OPTIMUM SCHEDULING OF ENERGY- INTENSIVE COMPRESSORS NETWORK UNDER REGULATED ELECTRICITY TARIFF

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in fulfilment of the requirements for the degree of

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DECLARATION

I declare that this project report entitled *"Optimum Scheduling of Energy – Intensive Compressor Network under Regulated Electricity Tariff"* is the result of my own work except as cited in the references

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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 of the award of the degree of Bachelor of Mechanical Engineering

Signature : ....

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Date : 24 JULY 2020

DEDICATION

This study is dedicated to my father, who taught me that the best kind of knowledge to have which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

ABSTRACT

Compressed air is a major source of power transfer which has been used in various kind of application in industries. The example of application that widely used are heavy lifting and transports, tire inflation, dust removal, vacuum packaging, cutting, and slicing and many more. Compression air is a major source of energy transfer. Industries have been professional in their initial designs to incorporate details on their systems so that the air compressors can automatically analyse on operating status and output parameters to the compressor operators. Most of heavy industries used compressors network where it can work at higher pressure points than commercial industries. Therefore, it going to use at high pressure at certain time. Regarding to that, the application of incentive-based strategy is going to apply to minimize the runtime of compressor. The objective of this case study where to investigate the current relation between the operational and energy scheduling of energy intensive. Then, formulate an optimization model for scheduling of energy-intensive compressors network under regulated electricity tariff. From that, the energy and cost benefits of the proposed optimization model will be defined. By using General Algebraic Modeling System (GAMS) software the operational of air compressor can be optimizing which the data from the research such as start-up and shutdown compressor, minimum and maximum runtime, and change of connection line to maximize the demand and inventory level for every compressor unit is input into GAMS software. The software will generate all the equation and come out with the minimum total power cost after 21 days operation.

ABSTRAK

Udara mampatan adalah sumber utama pemindahan tenaga yang telah digunakan dalam berbagai jenis aplikasi di industri. Contoh aplikasi yang digunakan secara meluas ialah pengangkatan dan pengangkutan berat, inflasi tayar, penyingkiran habuk, pembungkusan vakum, pemotongan, dan pemotongan dan banyak lagi. Udara mampatan adalah sumber utama pemindahan tenaga. Industri telah profesional dalam reka bentuk awal mereka untuk memasukkan perincian pada sistem mereka sehingga pemampat udara secara automatik dapat menganalisis status operasi dan parameter output kepada operator pemampat. Sebilangan besar industri berat menggunakan rangkaian pemampat di mana ia dapat berfungsi pada titik tekanan yang lebih tinggi daripada industri komersil. Oleh itu, ia akan digunakan pada tekanan tinggi pada waktu tertentu. Sehubungan dengan itu, penerapan strategi berbasis insentif akan diterapkan untuk meminimumkan waktu pemampatan pemampat. Objektif kajian kes ini adalah untuk mengkaji hubungan semasa antara penjadualan operasi dan tenaga dengan intensif tenaga. Kemudian, rumuskan model pengoptimuman untuk penjadualan rangkaian pemampat intensif tenaga di bawah tarif elektrik yang diatur. Dari itu, manfaat tenaga dan kos model pengoptimuman yang dicadangkan akan ditentukan. Dengan menggunakan perisian General Algebraic Modeling System (GAMS), operasi pemampat udara dapat mengoptimumkan data dari penyelidikan seperti pemampat pemula dan pemutus, runtime minimum dan maksimum, perubahan saluran sambungan untuk memaksimumkan permintaan dan tingkat persediaan untuk setiap unit pemampat dimasukkan ke dalam perisian GAMS. Perisian ini akan menghasilkan semua persamaan dan mengeluarkan dengan jumlah kos kuasa minimum setelah 21 hari beroperasi..

ACKNOWLEDGEMENT

First and foremost, I would like to take this opportunity to express my sincere acknowledgement to my supervisor Dr. Nur Izyan binti Zulkafli from the Faculty of Mechanical Engineering Universiti Teknikal Malaysia Melaka (UTeM) for her essential supervision, support and encouragement towards the completion of this project report. Special thanks to all my peers, my parent and siblings for their moral support in completing this degree. Lastly, thank you to everyone who had been to the crucial parts of realization of this project.

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LIST OF ABBREVIATION

TOU	Time of Use
ETOU	Enhance Time of Use
TNB	Tenaga Nasional Berhad
GAMS	General Algebraic Modeling System
MILP	Mixed-Integer Linear Programming

LIST OF SYMBOLS

t	Duration of each time
ω_i	Minimum runtime for compressors
$\widetilde{\omega_i}$	Total number at beginning of planning horizon for compressor
$X_{(i,t)}$	Compressor network operating during time period t
$S_{(i,t)}$	Start up at the beginning of t
$F_{(i,t)}$	Shut down in initial time t
$\tilde{X}_i$	Initial operating status
φ_i	Minimum shutdown time for compressor
$\tilde{Q}_{(i,t)}$	Operating production level of compressor
$K_{(i,t)}^{UT,min}$	Production level of compressor
$B_{(e,z,t)}^{UT,+}$	Flow of compressor network in storage tank for period t
$Z_{e,}$	Inventory can store compress air in tank
λ_n^{max}	Maximum number of products

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CHAPTER 1

INTRODUCTION

1.1 Background

Network compressor is commonly used in industrial sector for machinery. Compressor unit supply compress air to header where every single header link with storage tank and supply to the processing unit. To achieve the fourth industrial revolution, the concept describes manufacturing facilities for all machines including the air compressors with their corresponding sensor. In global market, most of the company applying for environmental regulation to ensure the energy will be maximized to save the cost. In demand side management it has several merits which is reducing the cost, and this is great for industries. (Basu, 2020) Generally, for industrial equipment most of the machine are interrelated from the initial to the final production system. The efficiency of compressor network is important to ensure the entire system which air storages, air dryer, receiver, and after-cooler in a good condition. For the operation system, the compressor network in industry need to maintain the efficiency of compressor by using optimization method. It will be easier for optimum scheduling of energy intensive. To present the better computationally methods for minimizing the cost of compression under dynamic condition where the industry should describe by time-dependent mass flow. Moreover, the operation process for network compressor through converting inexpensive electricity power must be justify achieving the optimal rate to reduce cost. Most of the utility system in industrial have make a system by directly linked with pipeline to ensure the high profit in production line based on the demand (Zulkafli & Kopanos, 2016). Moreover, the facilities in industries using compress air system as the main energy and it shows that how the network compressor influences in electrical energy such factor include type, model, size, motor power rating, system design and control mechanisms. The main reason where the causes of inefficient network compressor is when the heat loss which generated from the increased temperature in air and caused by friction from the part moving. Other than that, compress air system is consuming high amount of energy and there are huge losses due to pressure and air flow rate drop (Taheri & Gadow, 2017). If the right method applies for the network compressor system, it will be going to save cost and energy.

1.2 Problem Statement

To reduce cost for electricity, the optimum strategy must be planned to maintain the production line at maximum peak value. Regarding to the charged from electricity tariff, the optimum scheduling tools for each equipment in industry must be applied to make sure that all equipment uses in range of saving energy. In industrial sector the electricity price is depends on power consumption uses and it is much related with demand side management to control the power users for every equipment. Based on data in annual energy outlook 2019, the energy consumption increases 0.9% per year from 2018(*Annual Energy Outlook 2019*, 2019). From the increasing of energy consumption, the total demand for all fuel also increased. Therefore, this case study will be done by formulating the optimization model with ideal strategy for energy-intensive in compressor network. Besides, from this case study the current trend for the demand side management will be generated to make sure that the operation of energy-intensive in each mechanical equipment in industry will be calculated of energy-intensive in each mechanical equipment in industry will be calculated.

1.3 Objective of Study

(a) To investigate the current relation between the operational and energy scheduling of energy-intensive mechanical equipment.

(b) To formulate an optimization model for scheduling of energy-intensive compressors network under regulated electricity tariff.

(c) To evaluate the energy and cost benefits of the proposed optimization model through the use of comprehensive analysis.

1.4 Scope of Study

Based on the study it will be focusing on the development scheduling energy-intensive for compressor network. To achieve efficient energy use, sometimes it can be simplified energy efficient to reduce the amount of energy required to provide the losses from the machine equipment. From the case study it consists of 11 compressor which is (i1, i2, i3, i4, i5) for small compressor and (i6, i7, i8, i9, i10, i11) for big compressor. Each compressor supplies the compress air for every processing unit through storage tank and header. Every processing unit must consist of only one storage and one header. To achieve the optimum runtime, the time of uses (TOU) is important to make sure that compressor run in a certain peak or off-peak time. For example, by running the network compressor at certain time can provide from higher charge from electricity tariff. In certain cases, penalty cost will be charged if the final product from external sources and for the changes of utility unit. By using GAMS software, it will be easier to formulate the mathematical model to finding optimal solution to optimization problems.

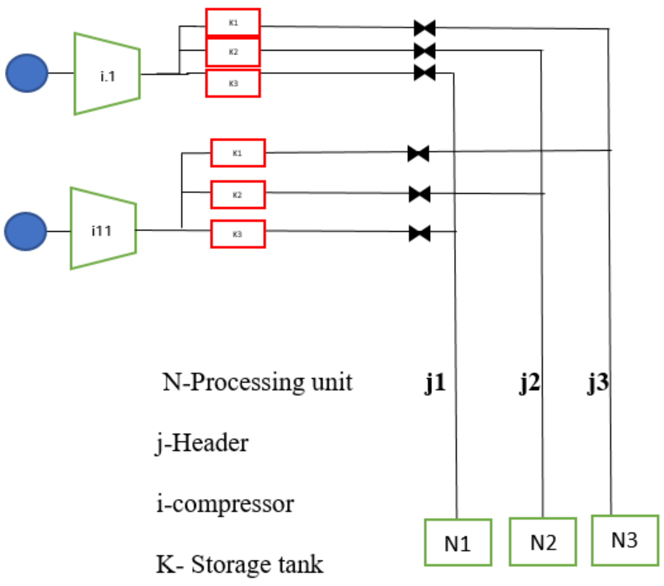

Figure 1.1 Layout of the Network Compressor

Table 1.1 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	

Table 1.2 Time Zone Classified

ETOU time zone		
Time zone	Industrial E3 HV ETOU	Hour
	Energy Charge (cent/kWh)	
Mid-peak	32.70	08:00-11:00 Hours
Peak	57.60	11:00-12:00 Hours
Mid-peak	32.70	12:00-14:00 Hours
Peak	57.60	14:00-17:00 Hours
Mid-peak	32.70	17:00-22:00 Hours
Off-peak	20.20	22:00-08:00 Hours

1.5 Expected Finding

From Table 1.3 below, the main problem is to calculate the maximum of the total profit. It consists of five type of chemical and each chemical through the two-chemical process. After the chemical through the process, it will be going to the final process which is packaging for each chemical. Regarding to the process three equipment will be used for process one and two equipment for process two. Each unit required a certain time in hour on each process as given table below.

