_{(i,j,t)}\right) \qquad \forall i \in K, j \in JI, t \in PH$$

$$MB_{(i,j,t)} \leq \lambda_{(j,t)} Y_{(i,j,t)} \forall i \in K, j \in JI, t \in PH \quad (10)$$

3.2.3 Production for utilities

Constraint (11) and (12) has a parameter (ρ_i^{min}) and (ρ_i^{max}) which represent the limit for lower and upper bound for mass flow rate ($M_{(i,j,t)}$) for the compressor. While constraints (13) and (14) has a parameter (π_i^{min}) and (π_i^{max}) which represent lower and upper bound for pressure ratio for the compressor unit.

$$M_{(i,j,t)} \geq \rho_i^{min} Y_{(i,j,t)} \quad (11)$$

$$M_{(i,j,t)} \leq \rho_i^{max} Y_{(i,j,t)} \quad (12)$$

$$P_{(i,j,t)} \geq \pi_i^{min} Y_{(i,j,t)} \quad (13)$$

$$P_{(i,j,t)} \leq \pi_i^{max} Y_{(i,j,t)} \quad (14)$$

3.2.4 Demands for Utilities

Constraints (15) proposed for linking the compressor unit to the production system. The utility system allows goods to meet the demand for production from an external source of purchase.The utility system may also remove some utility products from an external source if it exceeds demand. For these two actions, there is an advantage in which there will be penalty costs from purchasing and disposing of action. So, both of the actions are not recommended for the system.

$$\sum_{i\epsilon K} \sum_{n\epsilon JN} \sum_{j\epsilon JI} M_{(i,j,t)} + OJ_{(n,t)} = \theta_{(n,t)} + DISP_{(n,t)} \qquad \forall t \in PH \quad (15)$$

3.2.5 Objective Function

Constraints (16) represent the objective function for the optimization for the compressor network. The objective of this optimization is to achieved minimization for the total operating cost for the compressor network. The total operating cost consists of the start-up and shutdown action for the compressor, the cost related to the connecting line of the compressor, and the total power consumption and power cost for the compressor network.

$$\text{Min} = \Big[\sum_{i\epsilon K} \sum_{i\epsilon PH} \varepsilon_i D_{(i,t)} + \sum_{i\varepsilon PH} acq_{c_{(n,t)}} OJ_{(n,t)} + disc_{c_{(n,t)}} DISP_{(n,t)} + \sum_{i\epsilon K} \sum_{t\varepsilon PH} \chi_i S_{(i,t)} +$$
$$\varphi iF(i,t)+i\epsilon Kt\epsilon PHj\epsilon JI\delta i1Y(i,j,t)+\delta i2M(i,j,t)+\delta i3P(i,j,t)\delta i4Y(i,j,t)mit$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Description of the case study.

This study conducts operational planning on the compressor which in parallel connection. The total number of the compressor are eleven which five (*i1, i2, i3, i4, i5, i6, i7, i8, i9, i10, i11)* are the large compressor. All of the compressors are connected to the header (*j1, j2, j3)* but only can serve one header during a time period. Then, the headers are connected to the three processing units (*n1*, *n2*, *n3*) which supply the compressed air to the production system. In this case, each header only can serve one processing unit. To be concluded, header *j1* connected to processing unit *n1*, header *j2* connected to processing unit *n2*, and header *j3* connected to processing unit *n3*. The optimization to be set for a total of 30 days and divide into 1 day for a single time period. All the value of the minimum and maximum compressors load, compressor start-up and shutdown cost, and the pressure ratio of compressors are taken from (Zulkafli & Kopanos, 2016). Table 4.1.1 shows the main parameters in this study.

Table 4.1.1 Main parameters

Symbol	**Value**	**Unit**	**Description**
t	1	day	Duration for a single time period
PH	30	days	Total time periods in optimization
ω_i	6	days	Minimum online time after the start-up of the compressor
ψ_i	3	days	Minimum offline time after the shutdown of the compressor
o_i	20	days	Maximum online time for a small compressor
o_i	30	days	Maximum online time for large compressor

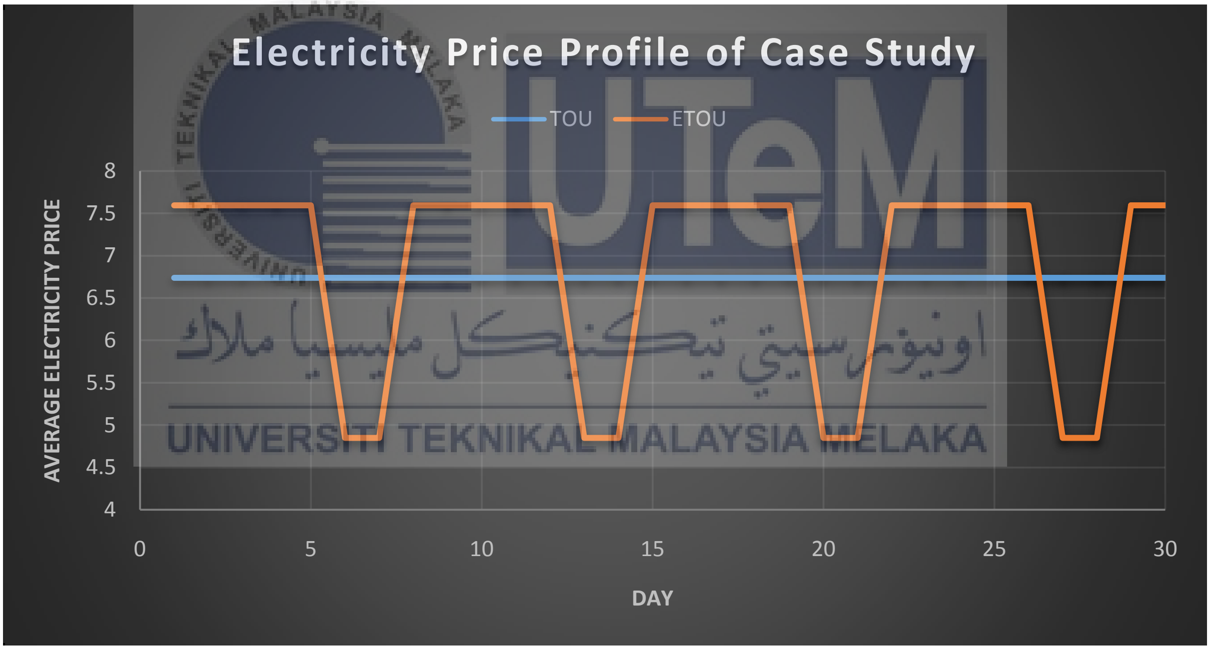

Figure 4.1.1 Electricity price profile for TOU and ETOU

Figure 4.1.1 shows two electricity price profiles (TOU and ETOU) used to get operating costs for a total of 30 days. Profile 1 (TOU) is the electricity during peak and off-peak period while profile 2 (ETOU) is the electricity price which is charged with peak, mid-peak and off-peak. Both electricity price profiles are from TNB tariff rates which retrieved from the official TNB website "https://www.tnb.com.my/faq/etou/ ". According to the figure, TOU has a constant average value while ETOU is otherwise. The average value for TOU is 6.738 (RM/kW/day) and ETOU is 7.594 (RM/kW/day) for the weekend while 4.848 (RM/kW/day). This is due to the electricity cost taken for TOU is the same for every day while the electricity cost for ETOU is different for weekdays and weekends.

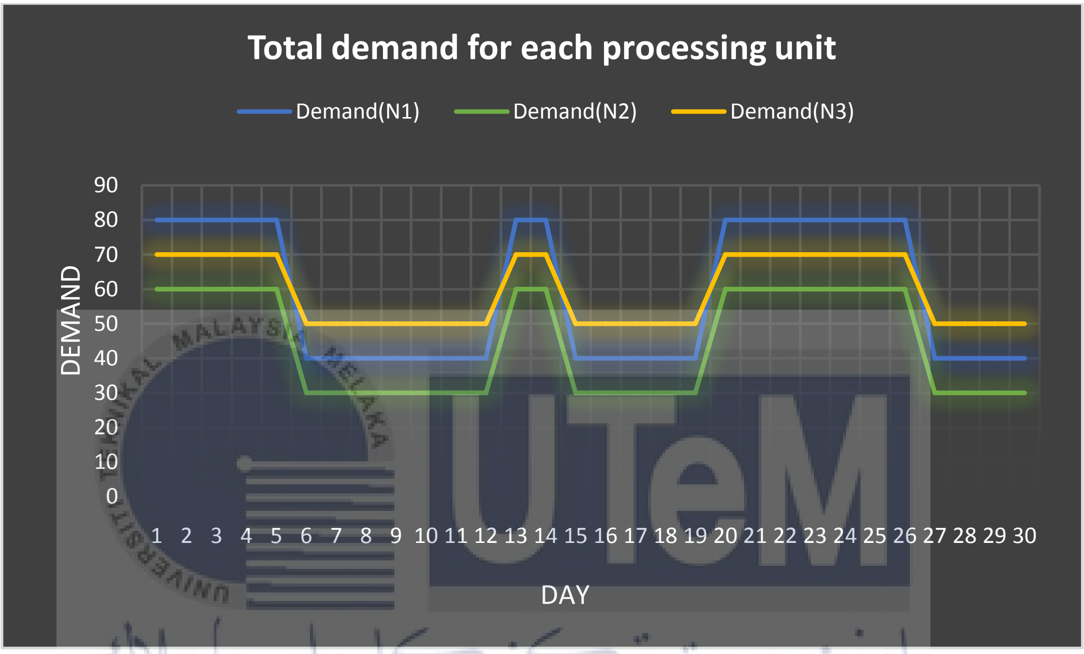

Figure 4.1.2 Demand for each processing unit

Figure 4.1.2 shows the compressed air demand for each processing for both optimizations. This model involves three processing units which are n1, n2, and n3. The optimization model is performed by using a general algebraic modeling system (GAMS) using CPLEX 12 solver with processor Intel(R) Core(TM) i5-4210U CPU @ 1.70GHz. The result obtained after 12 hours of running the simulation. The results are presented separately (TOU and ETOU).

