SIGNIFICANCE OF POLE, ZERO, DELAY AND INTEGRATOR IN PROCESS MODELLING OF SYSTEM

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

SIGNIFICANCE OF POLE, ZERO, DELAY AND INTEGRATOR IN PROCESS MODELLING OF SYSTEM

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**A report submitted
in fulfilment of the requirements for the degree of
Bachelor of Mechanical Engineering (Plant & Maintenance)**

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2022

DECLARATION

I declare that this project report entitled "Significance of Pole, Zero, Delay and Integrator in Process Modelling of System" is the result of my own work except as cited in the references

Signature : ....

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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 for the award of the degree of Bachelor of Mechanical Engineering (Plant & Maintenance).

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Signature	:	………………………………………
Supervisor's Name	:	………………………………………
Date	:	………………………………………

DEDICATION

I hereby dedicate this to Associate Professor Ir. Dr. Md Fahmi for his advice, his faith, and his patience in me, as well as the unconditional love and support of my parents throughout my journey towards the completion of this project.

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ABSTRACT

System identification is an approach of constructing mathematical model of a dynamical system using the instrumentation signal of input and output of the system. Among the choices of model in system identification is process model. Within the model, the presence of pole, zero, delay, and integrator may easily be incorporated. This project investigates the significance of these components in the transfer function of process model by analysing the result of process model estimation of 3 simulated systems to grasp a better understanding of their respective influence before moving on into analysis of process model result of a real industrial data of air compression system. The proposed methodology of this project involves the data import and pre-processing until the end of simulation and validation stages. The outcome of the simulation would undergo analysis and discussion to determine the significance of pole, zero, delay, and integrator in systems based on simulated and real industrial data. As results, the order of a system is indirectly reflected by the number of poles within a model, while zero affects the stability and step response of a system. Significance of delay is dependent on the nature of the system whereby a time lag exhibits to reach an optimum operating level. Lastly, integrator contributes in trend prediction of a system by restricting the range of model estimation from going out of track.

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ABSTRAK

Identifikasi sistem merupakan sebuah pendekatan untuk membina model matematik daripada sistem dinamik dengan menggunakan isyarat instrumentasi input dan output daripada sistem tersebut. Antara pilihan model dalam identifikasi sistem ialah model proses. Dalam model, terdapat kutub, sifar, penunda, dan penyepadu yang bekerjasama antara satu sama lain. Projek ini bertujuan untuk menyiasat kepentingan komponen ini dalam fungsi pemindahan model proses dengan menganalisis hasil anggaran model proses 3 sistem simulasi untuk pemahaman yang lebih lanjut atas pengaruh masing-masing sebelum beralih ke analisa hasil model proses data industri sebenar, iaitu sistem pemampatan udara. Metodologi yang dicadangkan bagi projek ini melibatkan pengimportan data dan pra-proses sehingga tamat peringkat simulasi dan pengesahan. Hasil simulasi akan melalui analisa dan perbincangan untuk menentukan kepentingan kutub, sifar, penunda, dan penyepadu dalam sistem berdasarkan data simulasi dan data industri yang benar. Sebagai hasil, susunan sistem secara tidak langsung dicerminkan oleh bilangan kutub dalam model, manakala sifar mempengaruhi kestabilan dan tindak balas langkah sistem. Kepentingan penunda bergantung pada sifat sistem yang mempunyai ketinggalan masa untuk mencapai tahap operasi yang optimum. Akhir sekali, penyepadu menyumbang dalam ramalan arah aliran sistem dengan mengehadkan julat anggaran model daripada keluar dari landasan.

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I would also like to thank my parents for their unconditional love and support which had given me strength to keep going throughout my years in university. For me, they will always be to sole purpose to strive better achievements in everything to provide a better living in the future.

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LIST OF ABBREVIATIONS

AR	-	Autoregressive
ARMAX	-	Autoregressive-Moving Average with Exogenous
ARX	-	Autoregressive with Exogenous
AST	-	Accelerated Stress Test
FIR	-	Finite Impulse Response
FPE	-	Final Prediction Error
GUI	-	Graphic User Interface
LHF	-	Left-Half-Plane
LOESS	-	Locally Estimated Scatterplot Smoothing
MSE	-	Mean Squared Error
PSM	-	*Projek Sarjana Muda*
RHP	-	Right-Half-Plane
SCADA	-	Supervisory Control and Data Acquisition
SI	-	System Identification
SOFC	-	Solid Oxide Fuel Cells

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CHAPTER 1

INTRODUCTION

1.1 Background

System identification is the construction of mathematical models from observed data of a dynamic system. A dynamic system is a system with memory which reacts with inputs of what is done previously. Mathematical roles are having increasingly important roles in the science and engineering of today, whereby among the solution of tasks involved simulation, control design and proper signal processing. It is important to master various techniques for model building and there are two general ways to model a dynamic system. First-principles modelling is by using the knowledge of physics or math behind a problem to form a model, whereas the data-driven modelling is by using measured data from a system to construct a model.

System Identification (SI) falls into the category of data-driven modelling. A system, for example, is a real thing like an indoor cooling system with input signals via thermostat and temperature sensors and outputs to be humidity and room temperature, whereby it is influenced by error, disturbance and outer environment. A model is an object where a real system is replaced with mathematical expressions. These expressions create an approximate relationship between the input signals and the output signals. Within the expressions representing the model, there are uncertainties in parameters. Hence, a wide variety of model structure is covered by SI in order to acquire a higher accuracy of system estimation. The model structure which this project is covering will focus on process modelling.

A continuous-time transfer function is the structure of a process model which defines the linear system dynamics in terms such as static gain, time constants, process zero, time delay, and enforced integration. Many industries are using process models to describe system dynamics as it could be applied to a wide variety of production environment due to its simplicity, transport delay estimation support, and easy interpretation of poles and zeros coefficients on the model. Different model structures could be created by altering the number of poles and zeros, and the participation of delay and integrator.

A modelling approach involves finding of known constants and fixed parameters following from equipment dimensions, constant physical and chemical properties and so on (Mikles and Fikar, 2007). This include the determination of significance of the delay and overshoot of a system. Most if not all of the dynamic systems encountered will have amount of time delay inherent to it. A significant amount of delay will either degrade the performance or make the system to be unstable, as the delay is subjected as old information to determine the current output of the controller. Meanwhile, not all process in the industry is suitable with the occurrence of overshoot. For example, an overshoot in temperature output of a chemical process causes disruption or reaction between molecular particles. Integrator serves as an output block with respect to time to prevent the values of output from exceeding specifiable levels. Accuracy of the model is improved via integrator when the range of overshoot data is limited down to a desirable range of data levels. Thus, old information taken into account during determination of current output has a lower tendency of disturbance or being unstable in the future. Hence, the goal of this project is to determine the influence of poles, zeros, delay and integrator on the search to obtain the best fit model suited for the system according to the data set given.