Table 1.3 Chemical with Process

	Chemical 1 $550	Chemical 2 $600	Chemical 3 $350	Chemical 4 $400	Chemical 5 $200
Process 1	12	20	-	25	15
Process 2	10	8	16	-	-

Solution:

By using GAMS method, it will be easier to formulate a mathematical model for optimal solution to optimization problem as shown in table below the total highest profit come out.

Table 1.4 Higher Chemical and Process

	Chemical 1	Chemical 2
Process 1	24000	-
Process 2	-	24000
Packing	-	19200
Total profit: 39120.000		

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this develop world, most of the equipment in industries use network compressor or air compressor as the main energy supply to move each part in every equipment. To make sure all equipment receive enough compress air to the machine, the system has been controlling with master controller and the ability of the unit can collect and communicate data. Regarding to the major uses of network compressor in industry, it is quick good to apply incentive based strategy for optimum scheduling of energy-intensive for compressor network to ensure that the daily use of power consumption for network compressor will be minimize. The operational for network compressor commonly depends on the uses of every equipment in certain time. By using optimum scheduling, the compressor network supply will be minimizing their operating cost where much more related with regulated electricity tariffs. In fact, most of the electricity today are mostly based on the fossil fuel power plant (Benato & Stoppato, 2019) and from that statement shows that, it is important to minimize the uses of electricity for future generation.

2.2 Demand side management

It becomes important to inspect on the optimum scheduling of power generation due to the increases of renewable energy needed. The extremely problem issue about nature in renewable energy resources and the higher loss will cause a bad effect on the industries sector. Based on the research showed that a good recommends to solve this issue by implementing all system in industries with demand side management. From that all problem regarding to the power consumption will be reduced (Basu, 2020). The recent issue makes the energy generation technologies mostly consist of renewable which have been triggered significant on the development for future sustainable solution.

Moreover, to gain the best development basically need more efficient consumption and the suitable keys related with that is demand side management (DSM) where the consumer can change their own profile for energy consumption. From this context, department in energy management system come into view at some of the implementation from operator system and mostly focus on the major application in energy uses at certain equipment. This platform will be calculating that optimization of energy consumption use according to preference on monitoring the data provided and how efficient use of energy (Gomes et al., 2019). According to the international energy agency's tactical plan, the demand side management is championed as the prime option of the entire energy policy verdicts. In demand side management system have several benefits such as reducing cost, increasing the reliability of the power system. In this department, it is more related to the time of use (TOU) program where some percentage of load demand to be fixed.

The demand side management are effective to be apply in industries because it effectively relief the problem on how to manage the uses of power consumption. It could be observed by make sure the peak of power load does not change, where's the maximum load has been transferred into the system such as the charging peak has moved from 19:00-18:00 to 16:00-18:00 (Wang et al., 2019). It shows that, the total unit in line order meet the power demand at peak period. The power output of expensive unit will easily reduce from the good demand shifting regarding to the proper algorithms. By using the optimal demand side management, it also can influence of peak shifting in certain value.

To reach sustainable development targets, growing body of literature on able demand side management theories, framework, policies and application in various sector all around the world. It helps from distinct actor by various ways such as lowering the bill payment for end-user, developing a strength point for the certain resources (Wang et al., 2019). Applying the optimal management, it will affect extra building can be connected to the network without installing new pipeline and good renewable energy sources can be reached (Wang et al., 2019).

2.3 Regulated tariffs

According to the Energy Information Agency (EIA) Tariff is the formation to determine the updated pricing for supplier charges to customer for energy consumption. An electricity tariff is the price unit at which electricity is sold and will be measured in rate per kilowatt-hour (kWh) of power consumed. For one kilowatt-hour (kWh) it refers to the amount of electricity consumed when the appliance of one kilowatt power rating runs in sixty minutes. Besides, electricity tariff is known as one unit of electricity where every appliance has different value of power ratings and differently power consumption calculated.

TARIFF CATEGORY	CURRENT RATE (1 JAN 2014)
TARIFF D - LOW VOLTAGE INDUSTRIAL TARIFF	
For the first 200 kWh (1 -200 kWh) per month	38.00 sen/kWh
For the next kWh (201 kWh onwards) per month	44.10 sen/kWh
The minimum monthly charge is RM7.20	
TARIFF E1 - MEDIUM VOLTAGE GENERAL INDUSTRIAL TARIFF	
For each kilowatt of maximum demand per month	29.60 RM/kW
For all kWh	33.70 sen/kWh
The minimum monthly charge is RM600.00	
TARIFF E2 - MEDIUM VOLTAGE PEAK/OFF-PEAK INDUSTRIAL TARIFF	
For each kilowatt of maximum demand per month during the peak period	37.00 RM/kW
For all kWh during the peak period	35.50 sen/kWh
For all kWh during the off-peak period	21.90 sen/kWh
The minimum monthly charge is RM600.00	
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	

Figure 2.1 Industrial Tariff

Electricity tariff are designed to deliver electricity utility for every companies with income and returns to cover working and maintenance costs. Moreover, for electricity tariff it does not affect the long term for marginal cost (LRMC) in electrical production (Pacudan, 2019). Environment, energy and climate change are main problems in Malaysia through the application of an effective energy management system, awareness is thus constantly spread among citizens to protect the ecosystem. The correlation between electricity consumption and CO2 emissions has been identified as the 3rd largest source, while capacity generation is forecast to increase annually. In 2016, in line with the increase in economic growth in Peninsular Malaysia, electricity is expected to increase by approximately 4% from 117,219 MWh to 121,956 MWh between 2015 and 2016 (Sulaima et al., 2019).

Optimal tariff arrangement that could produce a regulated utility to promote its customers ' energy efficiency, as it is privately informed of the usefulness of its demand reduction efforts. A selection of incentive-compatible two-part tariffs should be offered optimally by the regulator. If the energy efficiency efforts of the company have a high effect on the decrease of demand, the customer will pay a high fixed fee but a low per unit price, similar to the tariff structure to a better strategy that improves the incentives of the company to pursue energy conservation (Abrardi & Cambini, 2015).

2.4 Optimization of compressor regarding the time

Compresses air, which is provided by compressor which is an important resource for main production process in most process industries. Several compressors are depending on the purpose of the system in which they are integrated connect in series or parallel. There are several types of categorization for single and multi-period optimization. The single time optimization considers information of one-time interval which steady state and the multi period optimization utilizes information from the future based on the calculating method. The estimate of the demand and parameter of constrain are used in the optimization outline. The optimization outline suggest decisions are based on future information. Besides, the time scheduling of a compressor might influence the outcomes for current operation (Xenos et al., 2015).

2.5 Production scheduling

The production scheduling may be represented in two difference types of product that due to their production technological sequence use the equivalent equipment, but the various sequences kind of product and the equipment used. The time for each equipment means the production time in hour are different. The developed production scheduling is more related with strategy in every equipment and the purpose are to make sure that the production sequences will be minimize overall production time (Darya Plinere,2018). Based on Figure 2.4.1 shows that, the operational system used in industries for compressor network in a month.

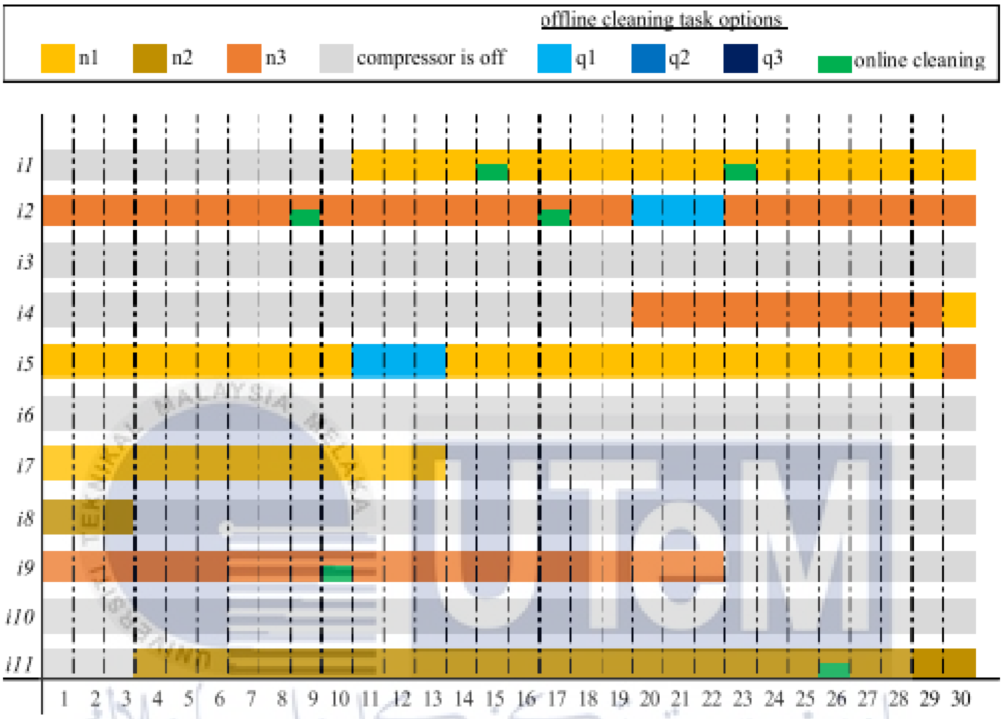

Figure 2.2 Example operational system in industries

Other than that, for production scheduling it is most interrelated with energy efficiency to enhance the efficient performance in system in order to prevent the equipment or machine from consuming energy when there is no working production (Gong et al., 2017). Production scheduling are consisting of 4 component such as planning, routing, scheduling and dispatching. For the planning component, mostly it is deciding in advanced what could happen in future and improve by planning an optimum scheduling. Production routing is the method to determining the route or path which product need and mainly this part is to discover and perform best in economical. Scheduling is the process must be completed regarding to time or date. While for dispatching relate to process of introducing production with proper plan of production.