4.2 Optimization Results and Discussions Under (TOU) Electricity Price Profile

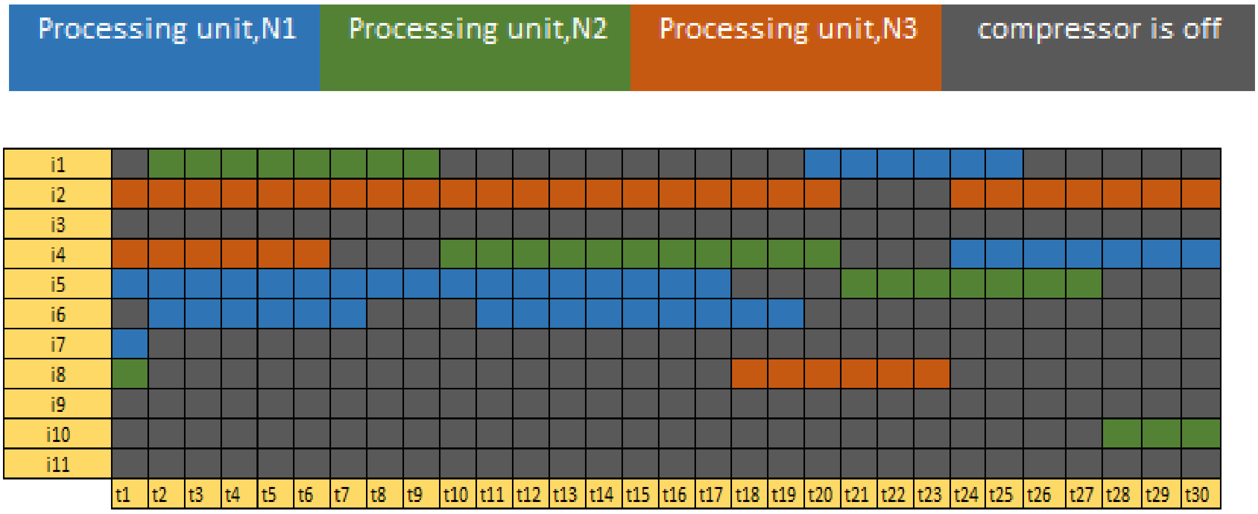

Figure 4.2.1 Optimal Operational Plan for Compressor under TOU Electricity Tariff

Figure 4.2.1 shows the optimal operational plan for the compressor network under the TOU electricity tariff in the optimizing process. According to the figure above, one small compressor (i3) and two large compressors (i9 & i11) are offline along the planning horizon. For all the fives small compressors, there are three compressors which (i2, i4, i5) operating from day 1 (t1). While for the large compressors, there are two compressors which (i7 & i8) operating from day 1 (t1). After half of the month, only seven compressors out of eleven are still operating which four of them are small compressors (i1, i2, i4, i5) and the rests are the large compressor (i6, i8, i11). In conclusion, the number of small compressors operates is higher compared to the large compressor for the early month, and also after half of the month. The pattern is considered based on demands puts not too high which the system does not require large compressors to operate heavily. The least usage of the large compressors will automatically reduce the electricity costs for the industry.

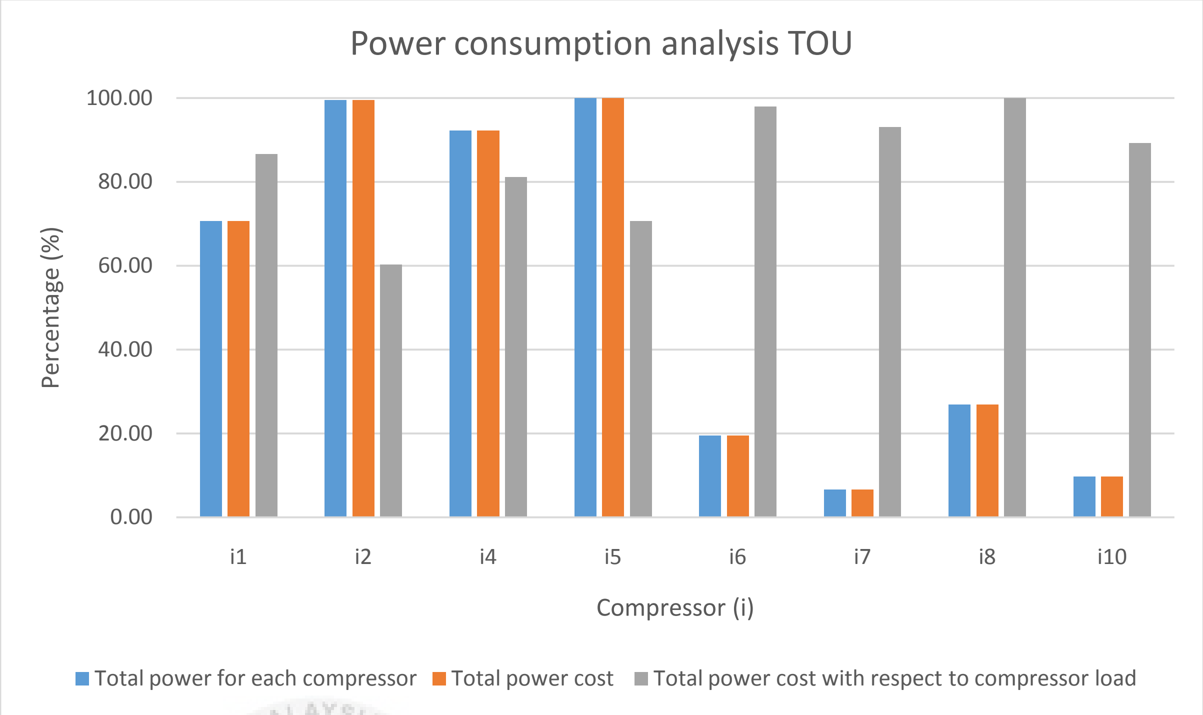

Figure 4.2.2 Power consumption analysis for TOU

Based on Figure 4.2.2, compressor *i2* is more efficient compare to *i8* because the percentage of the total power cost with respect to compressor load is lower for *i2* compare to *i8*. According to the trends, compressor *i2* also has a highpercentage total power for each compressor which almost 100 percent, because it is operating at the maximum runtime with 27 days overall through processing unit *n3*, referred figure 4.2.1. Different from compressors *i6*, *i7*, *i8*, *i10* which the total power cost is lower but higher in total power cost with respect to compressor load. This shows that all of these four compressors are not efficient compare to compressor i2. In conclusion the lower the total power cost, the higher the total power cost with respect to compressor load.