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1.2 Problem Statement

Problems raised during predictive and preventive control of a dynamical system are commonly solved via System Identification. Preferred outputs with the characteristics needed to be embedded within a system could be predicted using the best fit mathematical model. In process modelling, the number of poles and zeros, and the existence of delay and integrator which may easily be incorporated are determined by the user. To achieve the best fit model, it is crucial for users to know the effects of each parameters. Therefore, the ability to understand the significance of these components in the transfer function to obtain the best fit process model is essential for the industrial system.

1.3 Objective

The objectives of this project are as follows:

i. To perform system identification using process model.

ii. To investigate the effect of different number of poles in process model.

iii. To investigate the significance of zero, delay and integrator in process model.

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1.4 Scope of Project

The scopes of this project are:

i. This project will focus on the method of applying process model for system identification.

ii. This project requires utilisation of MATLAB software as simulation tool.

iii. This project aims to solve a single input - single output (SISO) system.

iv. Analysis on the behaviour of dynamical system and the mathematical modelling will be carried out based on best-fit index, final prediction error, and mean squared error.

1.5 General Methodology

The actions to be taken to obtain the objectives in this project are as below:

1. Literature Review

   Journals, articles, or any related informative materials regarding this project are reviewed to achieve adequate knowledge and understanding.

2. Trial Run with MATLAB's Toolbox

   A transfer function of process model is built from a sample data set. Performance of the transfer function of process model will be analysed.

3. Data Acquisition

   An industrial real-time data is needed to create a robust mathematical model. Data is provided by supervisor after the succession of trial run on SI using sample data of MATLAB.

4. Simulation of SI using Process Model

   Data set is replaced with real-time industrial data provided by supervisor via skillsets of mathematical model technique obtained from past trial run.

5. Analysis and Discussion

   Analysis are presented by analysing and validating the performance and quality of the mathematical model derived from simulation.

6. End Reporting

   A project report is written after the analysis of project is completed.

The methodology of this study is summarised in the flow chart as shown in Figure 1.1.

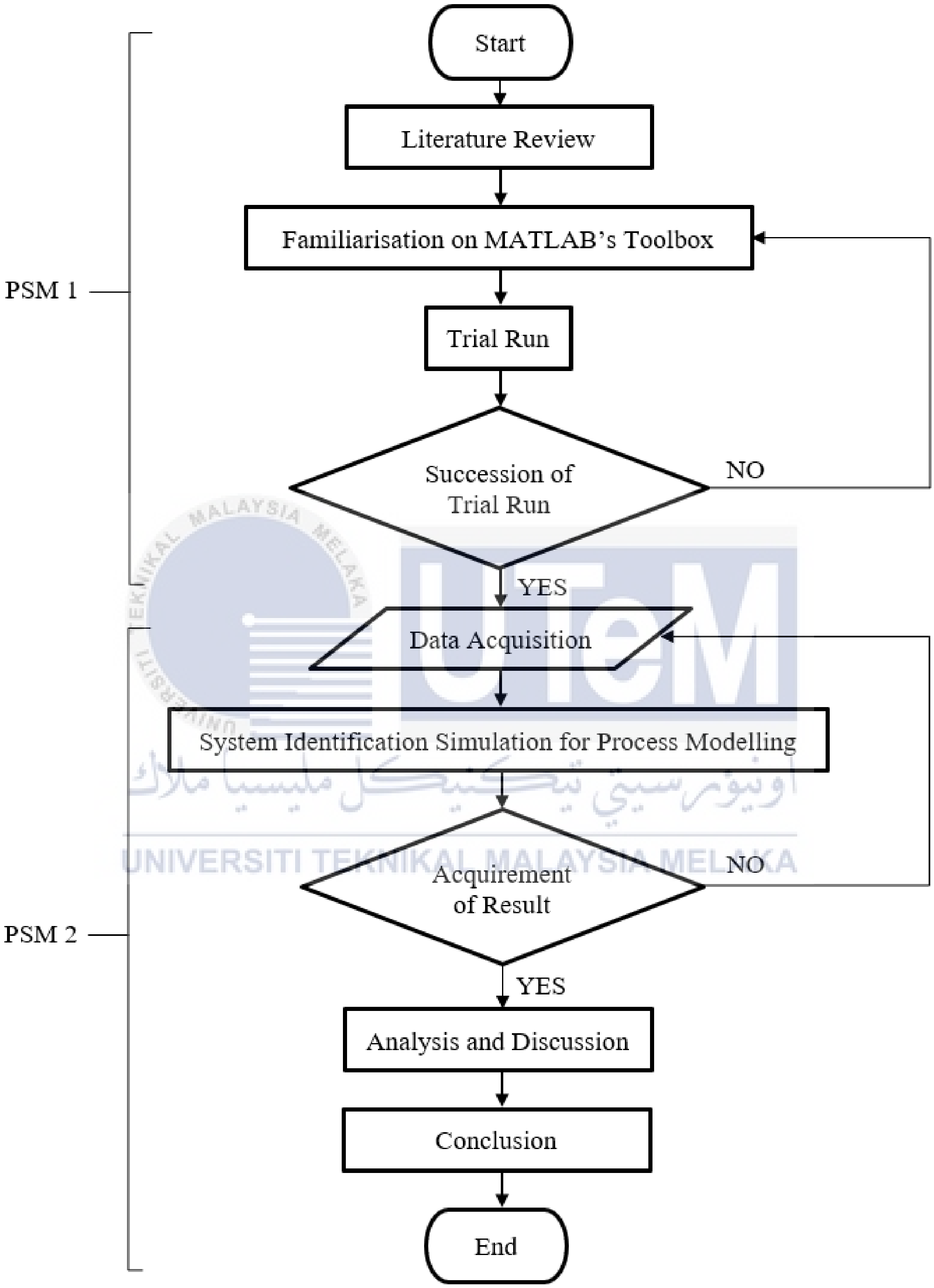

Figure 1.1: Flow chart of general methodology

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This literature review will focus on the discussion of three keywords regarding the research title: Process Model, Transfer Function and System Identification. This chapter serves as foundation of knowledge for the upcoming chapters of methodology and analysis of project report. References related to the research topic and field are summarised in this chapter.

2.2 System Identification

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Systems are usually referred as mechanism that generates an output by taking in input, whereby system response is the relationship of the output related to the input. The relationship between the system input and the system output could be modelled using mathematical equation, which is the transfer function in this case of study.

2.2.1 Mathematical Model

Ljung (1987) stated that relationships between system variables using mathematical descriptions could be described via mathematical models. Mathematical descriptions used such as differential equations could be further explained through different aspects such as linear or non-linear, continuous-time or discrete-time.

Mathematical models could be generated through construction of block diagram using first principles. The alternative way to generate mathematical models is through graphical models which are experimental based, which is also known to be system identification. Observation of data is needed using this method to obtain the input and output signals before carrying out data analysis to form a model.