2.6 Planning of a compressor network

Generally, process in industries and especially the most energy intensive, have installed a compressor network for discussion the utility needs of the main production system. A chronological approach is typically used for the planning of utility and production systems. First, the planning of the production system is completed considering simply upper bounds on the availability of utilities. Once the production plan is obtained, the utility demands of the production are known. This data is then used for finding the operational planning of the compressor network. This successive approach provides suboptimal solutions which is mainly in terms of energy efficiency and costs because the two interconnected systems are not optimized at the same time. Integrated planning of compressor network and production systems could result in significant energy savings, emissions and over- all costs reductions. Optimization framework for the planning of a network of compressors considering limitations on the number of compressors that could be under maintenance simultaneously. System with minimal team of maintenance and it shown that the reducing cost is possible to obtain the least amount of available assets (Zulkafli & Kopanos, 2016).

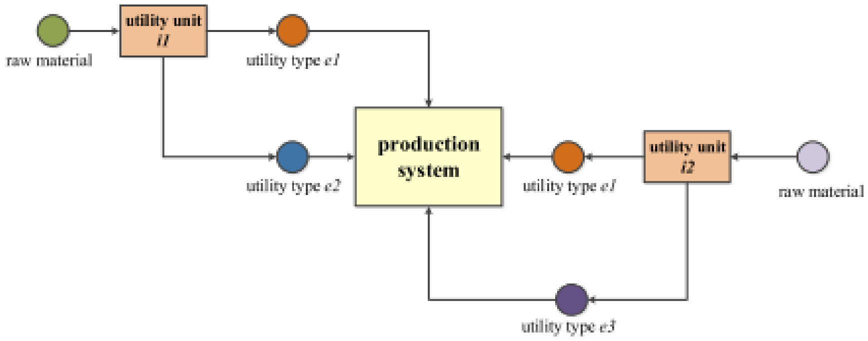

Figure 2.3 Layout of production and utility system

Regarding to the planning of the electricity supply system, it will raise some critical problems. To meet the increasing demand for electricity, all the planning must be followed continually and make sure that the capital requirement is larger. The planning of the electricity supply system is the critical issue which encountered where increasing cost, financial, environmental restraints or increasing fuel cost. Most of the modern facilities nowadays especially in digital computer enable many other actions to be studied. Modern facility easily to generate a spectrum of model needed from those formulated demand of data, through that it easily to simulating the future operation system in industries (G.Z. Ben-Yaacov, 1978).

2.7 Summary

To conclude, the previous example has been studied about the optimum scheduling of compressor network under regulated tariff. Based on that case study the great contribution of the present study has been tested to question on the running time of network compressor for 3 weeks with the difference value of demand for each processing unit. Regarding to the value of charged from regulated tariff in industries E3, the time of use (TOU) for the weekday and weekend remain unchanged but for the enhanced time of use (ETOU) it changes due to the price charged for weekend which lower than weekday. It is going to be an advantage for certain company which running the equipment in weekend.

Table 2.1 Summary of literature review

Author	Demand side	Regulated tariff	Production scheduling	Optimization of compressor	Planning of utility system
Benato and Stoppato,.2019	√	√		√	
Basu,.2020	√	√			√
Gomaz et al,.2019	√	√	√	√	
Wang et al,.2019	√	√		√	
Pacudan,.2019	√	√			√
Sulaima et al,.2019		√		√	
Abrardi Cambini,.2015		√			
Xenos et al,.2015				√	
(Darya Plinere,2018			√		
Gong et al., 2017			√		
Zulkafli & Kopanos,2016					√
G.Z. Ben-Yaacov,1978					√

CHAPTER 3

METHODOLOGY

3.1 Introduction

For this chapter it defines the methodology that used for this project which by using GAMS software. GAMS is designed for modelling to answering the linear problem of optimization. To make a huge maintainable project, GAMS software is the best way to overcome the application use for large scale modelling to modify new situation. Based on the Figure 3.1 below shows that, this case study starting from literature review to gain knowledge on how the pattern or trend of scheduling of network compressor in industries. Besides, from the previous data collected it will be easier to overcome the new scheduling for the network compressor to ensure that the demand for the network compressor parallel with the tariff will be charged. Regarding to that, the cost of electricity charged will be reduce once the optimum apparent scheduling for compressor network in industries have been implemented. If the result does not apparently show, then new modelling will be prepared.

3.2 General methodology

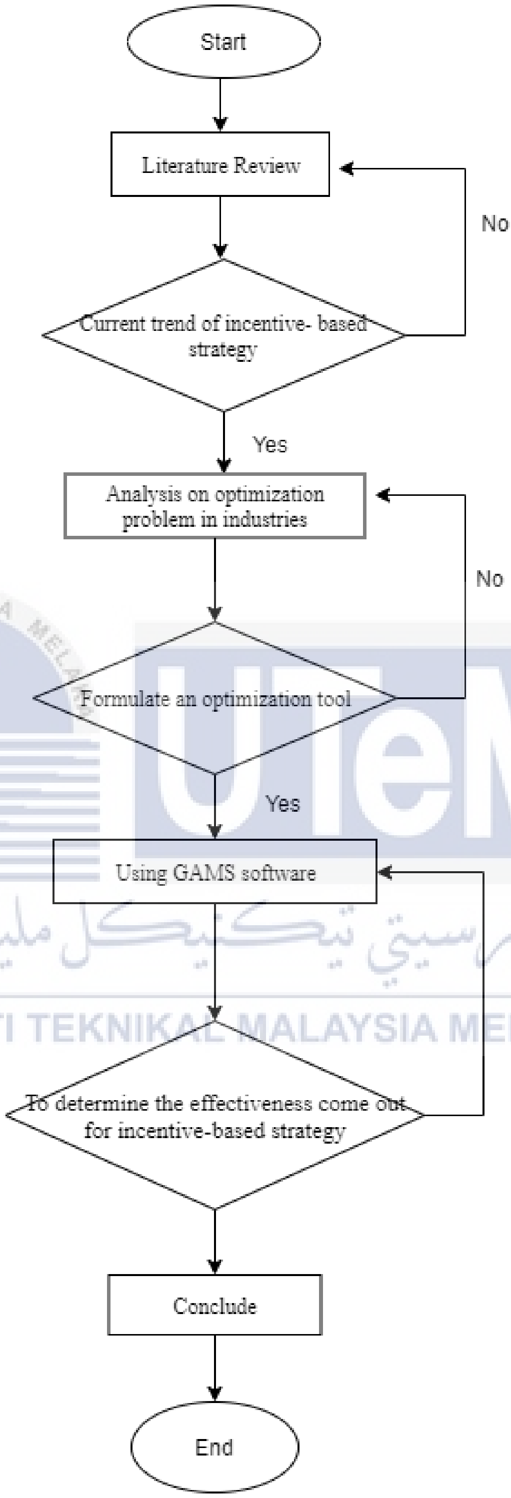

Figure 3.1 Flowchart

3.3 Methodology

To achieve the sample for modelling strategy of optimum scheduling of energy-intensive compressor network for an objective in this project related with listed below:

(a) Literature review

All journal or information related to this project will be examined to elaborate the evidence for this case study.

(b) Current trend of incentive-based strategy

Once the current trend come out from the previous review will be study for further action or strategy. It will make easier to analyst either the current affected for optimum scheduling in certain cases.

(c) Analysis on optimization problem in industries

Regarding to the application of network compressor in industries, all data or problem faces in industries will be examined to overcome the optimum scheduling and application in energy consumption.

(d) Formulate an optimization tool

All data come out will be formulated to generate tools.

(e) Using GAMS software

Games software will generate the mathematical model for finding the optimal solution to optimize the problem.

(f) Determine the effectiveness come out for incentive-based

Once the data or sample of model come out, the effectiveness for incentive-based strategy are easily to be determined.

Based on the Figure 3.1 shows that the flowchart in this research will starting by finding the literature review regarding to the optimization scheduling. It is depending on the operation of the equipment in industries. The current of incentive-based strategy came out and from that the planning or strategy for will be easily planned to ensure that the framework pattern followed by the objective function and all parameter involved. If the result does not satisfy, it will be going back to the literature review. After that, the problem regarding to the optimization problem in industries will be determined to formulate an optimization tools which consist of all data from previous running time in each equipment. From the data collected, it will be easier to insert into GAMS software. The model come out, describe the model once enter data and it will dedicate for solving optimization problems. Once the effective come out for incentive-based strategy, then conclusion will be made to ensure that the result have been successfully meet the main purpose of this project.

3.4 GAMS formulate scheduling

To ensure the concept of GAMS software and the optimum scheduling for network compressor was conduct on demand side management in industries. The value of mass flow rate demand has been preferred from the previous case study but still below than the maximum demand. Regarding to that, the initial value of production unit for (N1) has been setup with the maximum value of demand and it is depending on the demand need in industries. The demand created in GAMS software is to make sure that the formulating scheduling for run time of compressor network will be minimized to save the cost of electricity under latest regulated tariff. Time period of network compressor are measured by the total average hour per days.

The total demand for compressor unit for every production is important to indicate the actual value needs for compressor to operate. In this case study, the total compressor provided is 11 and each compressor will relate to header and storage tank. To make sure just only certain compressor running within 3 weeks, the application of GAMS is used. By that, the value of optimum scheduling will systematically manage for simulation study before taking decisions.