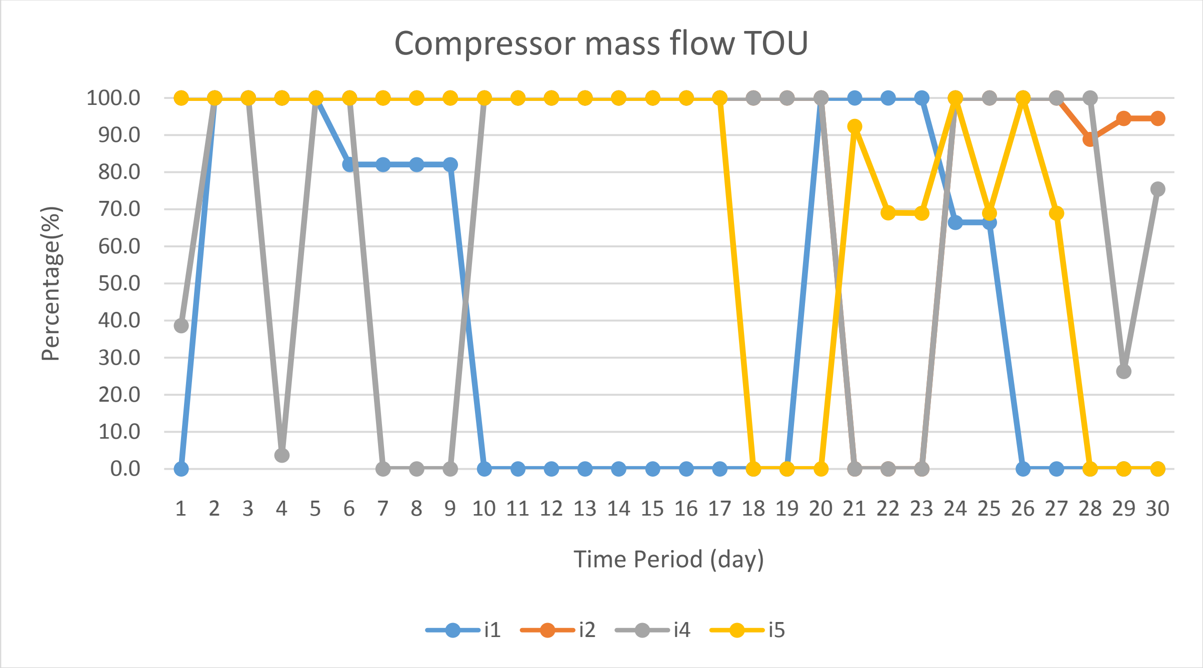

Figure 4.2.3(a) Mass flow rate each compressor (i1, i2, i4, i5) under TOU

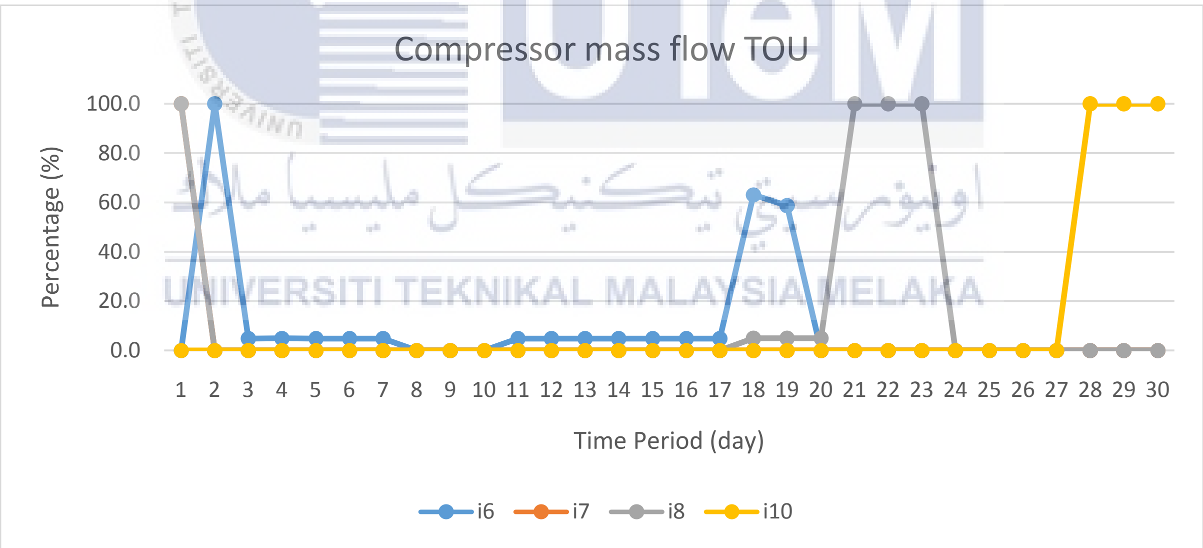

Figure 4.2.3(b) Mass flow rate each compressor (i6, i7, i8, i10) under TOU

Both figures 4.2.3(a) and 4.2.3(b) represent the mass flow rate for each compressor. The compressors that involve are compressors *i1, i2, i4, i5, i6, i7, i8, & i10*. The compressor that operates to supply compressed air to processing unit *n2* is compressor *i1, i4, i5, i8, & i10*. According to figure 4.2.3 (a) and (b), the pattern shows that compressor *i5* produces a steady compressed air mass flow rate compare to *i8* since *i5* is a more efficient compressor than *i8* referred figure 4.2.2. Based on figure 4.2.3(a) and (b), when compressor *i4* shutdown and *i5* startup at duration day 20, the compressor load for compressor *i6* shows a decreasing amount of mass flow rate. This is because when compressors *i5* startup, it starts up with a huge amount of mass flow which the percentage more than 90%. For the end of the planning horizon which are on period 28,29, and 30, there are only three compressors which remain operational. The compressors are *i2*, *i4*, and *i10*.

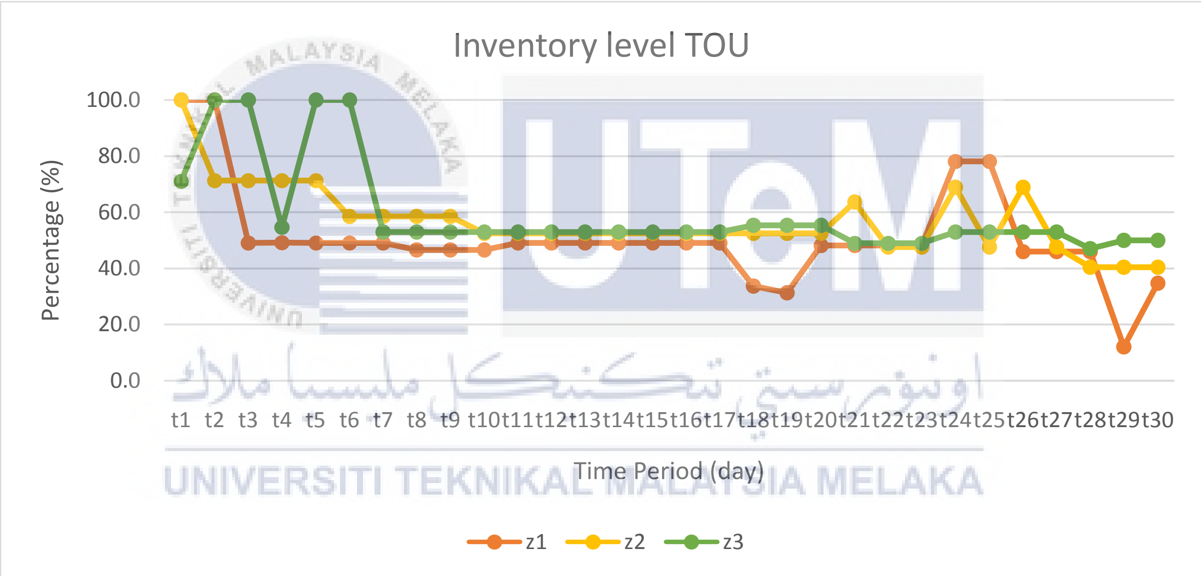

Figure 4.2.4 Inventory level regulated TOU tariff

Figure 4.2.4 shows the total of three storage tanks in this case study which is labeled as z1, z2, and z3. The pattern shows each of the storage tanks starts decreased together at periods day 6 and 7. This is due to periods 6 and 7 is during the weekend and most industries have very few compressors operating on weekends. Besides, the trend keeps steady in the middle of the month because of less demand from processing units. This steady pattern did not remain until the end of the planning horizon as there is an increasing inventory level starts on period 23. In this period, compressor i1 and i8 have 100% of mass flow rate, and i5 is around 70% (referred figure 4.2.3 (a) and (b)). To be concluded, the larger percentage of mass flow rate produces on period 23 leads to the increasing percentage of inventory level.

4.3 Optimization Results and Discussions Under (ETOU) Electricity Price Profile

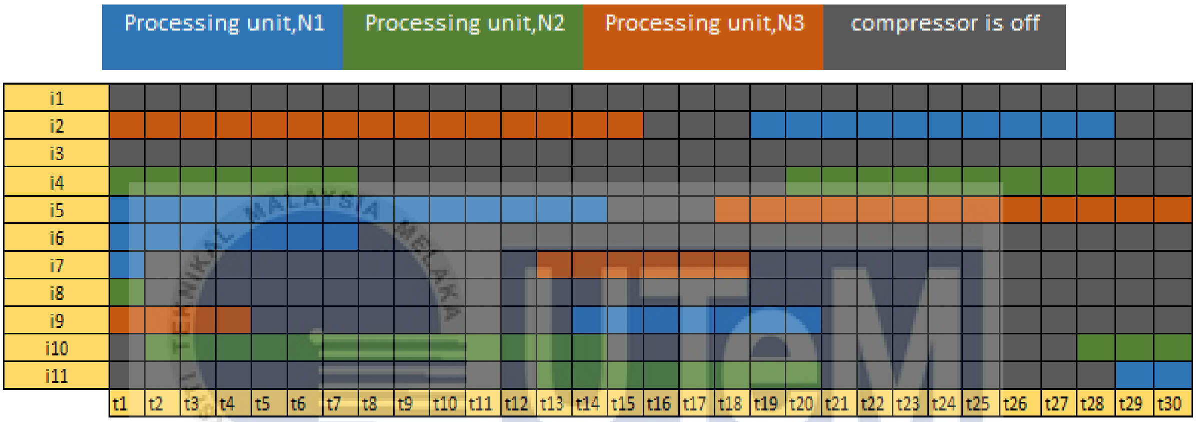

Figure 4.3.1 Optimal Operational Plan for Compressor under ETOU Electricity Tariff

Based on Figure, compressors (*i1 & i3*) remain shut down for the total planning horizon. There are seven in a total of compressors that operating on day 1 (*t1*) before compressors *(i7& i8)* shutdown on the next day *(t2)*. There is only a compressor out of five small compressors achieved the maximum runtime for small compressors because it is operating for 27 days overall. As ETOU offered off-peak during Saturday and Sunday, there is at least a minimum of four compressors operating every weekend. As a conclusion, the compressors used for 30 days operating is the balance from small and large compressors.