2.2.2 Definition of Dynamical System

A system is defined as an object with variables interacting with each other to produce output signals. Disturbances are variables which could not be controlled and it could be classified as either a measurable disturbance, or an unmeasurable disturbance which could only be noticed via its influence on the system's output. Other than that, inputs are variables which could be controlled. On the other hand, a dynamical system is a system which consists of time-domain variables and output. Therefore, the system is dependent on previous values of output, and not dependent on variables (Ljung, 1987).

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2.2.3 Definition of System Identification

A model could be developed through experimental data and variables by observing under specific duration using proven method to obtain data which suits the description of the mathematical model, whereby input-output of the system could be distinguished (Bittanti, 2019). The black-box model is a mathematical model which provides only logical definition of its input-output relationship, whereas the white-box model is classical model defined by the knowledge of physics and mathematical laws. Models tend to contain uncertain and unknown parameters and variables. Therefore, parameter could be estimated via experimentation analysis on the behaviour of the system under specific condition. Thus, system identification problems estimate unmeasurable variables from data of observed variables. The science term of identification refers to the designation of model based on experimentation groundworks.

2.2.4 Purpose of System Identification

Traditionally, mathematical models are acquired by describing input and output using applicable mathematical laws which are complicated and time consuming. Mathematical model obtained through this method may consists numerous complex equations, making it unpractical in real life. Accuracy of model may not be achieved mathematically as relationship between variables might not be reliable due to their unknown values, or analytic description. As actual system varies from the mathematical model, connection should not be made between real system with its mathematical description, whereas it is better to compare and relate specific features. Idealisation should dominate implementation as models should be accepted for its practicability. Hence, by using system identification method, the properties of models could be better understood. (Bittanti, 2019).

2.2.5 System Identification Process

System Identification process consists of four fundamental building blocks described by Ljung (1986).

- Data acquisition: Data of input and output are acquired throughout a time interval from a system in order to ensure data is informative and controllable. However, human or system errors might produce wrong data (outliers) and should be replaced with a logical value.
- Modelling: Model which may reproduce the measured data is selected prior to engineering knowledge and understanding after the construction of multiple models based on fundamental physical laws and other correlation.
- Validation: The selected model is then tested for their performance to ensure its capability for a sustainable description which meets the requirement of desired behaviour of system's output.
- Revision: Procedure loop is revised if the validation step is not passed. A weak model is usually due to insufficient informative data, inappropriate model set, or wrongly selecting the criterion of model.

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2.2.6 Black-Box Models

Autoregressive (AR) model is a commonly used linear prediction model where outputs are dependent on previous output only. Inputs and disturbance variables do not exhibit in this model. Furthermore, due to its simplicity, the model is restricted in problem-solving (Bittanti, 2019).

Bittanti (2019) also stated that Autoregressive with Exogenous input (ARX) model includes stimulus signal, increasing its efficiency in polynomial estimation as linear regression could be solved under diagnostic form. ARX model suits higher model order system as its solution fulfils the absolute minimum of a loss function. However, disturbance is included within its system dynamics. White noise may interfere the estimation of ARX model as the transfer function used by the model shares similar poles between its deterministic and stochastic parts.

Autoregressive-Moving Average with Exogenous input (ARMAX) model has flexibility in handling disturbance exist in early process due to its disturbance dynamics structure. White noise could be cancelled out due to the existence of moving average within the ARMAX model equation (Bittanti, 2019).

2.3 Process Model

2.3.1 Definition of Model and Process Model

Bequette (1998) stated that a process model is a set of equations included with the essential input data to solve the equations to allow the prediction on the behaviour of a process system. Meanwhile, a mathematical or physical system which obeys certain specified conditions, whose behaviour is used to understand a physical, biological, or social system to which it is analogous in some way is considered to be as what being defined as a model (McGraw-Hill, 2002). Models could be classified into two groups: fundamental or first-principles, and empirical. First-principles models are based on known physical-chemical relationships such as conservation of mass and energy, kinetics reaction, transport phenomena, and thermodynamic relationships. Fundamental model which is too complex in formulation or numerical solution is considered as empirical, such as least squares fit of an equation to experimental data. The main differences between fundamental and empirical model is that fundamental models are generally accurate over a larger range of conditions

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whereas empirical models are limited to the range of conditions used for the fit of the data. It is also important to understand that a model represents an approximation of an actual process only.

2.3.2 Application of Process Model

Improving and understanding process operation as objective in developing a dynamic process model varies according to their respective aspects or field.

- Control System Design: Feedback control systems are used to maintain process variables at desirable values (Bequette, 1998). For example, a control system adjusts the flowrate as input to ensure desirable temperature is achieved as an output. However, control system design is based on process model for a complex system with many inputs and outputs, whereas the model is tested via simulating the expected performance using computer simulation before being implemented on a process.
- Operator Training: A dynamic process model is capable in performing simulations to train process operators. For example, airplane pilots are trained using flight simulators. Proper response could be learnt during the encounter of upset conditions before having to experience them on the actual process.
- Process Design: Chemical reactor model is used to determine the appropriate size of reactor for the production of product under satisfactory rate. Thus, desired production rate could be achieved by designing a proper dynamic process model.
- Safety: Process models are commonly used to design safety system such as determining the time needed for a critical pressure to be achieved when a valve failed within a system.

2.3.3 Characteristic of Process Model

Hangos (2001) stated that characteristic of model has an impact on the solution techniques and its area of application. Criterion of the respective classifications is discussed in this section.

- Mechanistic model: This type of model appears in design and optimisation applications and is referred as a phenomenological model due to its derivation from mass, heat, and momentum transfer. Mechanisms are evident in the model description and is commonly known as the white box model.
- Empirical model: Knowledge of basic principles and mechanisms are not relied in this type of model as it is based on result of experiment and observation. Equation fitting is employed where parameters have little or no physical meaning due to the unknown underlying phenomena. Little is known upon the real mechanisms of the process, making it being called as the black box model.
- Grey box model: This type of model has combination of empirical and mechanistic models, and it is the most commonly used model in process engineering.

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- Stochastic model: Involves indescribable phenomena in terms of cause and effect in this type of model. Probability distributions are often associated in the description of this model.
- Deterministic model: This type of model has distinct cause and effect relationship.

2.3.4 Statistical Methods of Model Building

Heckert (2002) stated that there is often more than one statistical tool that could be used on a given modelling application. There is a wider opportunity for effective and efficient solutions due to the varieties of methods applicable to modelling problems. Under a few competing statistical methods, the best method is likely to be selected based on the end goal of the analysis and nature of the data.

2.3.4.1 Linear Least Square Regression

This method is widely used due to its widely adaptive range of circumstances outside its direct scope. Linear least square regression could be used directly with appropriate data set into a function.

Linear Least Square Regression Equation,

$$f(\vec{x};\vec{\beta}) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \tag{2.1}$$

Respective explanatory variable in the function is multiplied by an unknown parameter, while at most one unknown parameter will have no explanatory variable. The final function value is the result of the summation of all respective terms. The function is not necessarily be a straight line even though the term is referred as linear as unknown parameters are considered as variables, while explanatory variables as known coefficients. Hence, linear equation is able to solve for the values of the unknown parameters, making it overdetermined in most cases.