3.5 Implementation of GAMS to process optimization problem

First and foremost, the mathematical model for finding optimal solution should be known to generate the optimization problem. The whole coding for GAMS must also be include with the objective function with the related equation such as start-up, shutdown, penalty cost and power consumption for compressor network.


```
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,

*=================== 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) AND ORD(tt) GE max(1,(ORD(t)-omega(i)+1)) AND ORD(tt) LE
Eq4(i,t)$(K(i) AND PH(t) AND psi(i)>1)..
                                 1 - X(i,t) =G= SUM(tt$(PH(tt) AND ORD(tt) GE max(1,(ORD(t)-psi(i)+1)) AND ORD(tt) I
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;
```

Figure 3.2 Example of objective function

Regarding to the equation no 1 and 2, it is related to start up and shutdown of a compressor network. Other than that, equation 3 to 8 represent the minimum runtime and shutdown time for each compressor. From the above Figure it shows that how does the coding will be inserted to generate the optimal solution by using GAMS.

```
TABLE thita(n,t)        compressed air mass flow rate demand for process unit n in time period t


                         t1  t2  t3  t4  t5  t6  t7  t8  t9  t10 t11 t12 t13 t14 t15 t16 t17 t18 t19 t20 t21
                    n1   50  50  50  50  50  50  50  50  50   50  50  50  50  50  50  50  50  50  50  50  50
                    n2   40  40  40  40  40  40  40  40  40   40  40  40  40  40  40  40  40  40  40  40  40
                    n3   20  20  20  20  20  20  20  20  20   20  20  20  20  20  20  20  20  20  20  20  20
PARAMETER
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 /j1 50, j2 86, j3 129/
TABLE lamdaT(j,t)       problem-specific large number that could represent the capacity of header j
                         t1  t2  t3  t4  t5  t6  t7  t8  t9  t10 t11 t12 t13 t14 t15 t16 t17 t18 t19 t20 t21
                    j1   345 345 345 345 345 345 345 345 345 345 345 345 225 225 225 225 225 225 225 225 225
                    j2   225 225 225 225 225 225 225 225 225 225 225 225 180 180 180 180 180 180 180 180 180
                    j3   315 315 315 315 315 315 315 315 315 315 315 315 270 270 270 270 270 270 270 270 270;

PARAMETER

mi(t)               electricity price in time period t /t1 6.74, t2 6.74, t3 6.74, t4 6.74, t5 6.74, t6 6.74, t7 6.74,
omikron(i)          maximum online time after the startup of compressor i (maximum run time) /i1 20, i2 20, i3 20, i4 2
pe_min(i)           minimum pressure ratio of compressor i /i1 5, i2 4.2, i3 4.7, i4 4.78, i5 4.6, i6 5.1, i7 4.4, i8 4
pe_max(i)           maximum pressure ratio of compressor i /i1 6.5498, i2 6.16, i3 6.65, i4 5.68, i5 5.95, i6 6.17, i7
ro_min(i)           minimum compressed air mass flow rate from compressor i /i1 2.08, i2 1.7, i3 1.9, i4 1.773, i5 1.74
```

Figure 3.3 Example of demands cost

For this case study it would be focus on the demand of the compressor network where it shown at figure above. Value for each production have been set up which the demand high at n1 and decrease for the next production unit. Besides, mi is representing for electricity price which TOU or ETOU based on the electricity tariff.

3.6 Optimization Framework

For this part of modelling system by mixed integer linear programming it will shows that how the operation of scheduling system for network compressor regarding to the utility system and operation planning for production in industries. The most important part in this section will represent the optimization framework which has been divided into following part:

(a) The compressor system

(b) The production system

(c) The objective function

3.6.1 The compressor system

3.6.1.1 Constrain related to startup and shutdown

The following binary variable are first introducing the main operation aspect for utility units:

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

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

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

The model of start-up and shutdown action for operating status in compressor unit with constrains (1) and (2)

$$S_{(i,t)} - F_{(i,t)} = X_{(i,t)} - \tilde{X}_i \qquad \forall i \in I, t \in T : t = 1$$

$$S_{(i,t)} - F_{(i,t)} = X_{(i,t)} - X_{(i,t-1)} \qquad \forall i \in I, t \in T : t > 1 \tag{1}$$

$$S_{(i,t)} - F_{(i,t)} \leq 1 \quad \forall i \in I, t \in T \tag{2}$$

Regarding to the constraints (1), the utility system not operate based on the previous time period current time, thus start-up will take place (i.e., $S_{(i,t)} = 1$ and $F_{(i,t)} = 0$). The parameter of $\tilde{X}_i$ denotes for the working status of utility unit i before the start of planning horizon. If the utility unit i working before the planning horizon then $\tilde{X}_i = 1$ if not it will become zero. For constrain (2) it is not including for simultaneous realization for start-up and shutdown. The cost will be including if start-up and shut down included in objective function. Constrain (2) will not be included from the optimization model, as their corresponding will equal to zero.

3.6.1.2 Constraints minimum runtime and shutdown time

This constraint to make sure that the utility unit start-up at certain time period t, at least ω_i time period will operate.

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

$$X_{(i,t)} = 1 \quad \forall i,t \in I, t = 1,\dots,(\omega_i - \widetilde{\omega_i}) : 0 < 1 \quad \widetilde{\omega_i} < \omega_i \qquad (3)$$

Each utility shows the minimum runtime for parameter $\widetilde{\omega_i}$ in initial state. More detailed, it shows the parameter correspond for the total time at early of planning horizon in utility unit i.

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

$$X_{(i,t)} = 1 \quad \forall i,t \in I, t = 1,\dots,(\omega_i - \widetilde{\omega_i}) : 0 < 1 \quad \widetilde{\omega_i} < \qquad (4)$$

For constrain (4) model the value of minimum shutdown time (φ_i) after shutdown. This part to make sure that the utility unit of shutdown by the time t, not working for as a minimum φ_i time periods.

3.6.1.3 The Maximum Runtime

$$\sum_{t'=max\{1,t-0_i\}}^{t} X_{(i,t')} \leq 0_i \qquad \forall i \in MR_{i,} t \in T$$

$$\sum_{t'=max\{1,t-(0_i-\widetilde{\omega_i})\}}^{t} X_{(i,t')} \leq (0_i - \widetilde{\omega_i} \qquad \forall i \in MR_{i,} t = (0_i - \widetilde{\omega_i} + 1) : \widetilde{\omega} > 1 \qquad (5)$$

The related constrain (5) will be formulated to the maximum idle time in utility system. The value of maximum idle time is known as the maximum time period where the utility system switches off at last shutdown.

3.6.2 Production of compressor network

Operation of production of any compressor network unit ($\tilde{Q}_{(i,t)}$) must be in between its related lower and upper bounds ($K_{(i,t)}^{UT,min}$ and $K_{(i,t)}^{UT,max}$) when compressor operate as shown by:

$$K_{(i,t)}^{UT,min} X_{(i,t)} \leq \tilde{Q}_{(i,t)} \leq K_{(i,t)}^{UT,max} X_{(i,t)} \qquad \forall i \in I, t\, T \qquad (6)$$

3.6.2.1 Inventories for compressor

To remain the utility system contains several utility-dedicated inventory tanks. These tanks can obtain ($B^{UT,+}_{(e,z,t)}$) based on the utility unit which has been linked to:

$$B^{UT,+}_{(e,z,t)} = \sum_{i \in I_e} Q^{UT}_{(i,e,t)} \qquad \forall e \in E, z \in Z_{e,}, t \in T \qquad (7)$$

The compressor unit allocated inventory tank:

$$B^{UT,+}_{(e,z,t)} = \tilde{\beta}^{UT}_{(e,z,t)} + B^{UT,+}_{(e,z,t)} - \sum_{n \in IN_e \cap N_z} B^{UT,-}_{(e,z,n,t)} \qquad \forall e \in E, z \in Z_{e,} t \in T : t = 1$$

$$B^{UT}_{(e,z,t)} = B^{UT}_{(e,z,t-1)} + B^{UT,+}_{(e,z,t)} - \sum_{n \in IN_e \cap N_z} B^{UT,-}_{(e,z,n,t)} \qquad \forall e \in E, z \in Z_{e,} t \in T : t > 1 \qquad (8)$$

3.6.3 Production system for compressor unit

3.6.3.1 Production level for handling unit and process grade

$$K_{(i,t)} = \begin{cases} 1 \ final\ product\ during\ processing\ with\ time\ period\ t, \\ 0 \ \ otherwise. \end{cases}$$

$$\sum_{g \in G_n} K_{(n,g,t)} \leq \lambda^{max}_{n} \qquad \forall n \in N, \forall t \in T \qquad (9)$$

To ensure the volume of an end product will be represent in constrain (10) which should be comprise the upper and lower production level where $K^{FP,min}_{(n,g,t)}$ and $K^{FP,max}_{(n,g,t)}$ for every processing unit according to:

$$K^{FP,min}_{(n,g,t)} K_{(n,g,t)} \leq Q^{FP}_{(n,g,t)} \leq K^{FP,max}_{(n,g,t)} K_{(n,g,t)} \qquad \forall g \in G, n \in Ng, t \in T \qquad (10)$$

3.6.3.2 Inventories for air compressor

Regarding to the constrain (11) and (12) it shows that the equation related to air compressor inventories tank.

$$B_{(g,I,t)}^{FP,+} = \sum_{n \in (N_e \cap N_I)} Q_{(n,g,t)}^{FP} \qquad \forall g \in G, I \in L_{g,} t \in T$$

$$B_{(g,I,t)}^{FP} = \tilde{\beta}_{(g,I)}^{FP} + B_{(g,I,t)}^{FP,+} - B_{(g,I,t)}^{FP,-} \qquad \forall g \in G, I \in L_{g,} t \in T: t = 1 \qquad (11)$$

$$B_{(g,I,t)}^{FP} = \tilde{\beta}_{(g,I)}^{FP} + B_{(g,I,t)}^{FP,+} - B_{(g,I,t)}^{FP,-} \qquad \forall g \in G, I \in L_{g,} t \in T: t > 1 \qquad (12)$$

3.6.3.3 Changes of compressor to link in line

To model the active connection among utility units and connecting lines (j), the following binary variables are introduced:

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

$$\sum_{j \in J_i} Y_{(i,j,t)} = X_{(i,t)} \qquad \forall i \in I, t \in T \qquad (13)$$

Based on the above constrain it must be focus for the compressor network where link into the same line. Mainly it is depending on the compressor unit system to ensure the type of interest property.

3.6.4 Objective function

Regarding to the optimization target to minimize the total cost in production system. Below shows the objective function for production and utility system. The total cost must include:

(a) Compressor unit to connecting line

(b) Demand for compressor network

(c) Maximum and minimum runtime for start-up and shut down

(d) Pressure for compressor network

$$\text{Min} = \Big[\sum_{i\epsilon K} \sum_{i\varepsilon PH} \varepsilon_i D_{(i,t)} + \sum_{i\varepsilon PH} acq_{c_{(n,t)}} oJ_{(n,t)} + disc_{c_{(n,t)}} DISP_{(n,t)} + \sum_{i\epsilon K} \sum_{t\varepsilon PH} \chi_i S_{(i,t)} + \varphi_i F_{(i,t)} + \sum_{i\epsilon K} \sum_{t\varepsilon PH} \sum_{j\epsilon JI} \delta_i^1 Y_{(i,j,t)} + \delta_i^2 M_{(i,j,t)} + \delta_i^3 P_{(i,j,t)} \delta_i^4 Y_{(i,j,t)} mi_t\Big] \quad (14)$$

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

Based on this case study, the operational planning for the compressor network are in parallel. This study required to use GAMS software to optimize MILP model compressor network. From this study, the rate where start-up and shutdown compressor, minimum and maximum runtime, change of connection line to maximize the demand and inventory level for every compressor unit which is taken from previous studies (Zulkafli and Kopanos 2016). There are eleven compressor unit which are i1, i2, i3, i4, i5, i6, i7, i8, i9, i10, i11. Based on that, i1 to i5 are small compressor while the others are large compressor. Each compressor is set for 21 days includes during weekdays and weekend. Time of use and enhance time of use is charges according to regulated tariff from TNB.