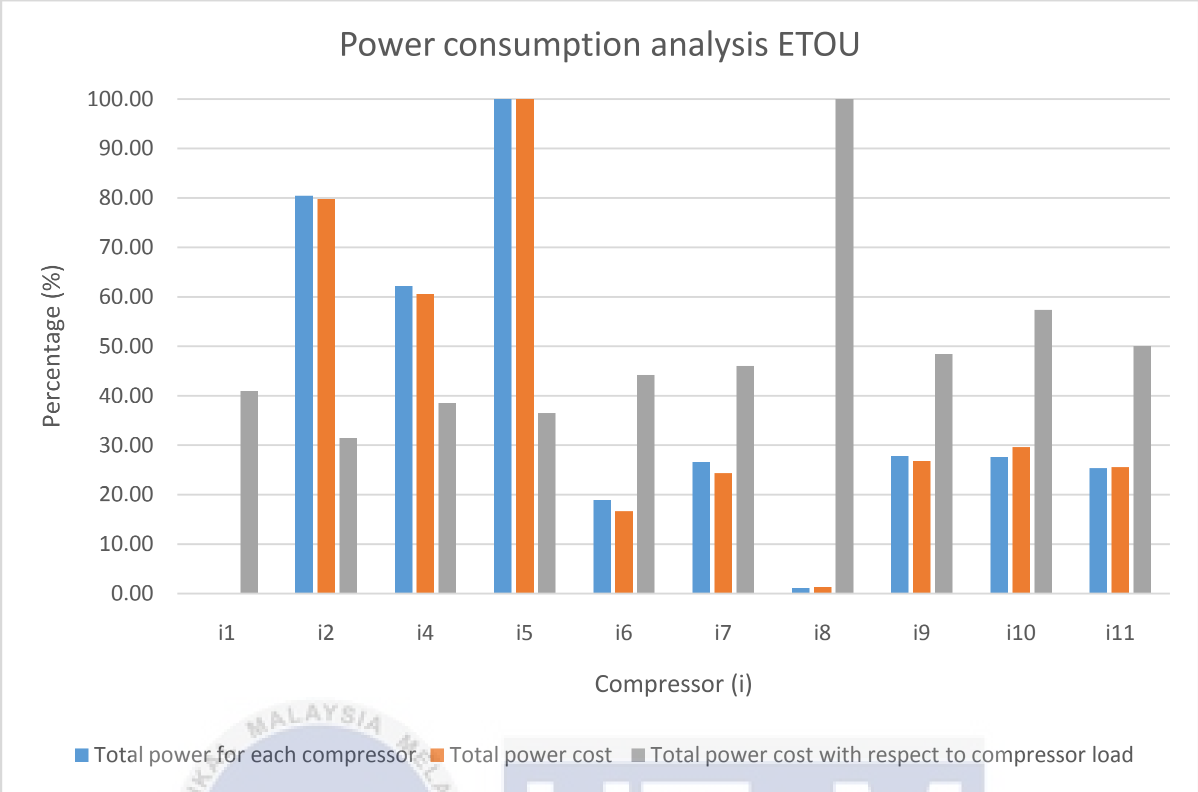

Figure 4.3.2 Power consumption analysis for ETOU

According to figure 4.3.2, compressor *i2* has higher power for each compressor, higher power cost and lower total power cost concerning compressor load compare to *i4* which have significantly different value with a high value of power compressor and power cost and the same time have high total power cost with respect to compressor load. It can be concluded that compressor *i2* is more efficient than *i4*. Besides, the pattern also shows that the compressors with lower total power costs will have a higher total power cost with respect to compressor load. This result will lead to inefficient operating of the compressor. For example, *i1* and *18* that have very low total power cost but have a huge value of total power cost with respect to compressor load.

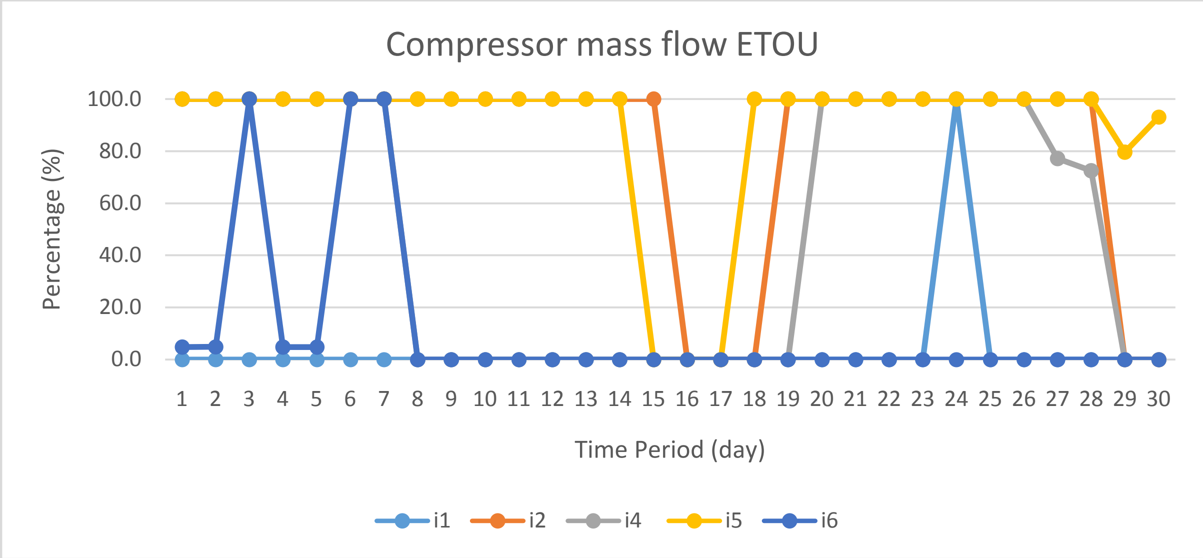

Figure 4.3.3(a) Mass flow rate each compressor (i1, i2, i4, i5, i6) under ETOU

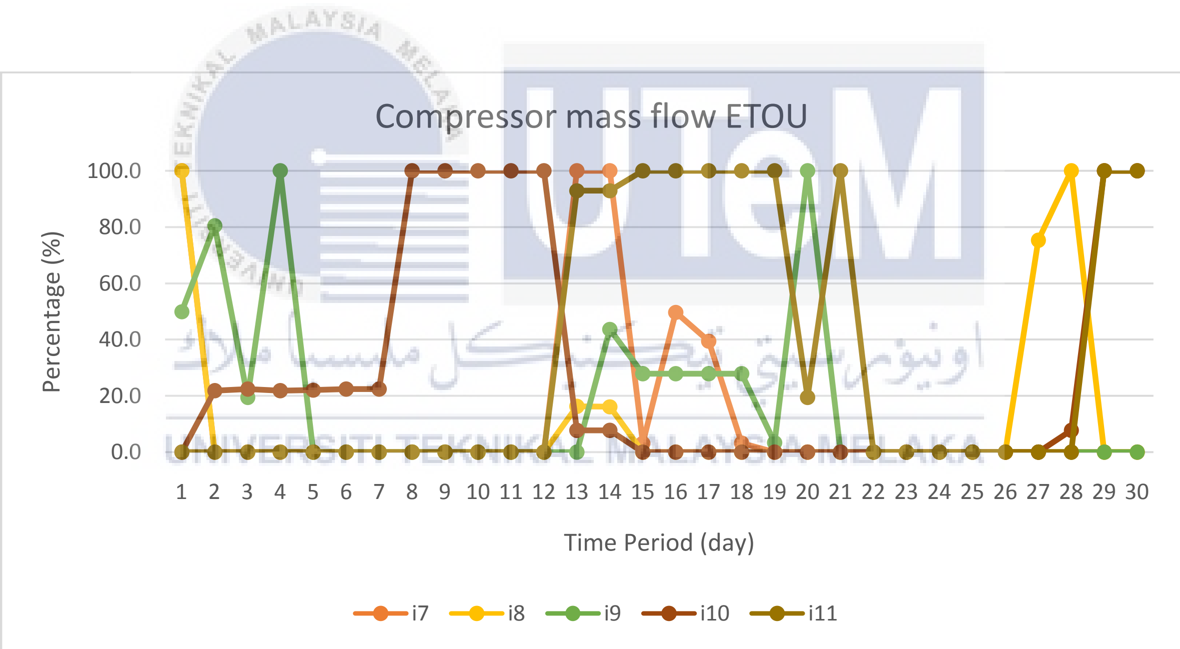

Figure 4.3.3(b) Mass flow rate each compressor (i7, i8, i9, i10, i11) under ETOU

Both figures 4.3.3(a) and 4.3.3(b) represent the mass flow rate for each compressor. The compressors that involve are compressors *i1, i2, i4, i5, i6, i7, i8, i9, i10 & i11*. The compressor that operates to supply compressed air to processing unit *n2* is compressor *i4, i8, i10 & i11*. According to figure 4.2.3 (a) and (b), the pattern shows that compressor *i4* produces a steady compressed air mass flow rate compare to *i8* since *i4* is a more efficient compressor than *i8* referred figure 4.3.2. Based on figure 4.2.3(a) and (b), when compressor *i4* starts up again at period 20, there is a decreased percentage mass flow rate at compressor *i11*. This because when *i4* start up again, it produces 100% of the mass flow rate. For the end of the planning horizon which are on period 29 and 30, there are only three compressors which remain operational. The compressors are *i5*, *i10*, and *i11*.