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Linear least squares regression is considered to be the primary tool for process modelling in science and engineering due to its completeness and effectiveness as most processes are inherently linear, or could be well-approximated by a linear model. Good result could be produced using small data sets. However, linear least squares have limitations in shape and produces poor extrapolation properties along with a high outlier sensitivity (Heckert, 2002).

2.3.4.2 Nonlinear Least Squares Regression

This method is an extension of linear least squares regression with a larger general class of functions. Nonlinear least square regression has very little limitations on the implementation of parameters. Function which has least squares criterion used to acquire the parameter are more suited with this method.

The Nonlinear Least Squares Regression Equation is,

$$y = f(\vec{x}; \vec{\beta}) + \varepsilon \tag{2.2}$$

whereby, the functional part is not linear with respect to unknown parameters, β.

Nonlinear models have the advantage for asymptotic behaviour processes as it could increase or decrease at a declining rate as the explanatory variables go to the extremes. Furthermore, this method uses data efficiently and produces good estimates of the unknown parameters using small data sets. However, this method is also very sensitive with the presence of outlier and may result in a defective nonlinear analysis (Heckert, 2002).

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2.3.4.3 Weighted Least Squares Regression

Heckert (2002) stated that certain models have fluctuating standard deviation of error term over the variables, which makes linear and nonlinear least squares regression unsuitable to be applied. Weighted least squares regression maximises efficiency of parameter estimation by giving each data point a suitable amount of influence over the parameter, producing less precisely measure points more influence while decreasing influence on highly precise points.

This method is not associated with specific function used as relationship description of process variables, whereas it reflects on the behaviour of random errors in a model. Thus, it could be used in both linear or nonlinear parameters by incorporating extra nonnegative constants or weights associated with each data point as its fitting criterion. Size of weight must be precisely informed through associated observation as weight estimated based on a small number of replicated observations may worsen the results of an analysis. Furthermore, this method is also sensitive to the effects of outliers.

2.3.4.4 Locally Estimated Scatterplot Smoothing (LOESS)

LOESS combines the simplicity and flexibility of linear and nonlinear least squares regression respectively by computationally applying simple models to localised subsets of data to produce a function that reflects the deterministic part of the variation in data. A specific degree of polynomial is fitted into a subset of data, while response of variables near the point are estimated. Subsets used for weighted least squares fit in LOESS are determined by the nearest neighbouring algorithm.

This method does not require the specification of a function to fit a model to every data within a sample as it only needs smoothing parameter value and the degree of local polynomial. On the other hand, a densely sampled data sets are needed to produce a good model as this method needs high quality empirical information on the local structure of the process to perform local fitting. Furthermore, it is difficult to transfer result of analysis to another as LOESS does not produce a regression function which could be easily represented using mathematical formula (Heckert, 2002).

2.3.5 Steps on Effective Process Model Development

The basic steps of model development consist of model selection, model fitting, and model validation. A given problem statement is analysed to understand its fundamental questions clearly. Plots of data along with process knowledge and assumption are the initial key to select the form of model to be fitted to the data. By using the selected model, model fitting is conducted to estimate the unknown parameters before being assessed to validate the assumptions being made. Modelling process is repeated using the information gained through validation step to select, change, or improve the model if the validation had proven the assumptions to be implausible. The flow chart shown in Figure 2.1 illustrates the basic model development process.

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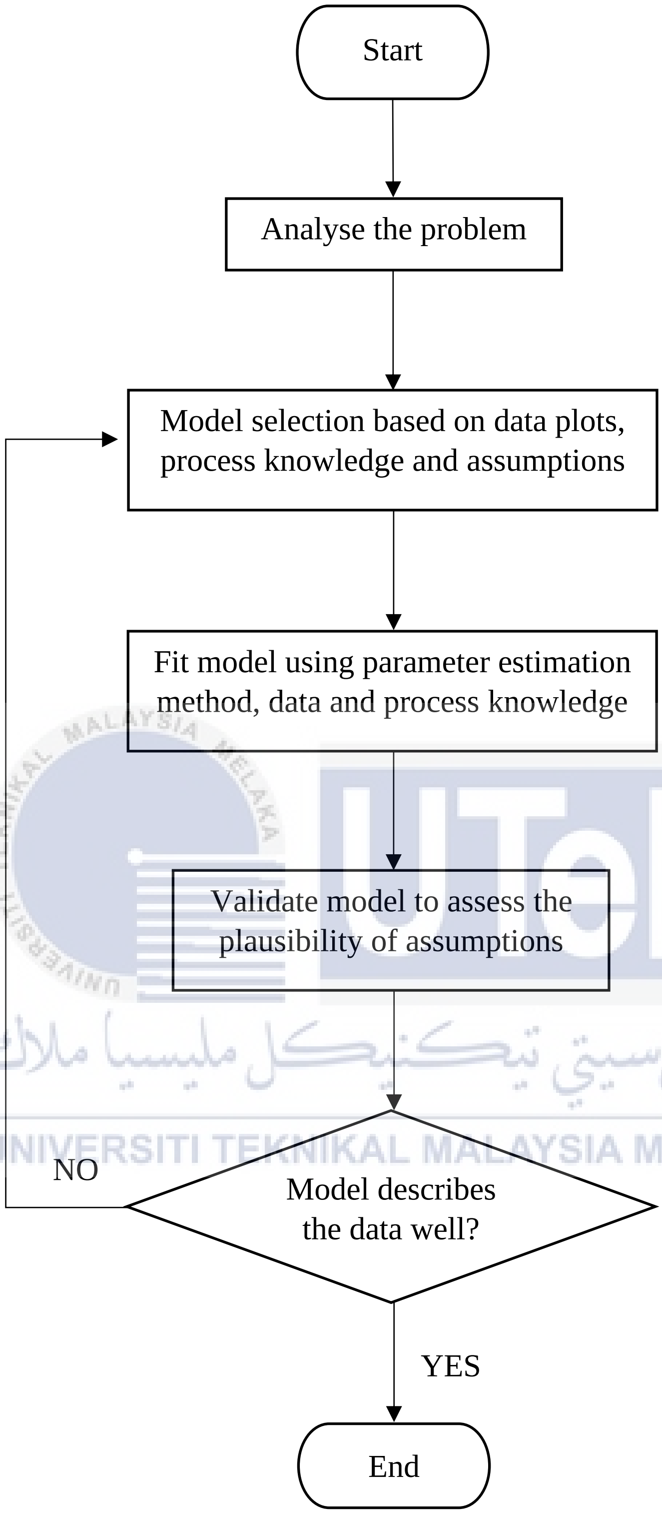

Figure 2.1: Flow chart of basic model development process.