4.2 Result for TOU case study

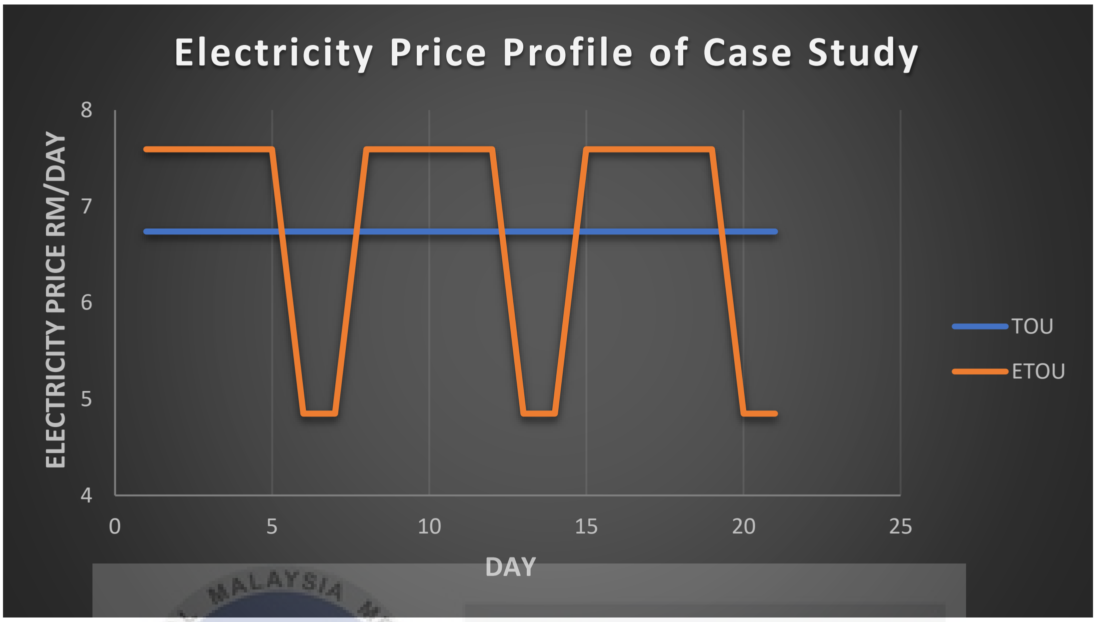

Figure 4.1 Electricity profile

Figure above show the electricity price profiles TOU and ETOU for the operating costs for 21 days. There are differences charges between TOU and ETOU which are TOU is the electricity price during peak and off-peak period while ETOU is the electricity price for peak, mid-peak and off-peak. The average price of electricity for TOU is 6.738 (RM/kW/day) which is constant charges for everyday while ETOU charges is 7.594 (RM/kW/day) for weekdays and 4.848 (RM/kW/day) for weekend. Both charges are different according to the charges from electricity tariff for E3 (High Voltage Peak/Off-peak Industrial Tariff) based on TNB website referring to https://www.tnb.com.my/commercial-industrial/pricing-tariffs1/.

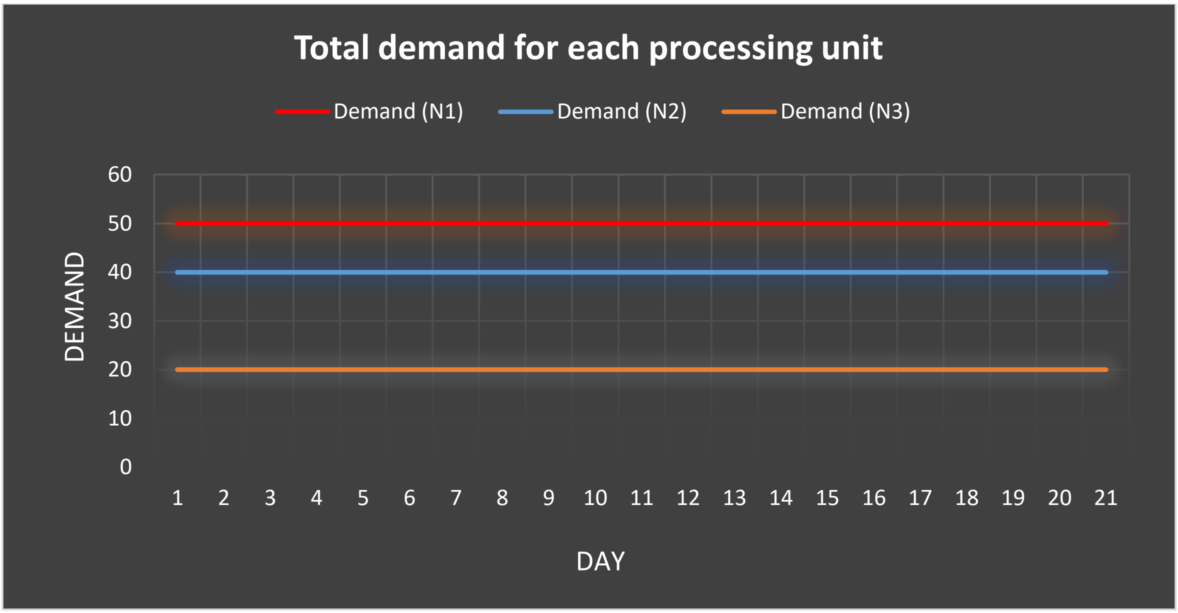

Figure 4.2 Demand for each processing unit

Figure 4.2 shows demand of compress air for each processing unit. This study is involving three processing unit which are n1, n2 and n3. The Figure shows that n1 is the maximum while n3 is the minimum demand and the value is constant during data collection duration. This optimization is analysed by using GAMS software with CPLEX 12 solver and the simulation will complete after 8 hours.

Table 4.1 Main parameter

Symbol	Value	Unit	Description
t	1	day	Duration for a single time period
PH	21	days	Total time periods in optimization
ω_i	4	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	21	days	Maximum online time for large compressor

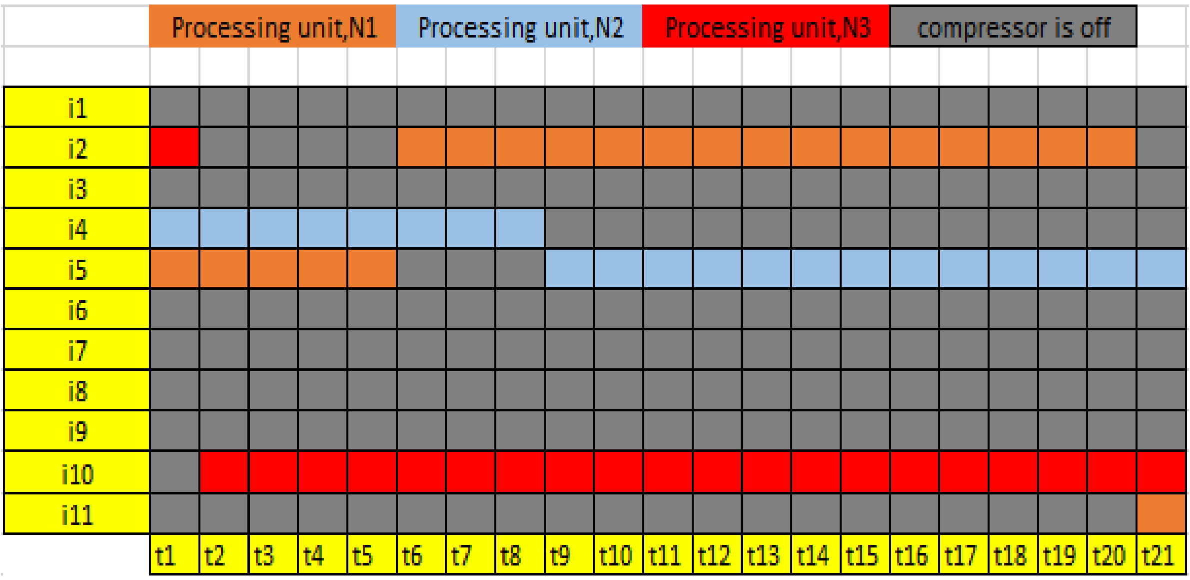

Figure 4.3 Operation of compressor network under time of use

Figure 4.3 show the operation of compressor network for TOU by following the charges from TNB. For this study, there are 11 compressor unit which consist of five small compressor and six large compressors. Figure above present that there are only three small compressors (i2, i4, i5) and two large compressors (i10, i11) operate during this planning. There are some of the compressor offline during this condition under TOU which is i1, i3, i6, i7, i8, and i9. For compressor i2 it shows that the compress air will supply for processing unit n3 at t1 while during t6 until t20 compress air will fulfil the demand for processing unit n2. To meet the demands of processing unit n2, compressor i4 will operate starting from t1 until t8. Next, for compressor i5 there is only 3 days continuously offline where from t6 to t8 and the rest operate regarding to the highest power consumption recorded. Compressor i10 will operate continuously from second day until the end of study duration to achieve the demand need for processing unit n3.

One large compressor and three small compressors operated the most during weekend. There is no effect during weekend according to the price charges for TOU. It seems that the number of small compressors is higher compare to large compressor due to the demand. The pattern of operating system is depending on the demand shows in Figure 4.2. According to the demand for each processing unit, the uses of large compressor is lower. Thus, this can reduce the cost of electricity in industries because the trend in power consumption analysis show that the total power cost respected to compressor load is higher at large compressor compare to small compressor.