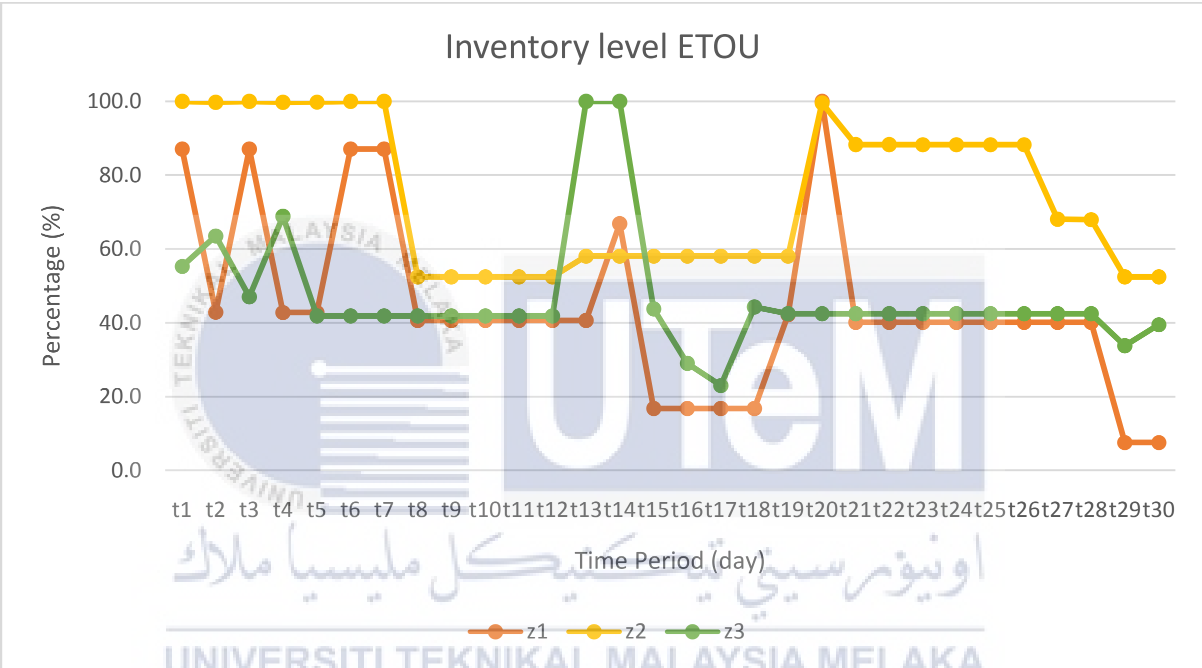

Figure 4.3.4 Inventory level regulated ETOU tariff

Figure 4.3.4 shows the total of three storage tanks in this case study which is labeled as z1, z2, and z3. During the first week (t1-t7), there is an unsteady flow on storage z1 and z3 which alternating increased and decreased. This situation happens occurs because one of the storage tanks which is z2 has 100% of inventory level. The total percentage for inventory level z1, z2, and z3 during this period also high because the compressors operate with a high mass flow rate which to satisfy the demands from the processing units. With the high percentage level during the first week, all the storage tank starts to decrease the inventory level in the second week. Based on figure 4.3.4, the inventory level always at the top peak during the weekend because there is a different price for ETOU during weekday and weekend.

4.4 Total Percentage Power Consumption (TOU vs ETOU)

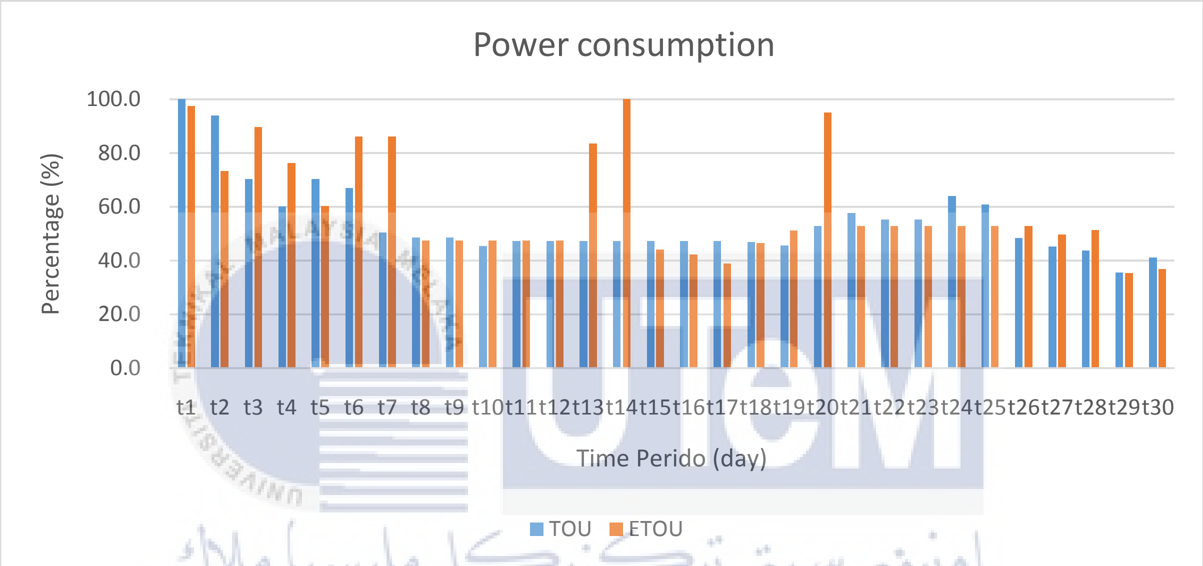

Figure 4.4.1 Total Percentage Power Consumption (TOU vs ETOU)

Figure 4.4.1 shows the overall profile of power consumption for both TOU and ETOU for 30days. The patterns of TOU start with huge power consumed for both with almost 100% and slowly decrease day by day until reach 30 days while for ETOU there is a higher value on the weekend (t6, t7, t13, t14). The percentage is higher for ETOU during this period is because as ETOU offer different price for the weekend and weekdays which weekend has a lower price with 4.848 (RM/kW/day), the industry takes the opportunity and focussed to operate the compressor with maximum capacity during the weekend which the result can reduce the total price for a month. This statement is supported by the result produced from the inventory level as shown in figure 4.3.4 which there is a high percentage of inventory level during the weekend. According to figure 4.3.1, the compressors that operated during the weekend are at least five compressors. In conclusion, the more compressors operate, the higher the inventory level as high total power consumption.

4.5 Total Operating Cost

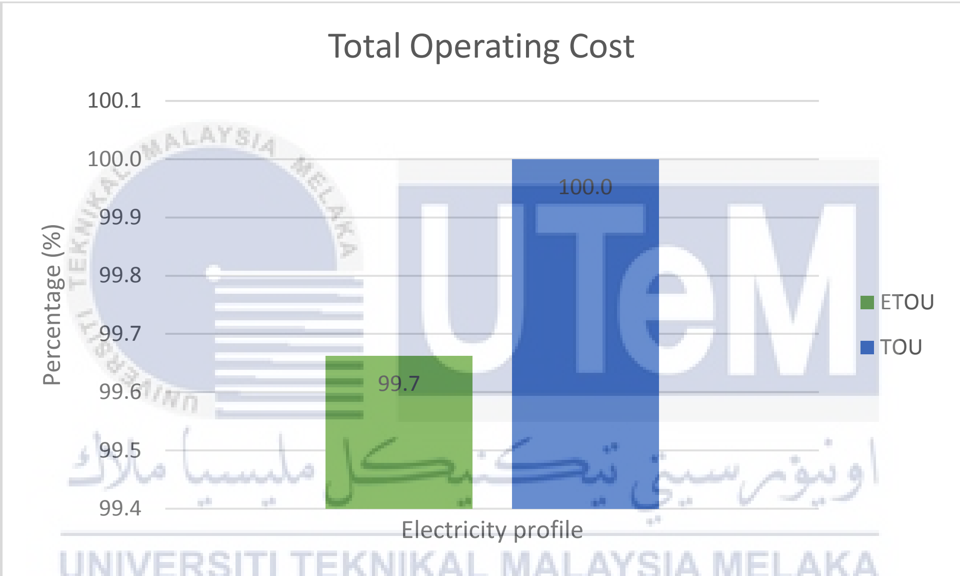

Figure 4.5.1 Total operating cost (TOU vs ETOU)