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2.4 Transfer Function

MATLAB's System Identification (SI) performs process modelling which generates algebraical models represented using transfer function by inserting only the input and output of a system. Although the process of obtaining transfer function is done computationally, it is important to understand the fundamentals and reasoning on the implementation of transfer function instead of differential equation.

2.4.1 Definition of Transfer Function

Whitworth (2019) stated that a transfer function is the ratio of the output of a system to the input of a system under zero initial conditions and equilibrium point of its Laplace domain (Figure 2.2).

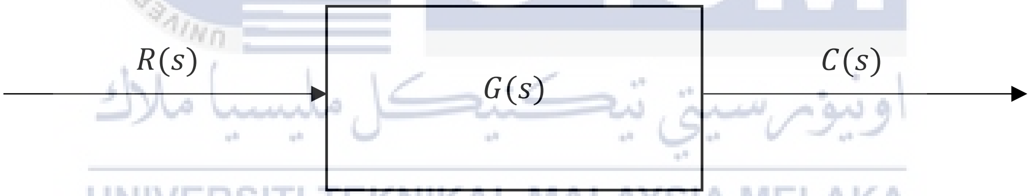

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Figure 2.2: Block diagram of a transfer function

Transfer Function Equation,

$$G(s) = \frac{C(s)}{R(s)} \tag{2.3}$$

whereby, $R(s)$ as input function, $C(s)$ as output function, and $G(s)$ as transfer function.

2.4.2 Using Transfer Function as Mathematical Representation

Nise (2015) mentioned that a mathematical representation such as that shown in Figure 2.2 is preferred, where both input and output, and system are in separated distinct parts. Although differential equation could also describe the relationship between both input and output of a system, it produces an unsatisfying representation from a system perspective. Transfer function however, is an established viable definition for a function whereby system's output to its input are algebraically related, yet allowing separation of the input, output, and system into three separate and distinct parts. Furthermore, Nyquist and Bode plots can be drawn from the open loop transfer function as they show the stability of the system when the loop is closed. Unknown time-invariant parameters could also be deduced via Laplace transform which further simplify the function to be represented in the model.

A General *n*th-order, Linear, Time-invariant Differential Equation is,

$$a_n \frac{d^n c(t)}{dt^n} + a_{n-1} \frac{d^{n-1} c(t)}{dt^{n-1}} + \cdots + a_0 c(t) = b_n \frac{d^m r(t)}{dt^m} + b_{m-1} \frac{d^{m-1} r(t)}{dt^{m-1}} + \cdots + b_0 r(t) \quad (2.4)$$

where $c(t)$ represents the output, $r(t)$ is the input, and the a_i's, b_i's, along with the form of differential equation are regarded as the system. By extracting the Laplace transform of both sides,

$$a_n s^n C(s) + a_{n-1} s^{n-1} C(s) + \cdots + a_0 C(s) + initial\ condition\ terms\ involving\ c(t)$$

$$= b_m s^m R(s) + b_{m-1} s^{m-1} R(s) + \cdots + b_0 R(s) + initial\ condition\ terms\ involving\ c(t) \quad (2.5)$$

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By assuming all initial conditions to be zero, Eq. (2.5) reduces to

$$(a_n s^n + a_{n-1} s^{n-1} + \cdots + a_0)C(s) = (b_m s^m + b_{m-1} s^{m-1} + \cdots + b_0)R(s) \tag{2.6}$$

A ratio between output transform, $C(s)$ and input transform, $R(s)$ could then be formed as follows:

$$G(s) = \frac{C(s)}{R(s)} = \frac{(b_m s^m + b_{m-1} s^{m-1} + \cdots + b_0)}{(a_n s^n + a_{n-1} s^{n-1} + \cdots + a_0)} \tag{2.7}$$

Referring to Eq. (2.7), the output, $C(s)$, input, $R(s)$, and the system represented by the ratio of polynomials with s on the right are distinctively separated, whereby the ratio, $G(s)$, is the transfer function evaluated with zero initial conditions. Hence, a transfer function could hereby represent any physical system which could be separated by a linear, time-invariant differential equation.

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2.4.3 Poles, Zeros, and System Response

Forced and natural response are the output response of a system. System is able to be described using qualitative attributes such as poles and zeros and their relationship to time response to avoid laborious and time-consuming techniques such as inversing a Laplace transform, or by solving a differential equation (Nise, 2015).

Poles are defined as the values of Laplace transform variable, s, which cause the transfer function to be infinite. It could also be referred as any roots of the denominator of the transfer function which are common to the roots of the numerator. Factor of the denominator could be crossed out by the same factor in the numerator. This will result in the root of this factor to be unable to cause the transfer function to be infinite.

Zeros are defined as the values of Laplace transform variable, s, which cause the transfer function to be zero. It could also be referred as any roots of the numerator of the transfer function which are common to the roots of the denominator. Factor of the numerator could be crossed out by the same factor in the denominator. This will result in the root of this factor to be unable to cause the transfer function to be zero.

By referring to an example of transfer function, $G(s)$ shown in Figure 2.3, a single pole and zero exists at $s = -5$ and $s = -2$, respectively. These values are then plotted on the complex s-plane as shown in Figure 2.4.

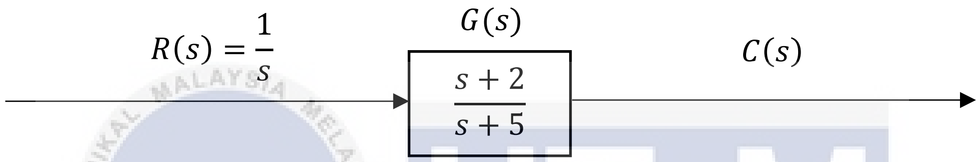

Figure 2.3: A system showing input and output

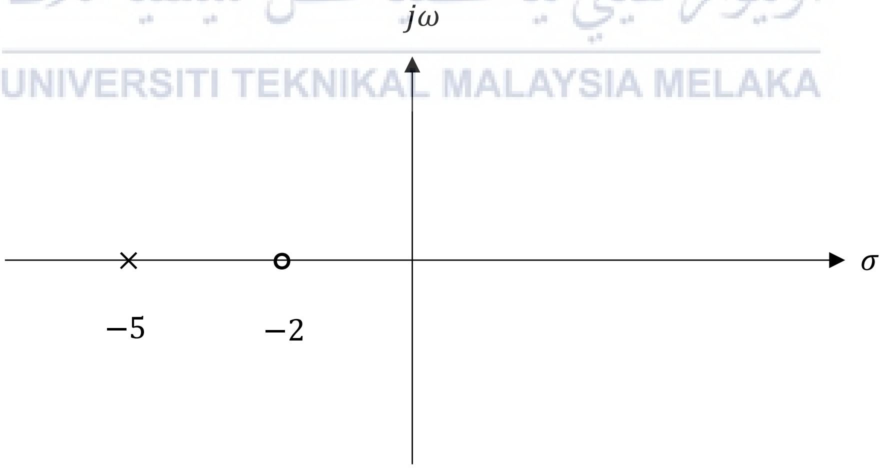

Figure 2.4: Pole-zero plot of the system

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Unit step response of the system could be found by multiplying the transfer function of Figure 2.3 by a step function to show the properties of the poles and zeros:

$$C(s) = \frac{(s+2)}{s(s+5)} = \frac{A}{s} + \frac{B}{s+5} = \frac{2/5}{s} + \frac{3/5}{s+5} \tag{2.8}$$

where

$$A = \left.\frac{(s+2)}{(s+5)}\right|_{s\to 0} = \frac{2}{5} \tag{2.9}$$

$$B = \left.\frac{(s+2)}{s}\right|_{s\to -5} = \frac{3}{5} \tag{2.10}$$

Therefore,

$$c(t) = \frac{2}{5} + \frac{3}{5}e^{-5t} \tag{2.11}$$

After going through the evolution of a system response as shown in Figure 2.5 and by going through Eq. (2.8) until Eq. (2.11), it could be concluded that the forced response is generated by the pole of the input function, whereas the natural response is generated by the pole of the transfer function. The pole on the real axis represents an exponential response of the form $e^{-\alpha t}$, whereby $-\alpha$ represents the pole location on the real axis. Exponential transient response will react quicker during its decay to zero if the pole is further to the left on the negative real axis. Both poles and zeros are also the amplitudes of forced and natural responses as shown through Eq. (2.9) and Eq. (2.10) respectively.

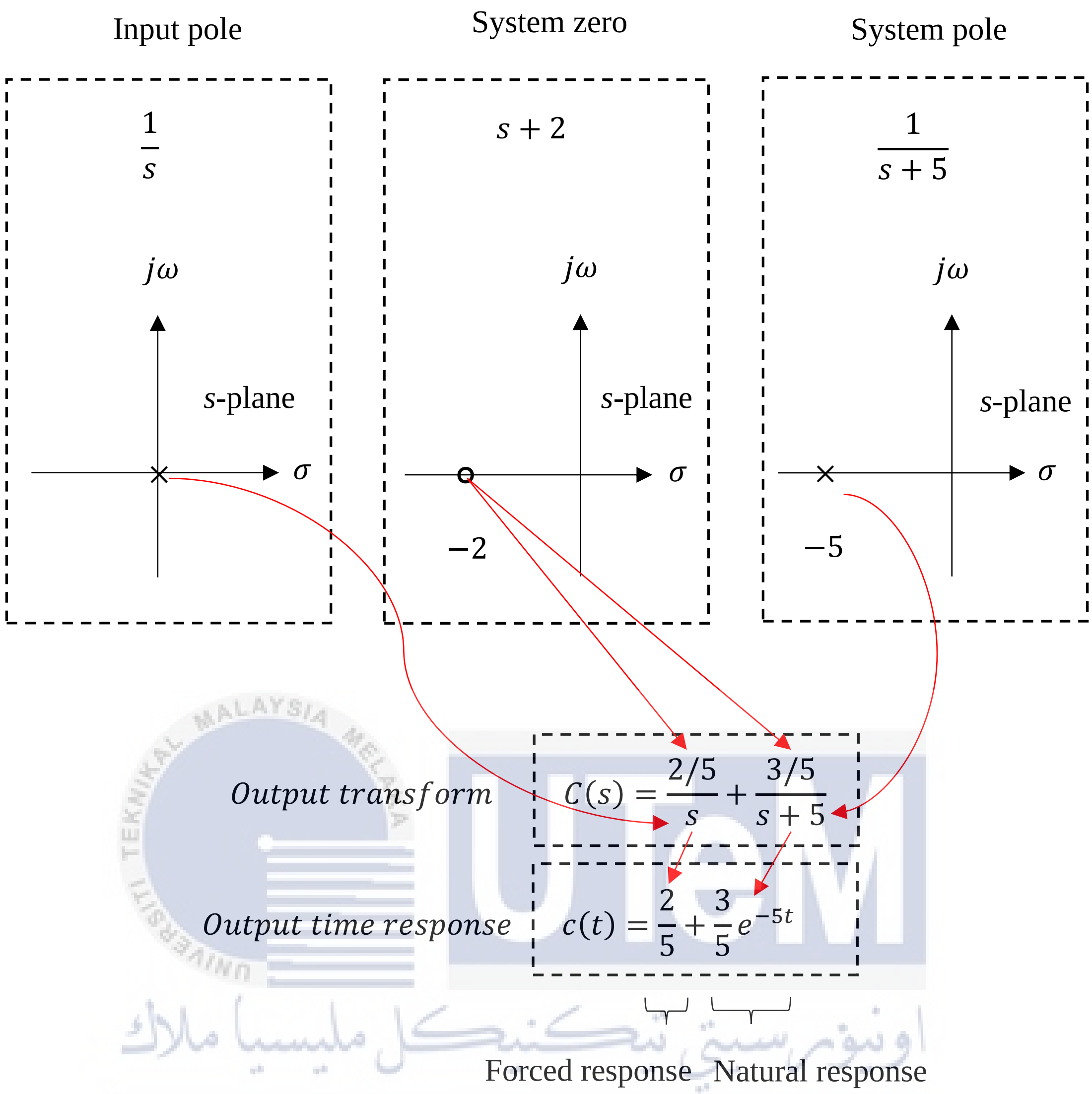

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Figure 2.5: Evolution of a system response

2.4.4 Influence of Poles in First-Order Systems

A first-order system without zeros as shown in Figure 2.6 is used throughout in this subsection to proof the influence of pole in first-order system.

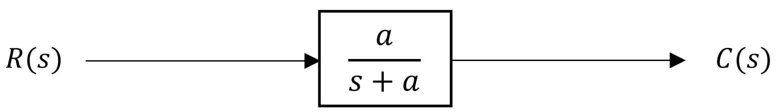

Figure 2.6: First-order system

By letting the input as a unit step, whereby $R(s) = 1/s$, the Laplace transform of step response could be denoted as:

$$C(s) = R(s)G(s) = \frac{a}{s(s+a)} \tag{2.12}$$

whereby the inverse transform is:

$$c(t) = c_f(t) + c_n(t) = 1 - e^{-at} \tag{2.13}$$

where input pole generates forced response $c_f(t) = 1$, whereas the system pole, $-a$ generates the natural response $c_n(t) = -e^{-at}$. Let us simplify the natural response to distinguish the significance of parameter a by letting $t = 1/a$.

$$e^{-at}|_{t=1/a} = e^{-1} = 0.37 \tag{2.14}$$

From Eq. (2.14), the $1/a$ is referred as time constant of the response, whereby is the time for e^{-at} to decay to 37% of its initial state. Time constant could be labelled as a transient response for first-order system as it relates to the speed at which a system responds to a step input. Therefore, the pole at $-a$ of the transfer function is located at the reciprocal of time constant. Hence, transient response is faster when the pole gets further away from the imaginary axis (Nise, 2015).