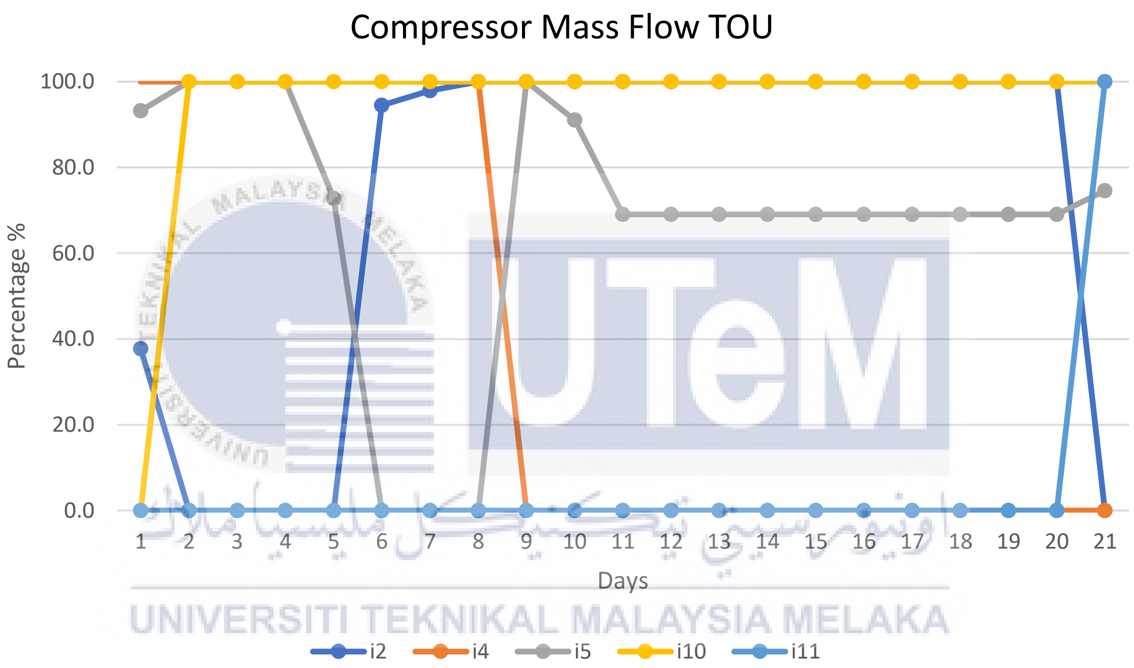

Figure 4.4 Mass flow rate for each running compressor

Graph in Figure 4.4 present the mass flow rate for each compressor unit (i2, i4, i5, i10, i11) which has been generate by using GAMS software. It shows the compressor mass flow rate from the lowest percentage of 0% until maximum percent. The y-axis (vertical) is total percentage of mass flow rate and the x axis (horizontal) is 21 days duration study. The Figure shows that compressor i11 operate at the lowest mass flow from t1 until t20 and maximize the flow at t21. Regarding on that, the correlation between Figure 4.3 and Figure

4.4 can be done where the value of mass flow rate is zero percentage when offline and reach it maximum value when start-up at t21.

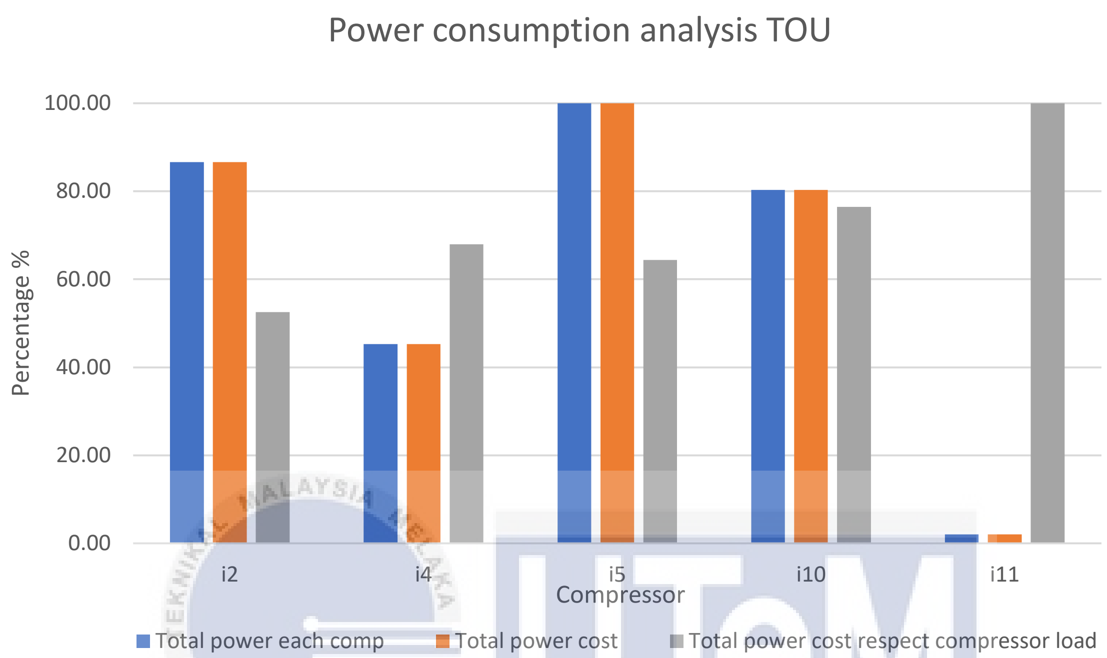

Figure 4.5 Power consumption for TOU

Figure 4.5 show that the power consumption analysis for TOU which blue bar indicated total power each compressor, orange present total power cost and total power cost respect with compressor load assign as grey bar. Generally, compressor i2 show the minimum percentage gain for the total power cost respect to compressor load compare to another compressor. The operational compressor for the processing unit n1 are i2, i5 and i11. Regarding to the processing unit, the most effective compressor is i2 where power cost respect to compressor load is the lowest while the total power cost respect to compressor load reach it maximum at i11. From Figure 4.3, it shows that compressor i11 only operate during t21. This is due to total power cost respect to compressor load is at maximum percentage. Compressor i11 is not efficient because of highest total power cost respect to load but minimum operating of compressor. Compressor i2 is at good operating of compressor which can meets the demand to reduce the cost. In conclusion the lower the total power cost, the higher the total power cost with respect to compressor load.

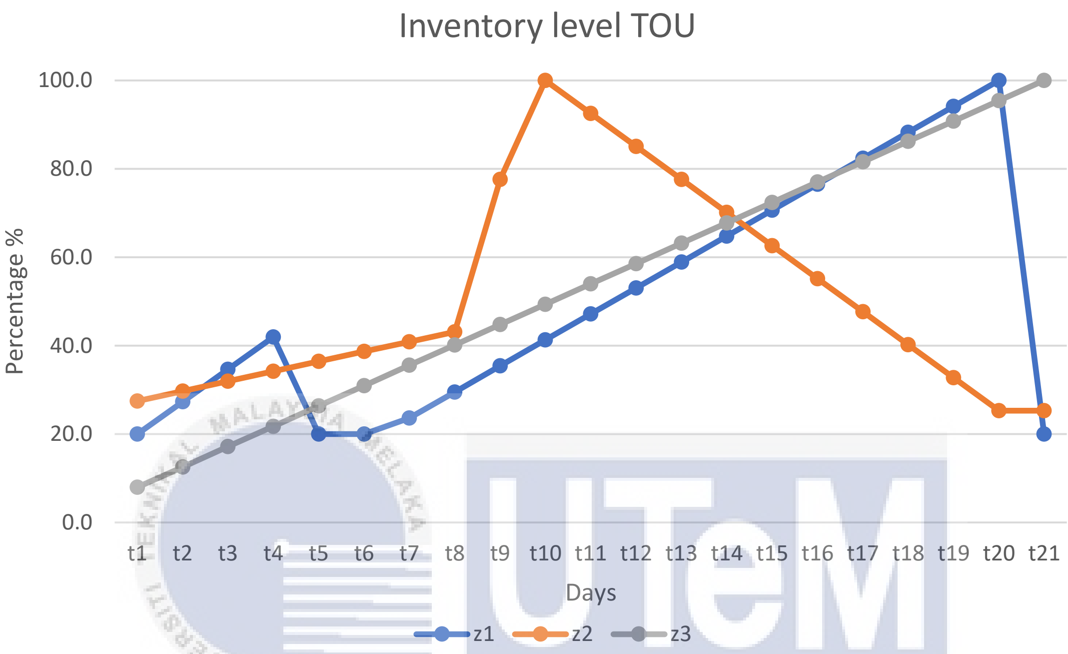

Figure 4.6 Inventory level for TOU

Figure 4.6 shows the pattern of inventory level for TOU by using GAMS software. The horizontal axis indicates the days of operating compressor whereas vertical axis indicates for the total percentage for the inventory level. There is three tank (z1, z2, z3) which each tank represents their own processing unit. Most of the tank has reach the maximum percentage where z2 at t10, z1 at t20 and z3 at t21. The minimum level achieve is z3 which below than 20%.