Figure 4.5.1 shows the total operational cost for the compressor network along the planning horizon. As a result, the total operating cost of TOU is higher than ETOU with the value is 99.7% for ETOU and 100% for TOU. The difference is 0.3%. This is due to ETOU has 3 different prices for 3 times zone which is off-peak, mid-peak, and peak on weekdays and only off-peak on weekends while TOU has fixed price which consists only off-peak and peak for each day. There is also different price for ETOU during the weekend. Although the difference percentage is small, overall the total cost can be reduced.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This project is proposed about the optimization model for optimum planning of industrial air compressors network under a different regulated tariff which are TOU and ETOU for 30 days. The method used to achieve the optimum planning for the network compressors is by developing an optimization model which is written as Mixed Integer Linear Programming (MILP) in General Algebraic Modelling System (GAMS) software. As a result, from the simulation, the ETOU electricity tariff is the best and effective. This is because the total operating cost in figure 4.5.1 shows that electricity tariff ETOU is lower compared to TOU with 0.3% different even both profiles have the same demand. Besides, the price offered from ETOU tariff which different prices on weekdays and weekends resulted in less total cost. As the price is low on the weekend, the industry uses this opportunity to stored more compressed air and increased the inventory level of the storage tank as shown in Figure 4.3.4. Based on Figure 4.4.1, the total power consumption for the ETOU profile is high on the weekend which means the industry uses the low price offer from ETOU for the weekend to run the operation. Last but not least, by using GAMS's software the optimization can be achieved for the industry especially on the cost.

5.2 Recommendation/Future Work

In this project, the analysis to have optimum planning of air compressors network under different electricity tariffs which comparison between ETOU and TOU is done. Recommend in the future that another study about optimization can be done. For examples:

1. Develop optimization model for compressors network which can minimize total cost operation even for the short period. (Xenos et al., 2015) stated that an optimization model employs the updated steady-state models to estimate the compressors' best load distribution to reduce power consumption and hence operating costs.
2. Study on incentive-based strategy for Demand Side Management. DSM refers to the management in reducing peak electricity demand and DSM has many beneficial effects, including preventing emergencies in the electrical system, reducing blackouts, and increasing the reliability of the network. It is revealed that in the case of demand-side management through centralized pricing, all customers can react simultaneously through home energy management systems, which could lead to some new peak consumption while DSM aims to reduce any peak consumption (Çakmak & Altaş, 2020).
3. Develop a planning tool which can reduce time management for engineer. (Lindholm & Johansen, 2018) stated that the production planning cycle is repetitive and demands engineering hours and expertise.

REFERENCES

Çakmak, R., & Altaş, İ. H. (2020). A novel billing approach for fair and effective demand-side management: Appliance level billing (AppLeBill). *International Journal of Electrical Power and Energy Systems*, *121*(March). https://doi.org/10.1016/j.ijepes.2020.106062

Kopanos, G. M., Xenos, D. P., Cicciotti, M., Pistikopoulos, E. N., & Thornhill, N. F. (2015). Optimization of a network of compressors in parallel: Operational and maintenance planning - The air separation plant case. *Applied Energy*, *146*, 453–470. https://doi.org/10.1016/j.apenergy.2015.01.080

Li, L., Huang, H., Zhao, F., & Liu, Z. (2017). Operation scheduling of a multi-hydraulic press system for energy consumption reduction. *Journal of Cleaner Production*, *165*, 1407–1419. https://doi.org/10.1016/j.jclepro.2017.07.158

Lindholm, J., & Johansen, K. (2018). ScienceDirect ScienceDirect ScienceDirect Is Design Automation a Feasible Tool for Improving Efficiency in Is Design Automation a Feasible Tool for Improving Efficiency in Production Planning and Manufacturing Conference 2017, Processes□ ? Production Planning and Manufacturing Processes□ ? Costing models capacity optimization in Industry Trade-off. *Procedia Manufacturing*, *25*, 194–201. https://doi.org/10.1016/j.promfg.2018.06.074

Liu, N., Zhang, Y. F., & Lu, W. F. (2015). A hybrid approach to energy consumption modeling based on cutting power: A milling case. *Journal of Cleaner Production*, *104*, 264–272. https://doi.org/10.1016/j.jclepro.2015.05.049

Logenthiran, T., Member, S., Srinivasan, D., Member, S., & Shun, T. Z. (2012). *Demand Side Management in Smart Grid Using Heuristic Optimization*. *3*(3), 1244–1252.

Nguyen, H. H., Uraikul, V., Chan, C. W., & Tontiwachwuthikul, P. (2008). A comparison of automation techniques for optimization of compressor scheduling. *Advances in Engineering Software*, *39*(3), 178–188. https://doi.org/10.1016/j.advengsoft.2007.02.003

Palensky, P., Member, S., Dietrich, D., & Member, S. (2011). *Demand Side Management : Demand Response , Intelligent Energy Systems , and Smart Loads*. *7*(3), 381–388.

Ramin, D., Spinelli, S., & Brusaferri, A. (2018). Demand-side management via optimal production scheduling in power-intensive industries: The case of metal casting process. *Applied Energy*, *225*(December 2017), 622–636. https://doi.org/10.1016/j.apenergy.2018.03.084

Tronchin, L., Manfren, M., & Nastasi, B. (2018). Energy e ffi ciency , demand side management and energy storage technologies – A critical analysis of possible paths of integration in the built environment. *Renewable and Sustainable Energy Reviews*, *95*(June), 341–353. https://doi.org/10.1016/j.rser.2018.06.060

Verderame, P. M., & Floudas, C. A. (2009). *Operational planning framework for multisite production and distribution networks*. *33*, 1036–1050. https://doi.org/10.1016/j.compchemeng.2008.09.008

Wang, H., Zhong, R. Y., Liu, G., Mu, W. L., Tian, X., & Leng, D. (2019). An optimization model for energy-efficient machining for sustainable production. *Journal of Cleaner Production*, *232*, 1121–1133. https://doi.org/10.1016/j.jclepro.2019.05.271

Wang, Y., Yang, Z., Mourshed, M., Guo, Y., Niu, Q., & Zhu, X. (2019). Demand side management of plug-in electric vehicles and coordinated unit commitment : A novel parallel competitive swarm optimization method. *Energy Conversion and Management*, *196*(May), 935–949. https://doi.org/10.1016/j.enconman.2019.06.012

Xenos, D. P., Cicciotti, M., Kopanos, G. M., Bouaswaig, A. E. F., Kahrs, O., Martinez-botas, R., & Thornhill, N. F. (2015). Optimization of a network of compressors in parallel : Real Time Optimization (RTO) of compressors in chemical plants – An industrial case study. *Applied Energy*, *144*, 51–63. https://doi.org/10.1016/j.apenergy.2015.01.010

Xenos, D. P., Kopanos, G. M., Cicciotti, M., & Thornhill, N. F. (2016). Operational optimization of networks of compressors considering condition-based maintenance. *Computers and Chemical Engineering*, *84*, 117–131. https://doi.org/10.1016/j.compchemeng.2015.08.008

Zulkafli, N. I., & Kopanos, G. M. (2016). Planning of production and utility systems under unit performance degradation and alternative resource-constrained cleaning policies. *Applied Energy*, *183*, 577–602. https://doi.org/10.1016/j.apenergy.2016.08.060

Ierapetritou MG, Wu D, Vin J, Sweeney P, Chigirinskiy M. Cost minimization in an energy-intensive plant using mathematical programming approaches. Ind Eng Chem Res 2002;41(21):5262–77.

Karwan MH, Keblis MF. Operations planning with real time pricing of a primary input. Comput Oper Res 2007;34(3):848–67.

Mitra S, Grossmann IE, Pinto JM, Arora N. Optimal production planning under time-sensitive electricity prices for continuous power-intensive processes. Comput Chem Eng 2012;38:171–84.