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2.4.5 Influence of Poles in Second-Order Systems

Nise (2015) states that second-order systems exhibit a wide range of responses compared to the simplicity of first-order systems. While first-order system's parameter generally influences the speed of the response, second-order systems change the form of the response. Two finite poles and no zeros will be based as foundation throughout this subsection.

The influence of poles in second-order systems could generally be categorised into four different responses as shown in Figure 2.7.

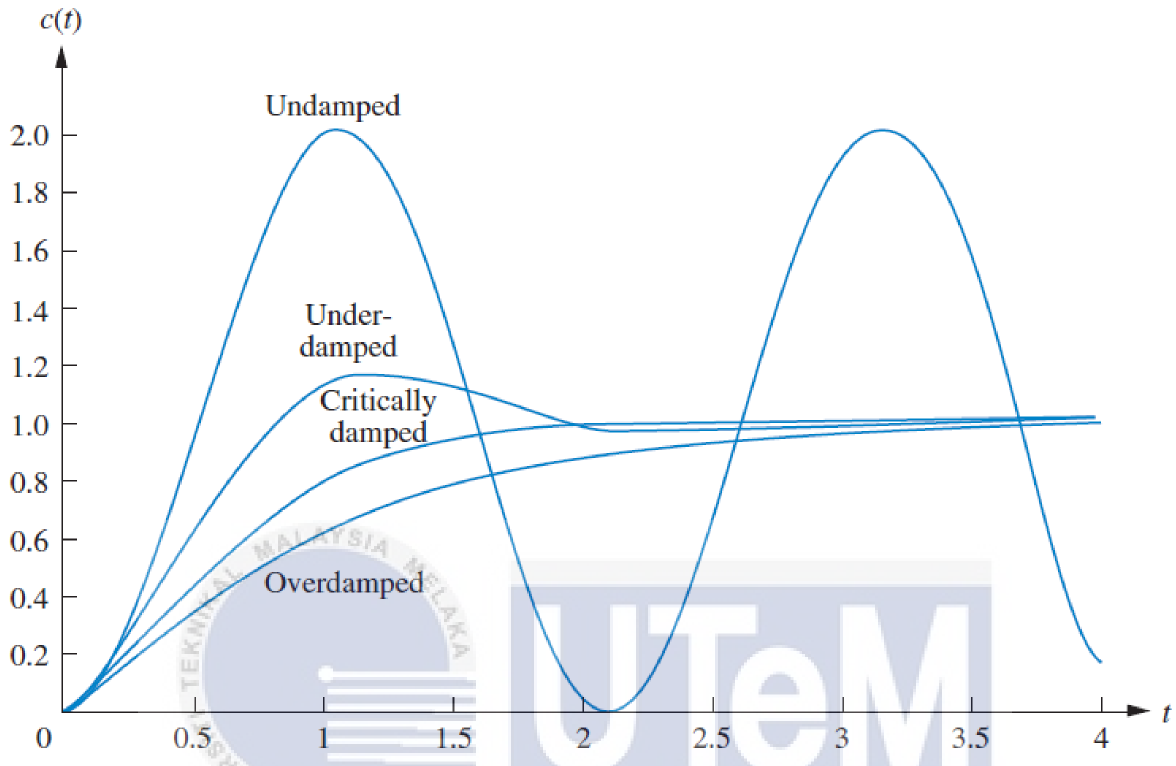

Figure 2.7: Step responses for second-order system damping cases

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2.4.5.1 Overdamped Response

Assume a system response by the function where the block diagram of a second-order overdamped system is shown in Figure 2.8.

$$C(s) = \frac{9}{s(s^2 + 9s + 9)} = \frac{9}{s(s + 7.854)(s + 1.146)} \tag{2.15}$$

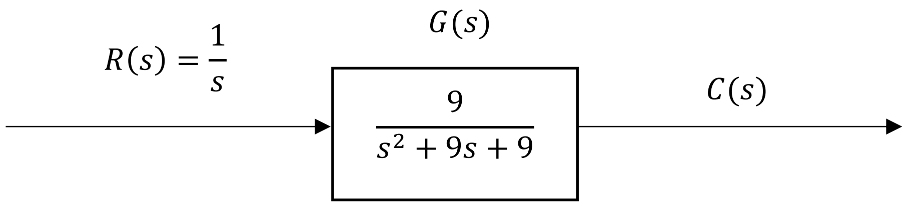

Figure 2.8: Second-order overdamped system

Pole at origin that refers to the unit step input and two real poles of the system in the function is shown in Figure 2.9. Input pole at origin causes constant forced response, while each respective pole from both system on the real axis causes a similar exponential frequency of exponential natural response to the pole location.

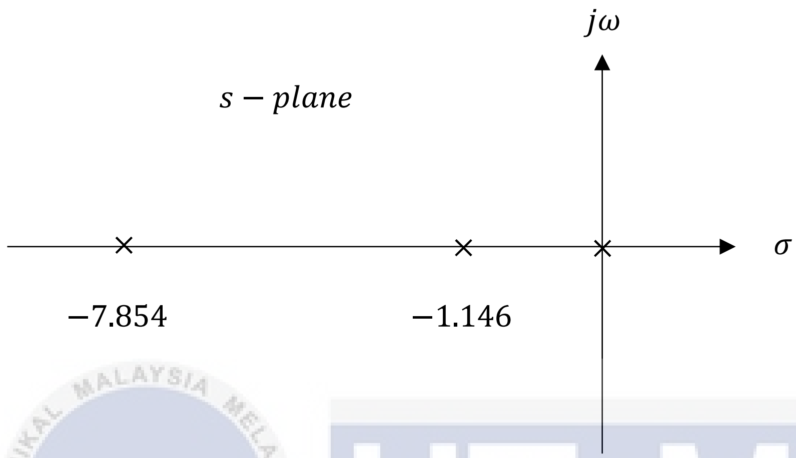

Figure 2.9: Second-order overdamped system's pole plot

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2.4.5.2 Underdamped Response

Assume a system response by the function where block diagram of a second-order underdamped system is shown in Figure 2.10.

$$C(s) = \frac{9}{s(s^2 + 2s + 9)} \tag{2.16}$$

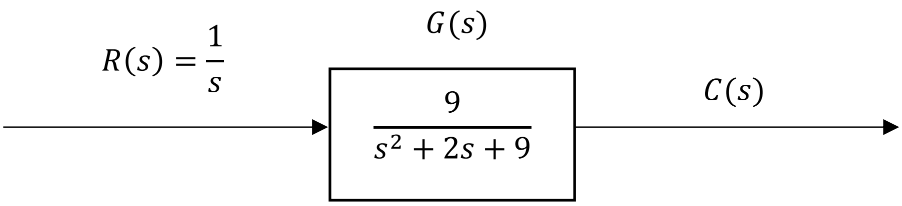

Figure 2.10: Second-order underdamped system

Two complex poles from the system while a pole at the origin is present in this function as shown in Figure 2.11. For underdamped condition, real part of pole generally matches the frequency of exponential decay of the sinusoid's amplitude, whereas imaginary part of poles matches the frequency of sinusoidal oscillation. Meanwhile, the input pole located at the origin generates the steady-state response.