4.3 Result for ETOU case study

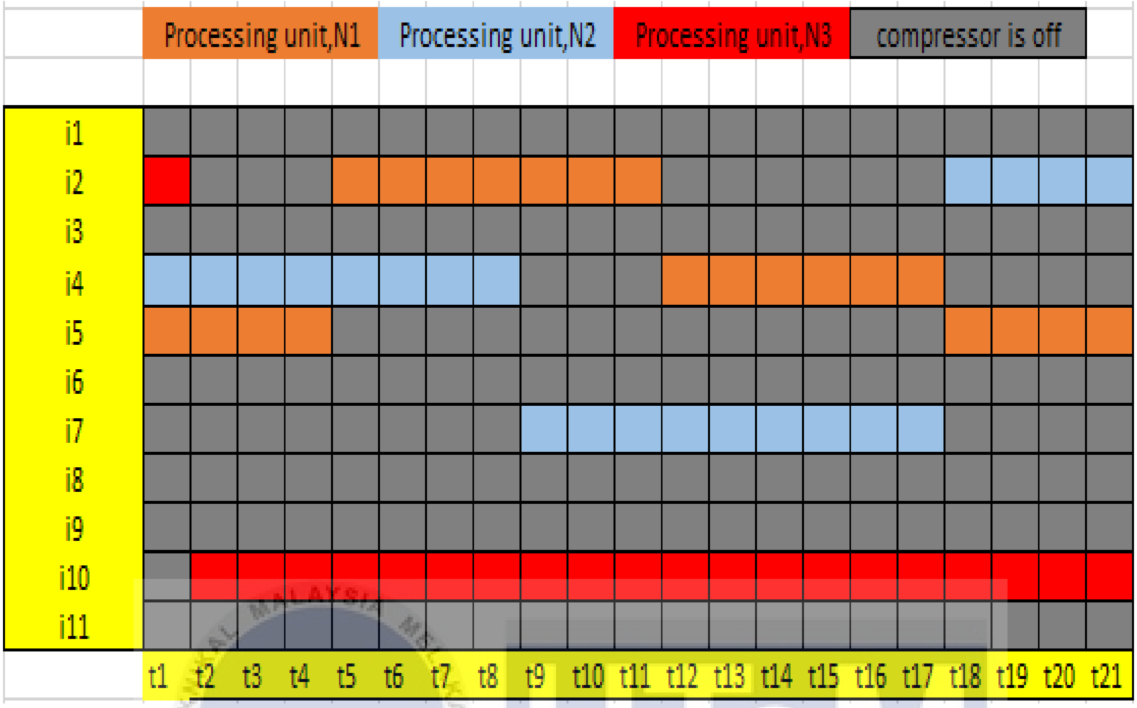

Figure 4.7 Operation of compressor network under enhance time of use

Figure 4.7 shows the operation of compressor network for ETOU by following the average price from TNB. It is present three small compressor unit operate and two large compressors. Through 3 weeks period i1, i3, i6, i8, i9 and i11 were completely switch off for this operation of compressor network under ETOU regarding to the demand. For compressor i2 it shows that compress air supply for processing unit n3 at t1 and during t5 until t11 compressor will fulfil the demand for n2. However, from t18 to t21 compressor operate to meet the demand for processing unit n2. For compressor i4 the operating starting from t1 until t8 then stop for 3 days and continue operate at t12 to t17 for processing unit n1. Hence, within 21 days there is only compressor i5 operate to fill-up the demand for processing unit n1 and work 4 days through initial to the end of research. For compressor i7 there are fully operating days for compressor to meet demand for processing unit n2 at period of t9 until t17.

There is an effect in weekend according to the electricity price profile in Figure 4.1. It seems that the number of small compressors operate is higher compare to large compressor based in Figure 4.7. According to the demand for each processing unit, the large compressor shows a difference for operating system during ETOU which more operating period compare in TOU.

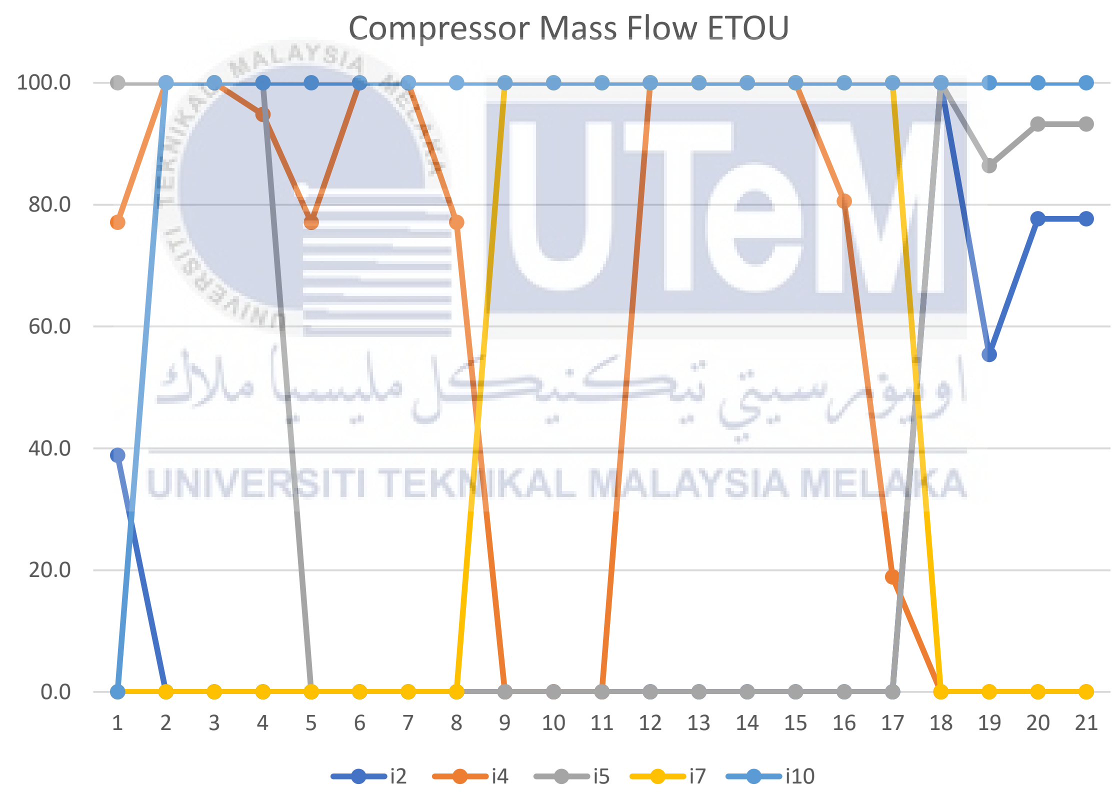

Figure 4.8 Mass flow rate for each running compressor

The graph from Figure 4.8 present the mass flow rate for each running compressor which has been generate by using GAMS software for ETOU. The Figure shown the compressor mass flow rate from lowest percentage of 0% until maximum percent. The y axis (vertical) is percentage of mass flow rate and the x axis (horizontal) is 21 days period based on duration study. Each line represents the compressor unit and header of every processing.

From the graph, it can be seen that compressor i10 running at the lowest mass flow for t1. However, compressor run with maximum capacity of mass flow on the next day until the end of study duration. On top of that, the operation of compressor network shown in Figure 4.7 run with large compressor during t2 until t21 regarding to the maximum mass flow rate.

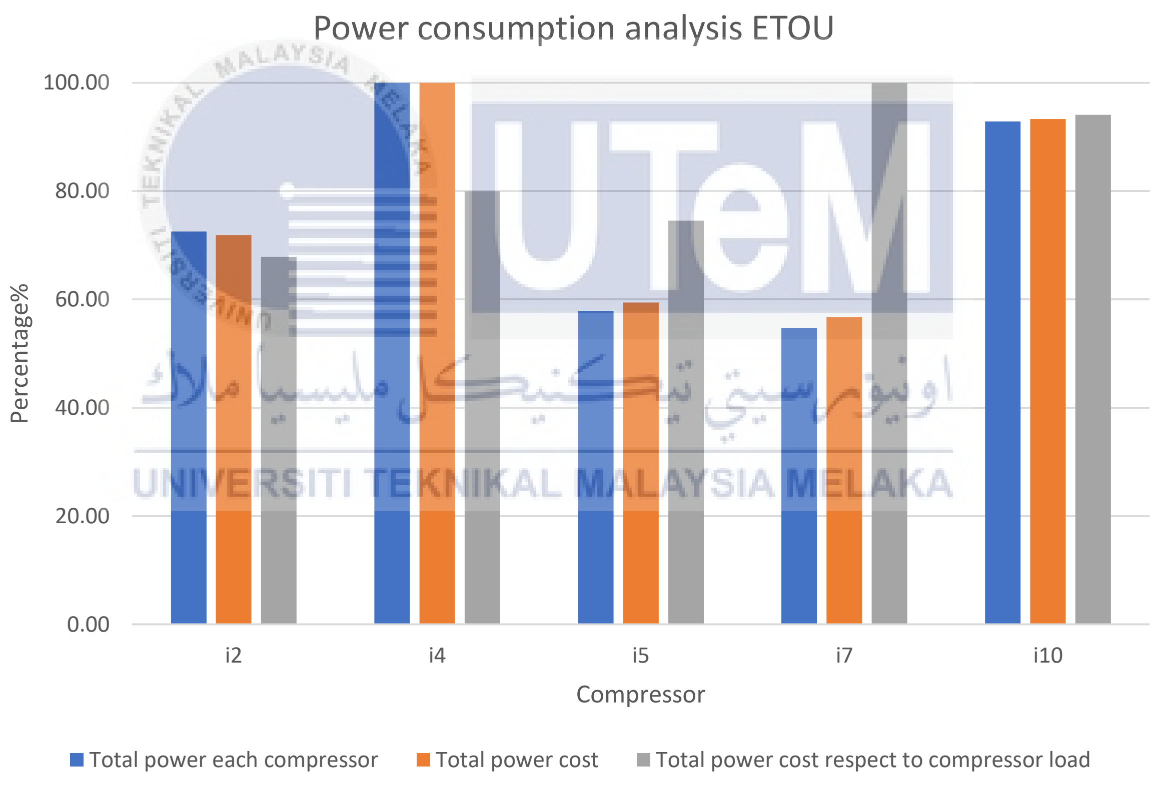

Figure 4.9 Power consumption for ETOU

Figure 4.9 shows that the power consumption analysis for ETOU which has been categorised by total power each compressor (blue), total power cost (orange) and total power cost respect with compressor load (grey). Generally, compressor i2 show the minimum percent of total power cost respect to compressor load which same with TOU and the maximum is compressor i7. The contrast from this Figure is small compressors shows more efficient compare to large compressors. The operating compressors for processing unit n1 are i2, i4 and i5. Since compressor i2 has lowest power consumption compare to compressor i4 and i5, it shows that i2 is the lowest power cost respect to compressor load although compressor i4 and i5 has increased to eighty percent. There was a good operating of compressor which can meets the demand to save the cost.