TNB ENHANCED TIME OF USE (ETOU). Retrive from https://www.tnb.com.my/faq/etou/

APPENDICES

APPENDIX A

Nomenclature

Sets

$\boldsymbol{i} \in I$	compressor units
$\boldsymbol{j} \in J$	headers units
$\boldsymbol{n} \in N$	process units
$\boldsymbol{t} \in T$	time periods

Subsets

K_i	set of compressors included in the optimization
PH_t	set of time periods included in the optimization (prediction horizon)

Parameters

α_i	the coefficient for the load curve of header *j*
β_i	the coefficient for the load curve of header *j*
δ_t^1	objective function coefficient factors for compressor *i*
δ_t^2	objective function coefficient factors for compressor *i*
δ_t^3	objective function coefficient factors for compressor *i*
δ_i^3	objective function coefficient factors for compressor *i*
δ_i^2	objective function coefficient factors for compressor *i*
δ_i^1	objective function coefficient factors for compressor *i*
ε_i	penalty cost for re-assigning header compressor *i* during its operation
n_t	maximum amount of available resources for maintenance in time period *t*
$\theta_{(n,t)}$	compressed air mass flow rate demand for process unit *n* in time period *t*
K_t	the conversion factor of mass flow aggregated mass amount in time period *t*
λ_j	the problem-specific large number that could represent the the capacity of header *j*
$\lambda_{(j,t)}^T$	the problem-specific large number that could represent the the capacity of header *j*
μ_t	electricity price in time period *t*

o_i	maximum online time after the start-up of the compressor *i* (maximum runtime)
π_i^{min}	the minimum pressure ratio of compressor *i*
π_i^{max}	the maximum pressure ratio of compressor *i*
ρ_i^{min}	minimum compressed air mass flow rate from compressor *i*
ρ_i^{max}	maximum compressed air mass flow rate from compressor *i*
$acq\_c_{(n,t)}$	cost of acquiring compressed air from external sources to meet demand of process unit *n* in period *t*
$discp\_c_{(n,t)}$	cost for disposing compressed air from external sources that are not needed at process unit *n* in period *t*
φ_i	the shutdown cost for compressor *i*
χ_i	the start-up cost for compressor *i*
ψ_i	minimum offline time after the shutdown of compressor *i* (minimum shutdown time)
ω_i	minimum online time after the start-up of compressor *i* (minimum run time)
$\tilde{\varphi}_{(i,j)}$	the active connection between compressor *i* and header *j* just before the beginning of current prediction horizon
$\tilde{\chi}_i$	operating status of compressor i just before the beginning of the current scheduling horizon
$\widetilde{\omega}_i$	total number of time periods at the end of the past prediction horizon that compressor *i* has been continuously offline since its last start-up
$\widetilde{ds}_i$	the initial value of DS at the beginning of the prediction horizon
$TOTAL\_MASSFLOWRATE_i$	total mass flow rate for compressor *i*
$PWRCOMP\_CONS_i$	power consumption for compressor *i*
$PWRCOMP\_COST_i$	power consumption cost for compressor *i*
$POWER\_CONS_t$	power consumption for a period time *t*
$COST\_ELEC_t$	power consumption cost for a period time *t*

Positive Variables

$M_{(i,j,t)}$	compressed air mass flow rate from compressor *i* supplied to header j belongs to J_i in time period *t*
$MB_{(i,j,t)}$	total compressed air mass flow rate supplied to header j belongs to J_i that is served by compressor i in time period t (auxiliary variable)
$OJ_{(n,t)}$	compressed air mass flow rate acquired from external sources for process unit n in time period *t*
$DISP_{(n,t)}$	compressed air mass flow rate disposed of process unit *n* in time period *t*
$P_{(i,j,t)}$	the outlet pressure of compressor *i* that serves header *j* belongs J_i in time period *t*

Binary Variables

$X_{(i,t)}$	=1, if compressor *i* is operating during time period *t*
$Y_{(i,j,t)}$	=1, if compressor *i* serves header *j* belong to Ji during time period *t*
$S_{(i,t)}$	=1, if compressor *i* start-up at the beginning of time period *t*
$F_{(i,t)}$	=1, if compressor *i* shut down at the beginning of time period *t*
$D_{(i,t)}$	=1, if compressor *i* changes the header from time period *t*-1 to *t*

APPENDIX B

GAMS Code

```
$TITLE COMPRESSORS NETWORK (UTILITY_SYSTEM_RH, SEQ=1)

$include FINAL

OPTIONS
iterlim = 10000000, limrow = 1000, limcol = 0,
reslim = 28000,      mip = cplex, optca = 0.00, optcr = 0.00, solprint =
off;

$offlisting $offsymxref offsymlist

SETS
i(*)                 compressors
j(*)                 headers
n(*)                 process units
t(*)                 time periods
z(*)                 storage tanks
K(i)                 set of compressors included in the optimization
PH(t)                set of time periods included in the optimization
(prediction horizon)

JI(j,i)              set of headers that are connected to compressor i
JZ(j,z)              set of headers that are connected to storage tank z -->
ASSUMPTION: a storage tank z is connected to exactly one dedicated-header j
ZN(z,n)              set of storage tanks that are connected to process unit n
--> ASSUMPTION: a process unit n is connected to exactly one dedicated-
storage tank z
ZE(z)                set of storage tanks included in the optimization

ALIAS (t,tt),(i,ii);


PARAMETERS
alpha(j)             coefficient for the load curve of header j
bita(j)              coefficient for the load curve of header j
delta1(i)            objective function coefficient factors for compressor i
delta2(i)            objective function coefficient factors for compressor i
delta3(i)            objective function coefficient factors for compressor i
epsilon(i)           penalty cost for re-assigning header compressor i during
its operation
hita(t)              maximum amount of available resources for maintenance in
time period t
thita(n,t)           compressed air mass flow rate demand for process unit n in
time period t
kapa(t)              conversion factor of mass flow to aggregated mass amount
in time period t
lamda(j)             problem-specific large number that could represent the
capacity of header j
lamdaT(j,t)          problem-specific large number that could represent the
capacity of header j
mi(t)                electricity price in time period t
```

```
omikron(i)         maximum online time after the startup of compressor i
(maximum run time)
pe_min(i)          minimum pressure ratio of compressor i
pe_max(i)          maximum pressure ratio of compressor i
ro_min(i)          minimum compressed air mass flow rate from compressor i
ro_max(i)          maximum compressed air mass flow rate from compressor i
acq_c(n,t)         cost for acquiring compressed air from external sources to
meet the demand of process unit n in period t
disp_c(n,t)        cost for disposing compressed air from external sources
that is not needed at process unit n in period t
fi(i)              shutdown cost for compressor i
xi(i)              startup cost for compressor i
psi(i)             minimum offline time after the shutdown of compressor i
(minimum shutdown time)
omega(i)           minimum online time after the startup of compressor i
(minimum run time)

fip(i,j)           active connection between compressor i and header j just
before the beginning of the current prediction horizon
xip(i)             operating status of compressor i just before the beginning
of the current scheduling horizon
psip(i)            total number of time periods at the end of the past
prediction horizon that compressor i has been continuously off-line since
its last shutdown
omegap(i)          total number of time periods at the end of the past
prediction horizon that compressor i has been continuously on-line since
its last startup
gap_onp(i)         total number of time periods at the end of the past
prediction horizon that from the last online flexible maintenance tasks in
compressor i
dsp(i)             initial value of DS at the beginning of the prediction
horizon
delta4(i),sc1(i),sc2(i),sc3(i),sc4(i),w_flow(i),p_in(i,t)
CPUs

g_min(z)
g_max(z)
bitap(z)
ksi_min(z)
ksi_max(z) ;
```

BINARYVARIABLES

```
X(i,t)             is 1 if compressor i is operating during time period t
Y(i,j,t)           is 1 if compressor i serves header j belongs to Ji during
time period t
S(i,t)             is 1 if compressor i starts up at the beginning of time
period t
F(i,t)             is 1 if compressor i shuts down at the beginning of time
period t
D(i,t)             is 1 if compressor i changes header from time period t-1
to t
```