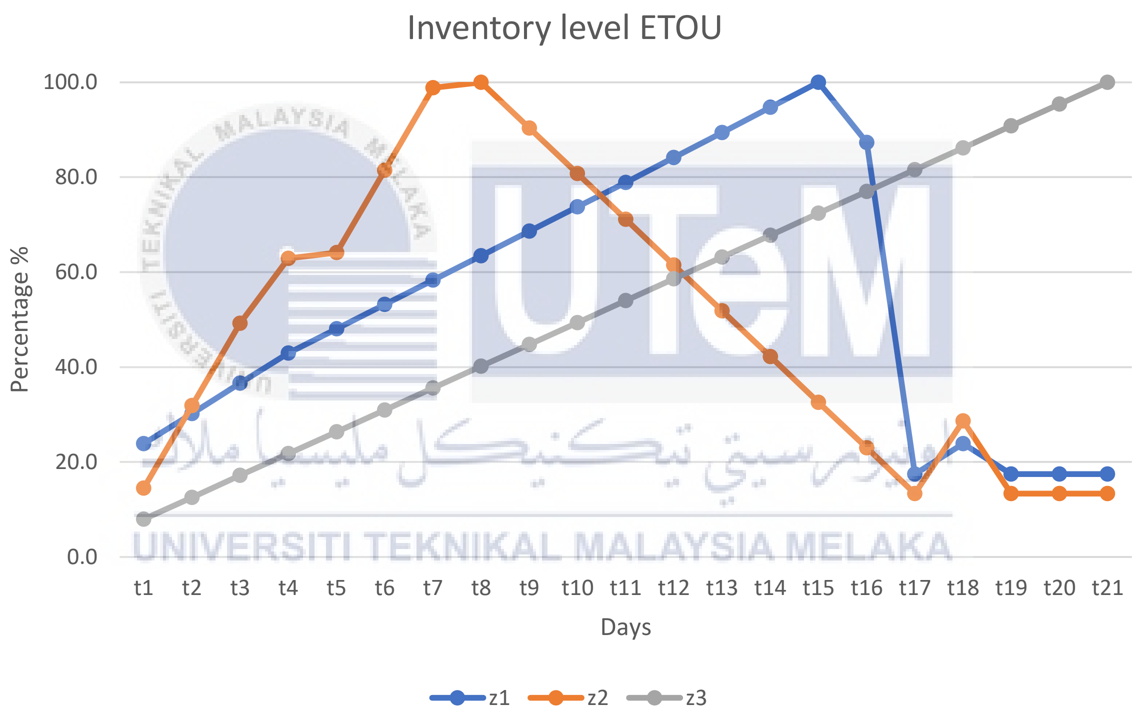

Figure 4.10 Inventory level for ETOU

From the figure above, it is shows that the pattern of inventory level for ETOU by using GAMS software. The horizontal axis indicates the days of operating compressor whereas vertical axis indicates for the total percentage for the inventory level. There are three tank z1, z2 and z3 which each tank represents their own processing unit. Most of the tank has reach for the maximum percentage where z2 at t8, z1 at time period t15 and z3 at t21.

4.4 Summary of Optimization

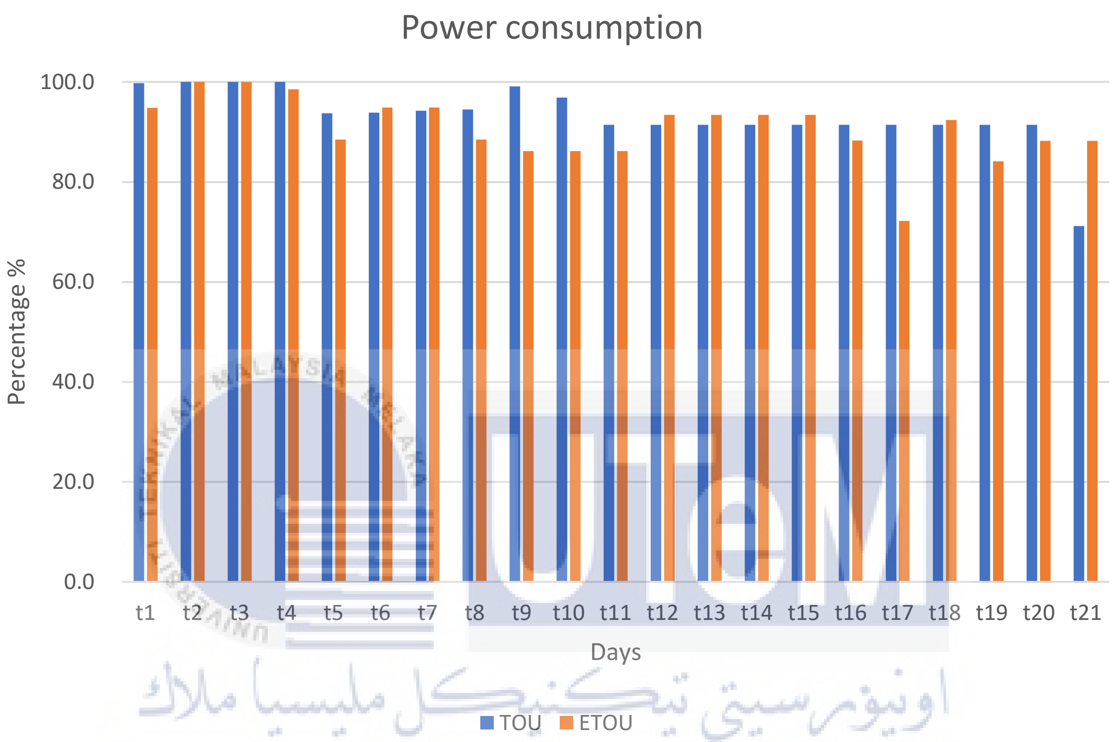

Figure 4.11 Power consumption over time

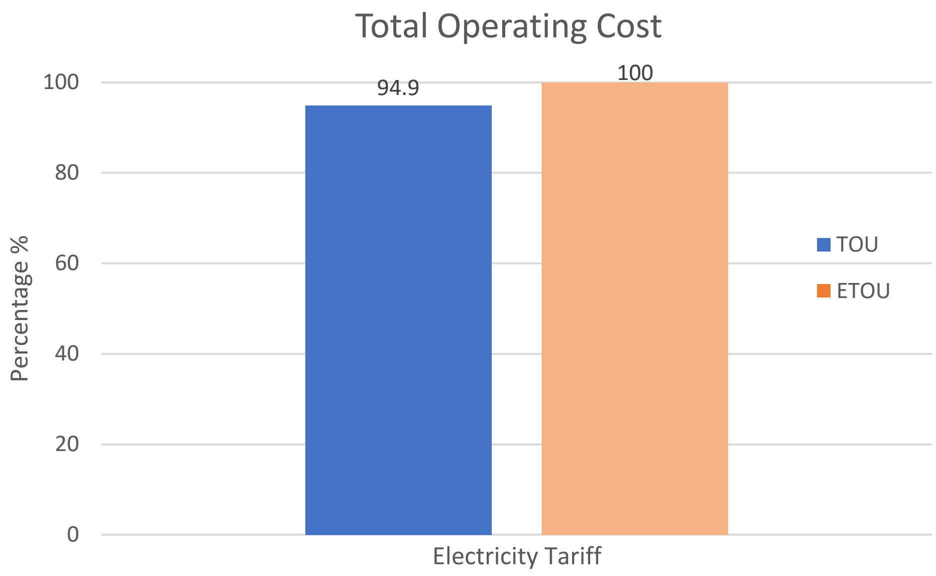

Figure 4.12 Operating cost

Figure 4.11 shows the power consumption over time between TOU and ETOU with the total of 100% percentage. It demonstrates that most of the power consumption similar during weekend for the first and second week but a bit differences in third week of weekend which TOU for t21 drastically show the differences. Other than that, t2 and t3 reached for the maximum percentage in both TOU and ETOU while the minimum in t17 for ETOU and t21 for TOU. From Figure 4.12, it shows overall operating system for TOU and ETOU. Generally, it shows that a bit differences for both in operating system which only have 5.1% differences. Based on that, the most efficient operating is TOU even the charges fixed during weekdays and weekend.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Generally, this study shows that the power cost for each compressor unit significantly influenced by the regulated tariff charge given by TNB. On top of that if the price charge increases the total cost for compressor unit increase. Then, application of optimization using GAMS software is very helpful in planning the scheduling operation of compressor unit. Based on the results obtained in chapter 4, the total operating cost for time of use (TOU) is the best choice to operate the compressor. This is because the different for total cost between TOU and ETOU is 5.1%. Regarding to that, it can easily conclude where the result obtains from the GAMS software determine that TOU charge from TNB is the most efficient for this study. Generally, the objective of this study is to investigate the current relation between operational and scheduling of energy intensive by using an optimization model of compressor network under regulated tariff that has been define by the result in previous chapter.

Finally, it is worth to conclude that most of the result obtain are depend on the electricity price profile. The charges trend is not fixed and mostly increase every year depends on the classification. Hopefully, the findings of this study will lead to the discovery of new counter measure, categories, and program with greater ability to reduce the uses of electricity in industries especially for compressor network.

5.2 Recommendation

It is recommended that the future effort to extend the scope of this report by including the additional survey in industries that related with the uses of compress air. In order to fulfil the specification, it is recommended to determine maintenance scheduling for each compressor (Roger Cline, John Germann, 2009). Other than that, it is recommended to get the real data transferred into the software and the corresponding smart data can be analysed (Tretsiak, Häberlein and Bäker, 2016). Besides, it is good to include the performance of each compressor network for 21 days operating because the performance of compressor is one of the main factors that will be a major effected (Tippayawong et al.,2020).

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Appendix A List of Sets and Parameter

Table A.1 List of sets

SETS	Description
i	Compressors
j	Headers
n	Processing units
z	Storage tank
t	Time periods
K	Set of compressors included in the optimization
PH	Set of time periods included in the optimization
JI	Set of headers that are connected to compressor i
JN	Set of headers that are connected to process unit n
JZ	Set of headers that are connected to storage tank
ZN	Set of storage tank that are connected to process unit n
ZE	Set of storage tank include in the optimization

Table A.2 List of parameters

Parameters	Description
alpha	Coefficient for the load curve of header j
bita	Coefficient for the load curve of header j
delta1	Objective function coefficient factors for compressor i
delta2	Objective function coefficient factors for compressor i
delta3	Objective function coefficient factors for compressor i
epsilon	Penalty cost for re- assigning header compressor i during its operation
hita	Maximum amount of available resources for maintenance in time period t
thita	Compressed air mass flow rate demand for process unit n in time period t
lamda	Problem-specific large number that could represent the capacity of header j
lamdaT	Problem-specific large number that could represent the capacity of header j
Omicron	Maximum run time
ro_min	Minimum compressed air mass flow rate from compressor i
ro_max	Maximum compressed air mass flow rate from compressor i
omega	Minimum run time
xip	Operating status of compressor i just before the beginning of the current scheduling horizon
omegap	Total number of time periods at the end of the past prediction horizon that compressor i has been continuously online since its last start-up

Appendix B GAMS code

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

$include ETOU

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 begining 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) ;



BINARY VARIABLES

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


POSITIVE VARIABLES

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 storgare 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) AND ORD(tt) GE max(1,(ORD(t)-
omega(i)+1)) AND ORD(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) AND ORD(tt) GE
max(1,(ORD(t)-psi(i)+1)) AND ORD(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) AND JI(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) AND ORD(tt) GE max(1,(ORD(t)-omikron(i)))

AND ORD(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) AND ORD(tt) GE max(1,(ORD(t)-(omikron(i)-

omegap(i)))) AND ORD(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))/s
c2(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,lamda,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,thi
ta,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)*mi(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)*mi(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;
```