POSITIVEVARIABLES

```
M(i,j,t)           compressed air mass flow rate from compressor i supplied
to header j belongs to Ji in time period t
MB(i,j,t)          total compressed air mass flow rate supplied to header j
belongs to Ji that is served by compressor i in time period t (auxiliary
variable)
OJ(n,t)            compressed air mass flow rate acquired from external
```

```
sources for process unit n in time period t
DISP(n,t)        compressed air mass flow rate disposed from process unit n
in time period t
P(i,j,t)         outlet pressure of compressor i that serves header j
belongs Ji in time period t
B_IN(z,t)        inlet mass flow rate to storage tank z
B(z,t)           inventory level of storage tank z
B_OUT(z,n,t)     outlet mass flow rate from storage tank z

VARIABLES
OF               objective function (total cost)



EQUATIONS        Eq1,Eq2,Eq3,Eq4,Eq5, Eq6a,Eq6b,Eq7a,Eq7b,
Eq8,Eq9a,Eq9b,Eq9c,Eq10, Eq17,Eq18, Eq20, Eq21,Eq22,OBJ, Eq23, Eq24,
Eq25,Eq26,Eq27,Eq28 ;

*=================== Starts up and Shutdown Action ===================
Eq1(i,t)$(K(i) AND PH(t))..      S(i,t) - F(i,t) =E= X(i,t) -
xip(i)$(ORD(t)=1) - X(i,t-1)$(ORD(t)>1);
Eq2(i,t)$(K(i) AND PH(t))..      S(i,t) + F(i,t) =L= 1;

*=================== Minimum Runtime and Shutdown time ===================
Eq3(i,t)$(K(i) AND PH(t) AND omega(i)>1)..
                                 X(i,t) =G= SUM(tt$(PH(tt) ANDORD(tt) GE
max(1,(ORD(t)-omega(i)+1)) ANDORD(tt) LE ORD(t)),S(i,tt));
Eq4(i,t)$(K(i) AND PH(t) AND psi(i)>1)..
                                 1 - X(i,t) =G= SUM(tt$(PH(tt) ANDORD(tt)
GE max(1,(ORD(t)-psi(i)+1)) ANDORD(tt) LE ORD(t)),F(i,tt));
Eq17(i,t)$(K(i) AND PH(t) AND (ORD(t) LE  (omega(i)-omegap(i))) AND
(omegap(i)>0 AND omegap(i)<omega(i)))..
                                 X(i,t) =E= 1;
Eq18(i,t)$(K(i) AND PH(t) AND (ORD(t) LE  (psi(i)-psip(i))) AND (psip(i)>0
AND psip(i)<psi(i)))..
                                 X(i,t) =E= 0;

*=================== Assignment of Utility Units to Connecting Lines
===================
Eq5(i,t)$(K(i) AND PH(t))..      SUM(j$(JI(j,i)),Y(i,j,t)) =E= X(i,t);

*=================== Production for Utilities ===================
Eq6a(i,j,t)$(K(i) AND PH(t) AND JI(j,i))..
                                 M(i,j,t) =G= ro_min(i)*Y(i,j,t);
Eq6b(i,j,t)$(K(i) AND PH(t) AND JI(j,i))..
                                 M(i,j,t) =L= ro_max(i)*Y(i,j,t);

Eq7a(i,j,t)$(K(i) AND PH(t) AND JI(j,i))..
                                 P(i,j,t) =G= pe_min(i)*Y(i,j,t);
Eq7b(i,j,t)$(K(i) AND PH(t) AND JI(j,i))..
                                 P(i,j,t) =L= pe_max(i)*Y(i,j,t);

*=================== Outlet Pressure for Compressor ===================
Eq8(i,j,t)$(K(i) AND PH(t) AND JI(j,i))..
                                 P(i,j,t) =E= alpha(j)*MB(i,j,t) +
bita(j)*Y(i,j,t);
Eq9a(i,j,t)$(K(i) AND PH(t) AND JI(j,i))..
                                 MB(i,j,t) =G= SUM(ii$(K(ii) AND
JI(j,ii)),M(ii,j,t)) - lamdaT(j,t)*(1-Y(i,j,t));
Eq9b(i,j,t)$(K(i) AND PH(t) AND JI(j,i))..
                                 MB(i,j,t) =L= SUM(ii$(K(ii)
```

```
ANDJI(j,ii)),M(ii,j,t)) + lamdaT(j,t)*(1-Y(i,j,t));
Eq9c(i,j,t)$(K(i) AND PH(t) AND JI(j,i))..
                                 MB(i,j,t) =L= lamdaT(j,t)*Y(i,j,t);

*=================== Demands for Utilities ===================
*Eq10(n,t)$PH(t)..                SUM((i,j)$(K(i) AND JN(j,n) AND
JI(j,i)),M(i,j,t)) + OJ(n,t) =E= thita(n,t) + DISP(n,t);
Eq10(n,t)$PH(t)..                SUM(z$ZN(z,n),B_OUT(z,n,t)) + OJ(n,t) =E=
thita(n,t) + DISP(n,t);


*=================== Assignment changes related to utility units to
connecting lines ===================
Eq20(i,j,t)$(K(i) AND PH(t) AND JI(j,i))..
                                 D(i,t) =G= Y(i,j,t) - fip(i,j)$(ORD(t)=1)
- Y(i,j,t-1)$(ORD(t)>1) - S(i,t);

*=================== Maximum Runtime =================
Eq21(i,t)$(K(i) AND PH(t))..      SUM(tt$(PH(tt) ANDORD(tt) GE
max(1,(ORD(t)-omikron(i))) ANDORD(tt) LE ORD(t)),X(i,tt))
                                 =L= omikron(i);
Eq22(i,t)$(K(i) AND PH(t) AND (ORD(t)=(omikron(i)-omegap(i)+1)) AND
(omegap(i)>1))..
SUM(tt$(PH(tt) ANDORD(tt) GE max(1,(ORD(t)-(omikron(i)-omegap(i))))
ANDORD(tt) LE ORD(t)),X(i,tt))
                                 =L= (omikron(i)-omegap(i));

*======================================inventory
tanks=====================================
Eq23(z,t)$(PH(t) AND ZE(z))..        B_IN(z,t) =E= SUM((i,j)$(K(i) AND JI
(j,i) AND JZ(j,z)),M(i,j,t));
Eq24(z,t)$(PH(t) AND ZE(z))..        B_IN(z,t) =G= g_min(z);
Eq25(z,t)$(PH(t) AND ZE(z))..        B_IN(z,t) =L= g_max(z);

Eq26(z,t)$(PH(t) AND ZE(z))..        B(z,t) =E= bitap(z)$(ORD(t)=1) +
B(z,t-1)$(ORD(t)>1) + B_IN(z,t)- SUM(n$ZN(z,n),B_OUT(z,n,t));
Eq27(z,t)$(PH(t) AND ZE(z))..        B(z,t) =G= ksi_min(z);
Eq28(z,t)$(PH(t) AND ZE(z))..        B(z,t) =L= ksi_max(z);

*=================== Objective Functions =================

OBJ..                          OF =E= SUM((i,t)$(K(i) AND
PH(t)),(epsilon(i)*D(i,t)))
                                 + SUM((n,t)$PH(t),(acq_c(n,t)*OJ(n,t) +
disp_c(n,t)*DISP(n,t)))
                                 + SUM((i,t)$(K(i) AND
PH(t)),((xi(i)*S(i,t)+(fi(i)*F(i,t)))))
                                 + SUM((i,j,t)$(K(i) AND PH(t) AND
JI(j,i)),(delta1(i)*Y(i,j,t)+delta2(i)*(M(i,j,t)/sc1(i))+delta3(i)*(P(i,j,t
)/p_in(i,t))/sc2(i)+delta4(i)*(w_flow(i)/sc3(i))*Y(i,j,t))*sc4(i)*mi(t));

MODEL UTILITY_SYSTEM_RH /ALL/ ;

DISPLAY
i,j,n,t,K,PH,JI,JZ,ZN,alpha,bita,delta1,delta2,delta3,epsilon,hita,thita,la
mda,mi,omikron,pe_min,pe_max,ro_min,ro_max,acq_c,disp_c,fi,xi,psi,omega,fip
,xip,psip,omegap,delta4,sc1,sc2,sc3,sc4,w_flow,i,j,n,t,K,PH,JI,JZ,ZN,alpha,
bita,delta1,delta2,delta3,epsilon,hita,thita,lamda,mi,omikron,pe_min,pe_max
,ro_min,ro_max,acq_c,disp_c;
```

```
UTILITY_SYSTEM_RH.optfile = 1;
SOLVE UTILITY_SYSTEM_RH using MIP minimizing OF;

CPUs = UTILITY_SYSTEM_RH.resusd;

DISPLAY
CPUs,OF.L,M.L,MB.L,P.L,Y.L,X.L,S.L,F.L,D.L,DISP.L,OJ.L,B.L,B_IN.L,B_OUT.L;

PARAMETERS TOTAL_MASSFLOWRATE (i);
TOTAL_MASSFLOWRATE(i)= SUM((j,t),M.L(i,j,t));

PARAMETERS PWRCOMP_CONS(i);
PWRCOMP_CONS(i) = SUM((j,t)$(K(i) AND PH(t) AND
JI(j,i)),(delta1(i)*Y.L(i,j,t)+delta2(i)*(M.L(i,j,t)/sc1(i))+delta3(i)*(P.L
(i,j,t)/p_in(i,t))/sc2(i)+delta4(i)*(w_flow(i)/sc3(i))*Y.L(i,j,t))*sc4(i));

PARAMETERS PWRCOMP_COST(i);
PWRCOMP_COST(i) = SUM((j,t)$(K(i) AND PH(t) AND
JI(j,i)),(delta1(i)*Y.L(i,j,t)+delta2(i)*(M.L(i,j,t)/sc1(i))+delta3(i)*(P.L
(i,j,t)/p_in(i,t))/sc2(i)+delta4(i)*(w_flow(i)/sc3(i))*Y.L(i,j,t))*sc4(i)*m
i(t));

PARAMETER COST_ELEC;
COST_ELEC(t) = SUM((i,j)$(K(i) AND PH(t) AND
JI(j,i)),(delta1(i)*Y.L(i,j,t)+delta2(i)*(M.L(i,j,t)/sc1(i))+delta3(i)*(P.L
(i,j,t)/p_in(i,t))/sc2(i)+delta4(i)*(w_flow(i)/sc3(i))*Y.L(i,j,t))*sc4(i)*m
i(t));

PARAMETER POWER_CONS;
POWER_CONS(t) = SUM((i,j)$(K(i) AND PH(t) AND
JI(j,i)),(delta1(i)*Y.L(i,j,t)+delta2(i)*(M.L(i,j,t)/sc1(i))+delta3(i)*(P.L
(i,j,t)/p_in(i,t))/sc2(i)+delta4(i)*(w_flow(i)/sc3(i))*Y.L(i,j,t))*sc4(i));
DISPLAY COST_ELEC,POWER_CONS,PWRCOMP_CONS,TOTAL_MASSFLOWRATE;
```