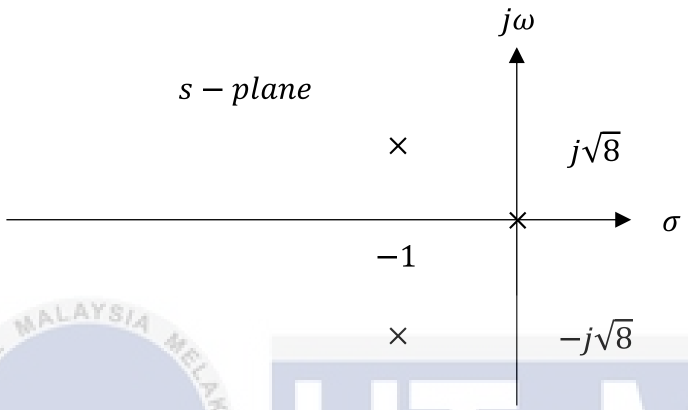

Figure 2.11: Second-order underdamped system's pole plot

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2.4.5.3 Undamped Response

Assume a system response by the function where block diagram of a second-order undamped system is shown in Figure 2.12.

$$C(s) = \frac{9}{s(s^2 + 9)} \tag{2.17}$$

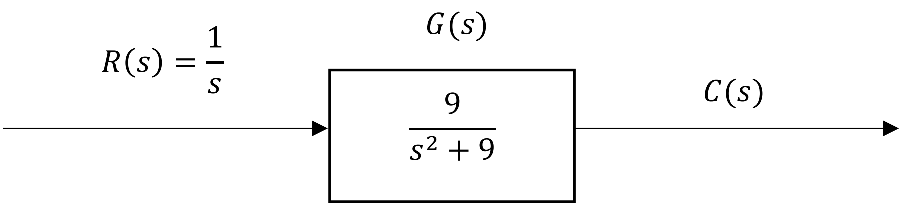

Figure 2.12: Second-order undamped system

The pole at origin is retrieved from the unit step input, and two imaginary poles are based from the system as shown in Figure 2.13, whereby input pole generates the constant forced response, and a sinusoidal natural response with an equal frequency to the location of imaginary poles are generated by the two system poles. The term, undamped implies that exponential does not decay due to the absence of real pole.

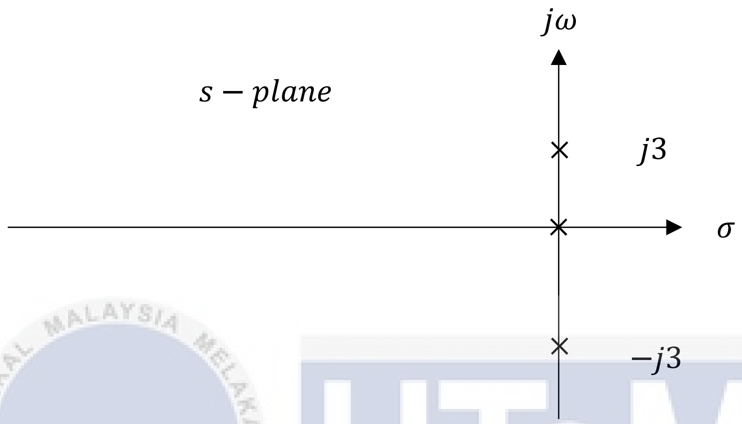

Figure 2.13: Second-order undamped system's pole plot

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2.4.5.4 Critically Damped Response

Assume a system response by the function where block diagram of a second-order critically damped system is shown in Figure 2.14.

$$C(s) = \frac{9}{s(s^2 + 6s + 9)} = \frac{9}{s(s+3)^2} \tag{2.18}$$

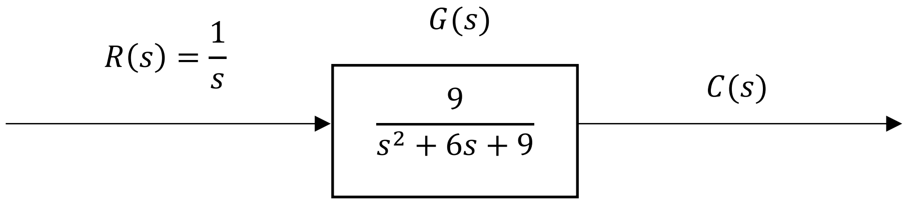

Figure 2.14: Second-order critically damped system

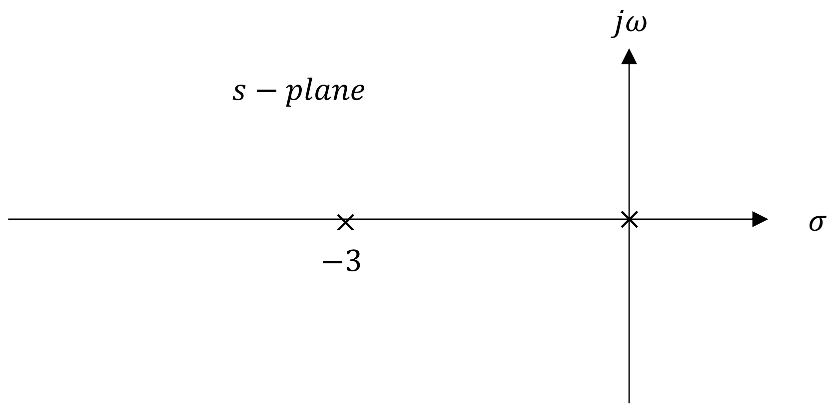

Figure 2.15: Second-order critically damped system's pole plot

Figure 2.15 illustrated a pole at origin generated by unit step input, while two multiple real poles generated from the system. Input pole provides constant forced response, whereas the two poles at real axis of -3 generate the natural response. Natural response in this case consist of an exponential multiplied by time. This means that the location of real poles is equal to the exponential frequency. This response is the fastest among all responses, along with its absence of overshoot.

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2.4.6 Location of Poles

Nise (2015) classified movement of poles into constant real part, constant imaginary part, and constant damping ratio. During constant real part movement, poles move in vertical direction as shown in Figure 2.16(a), whereby envelope remains during increment of frequency as the real part of the pole is unchanged. Sinusoidal response increases in frequency when the poles move further away from zero. Settling time is maintained under all frequencies as all curves fit under the same exponential decay curve. This is also due to the increase in overshoot, which causes rise time to decrease.

As poles move to the left as shown in Figure 2.16(*b*), response damps out faster while maintaining the same frequency and peak time. This is due to the effect of constant imaginary part. Moving on, poles with constant radial line movement affect the speed of overshoot, but not the amplitude as shown in Figure 2.16(*c*).

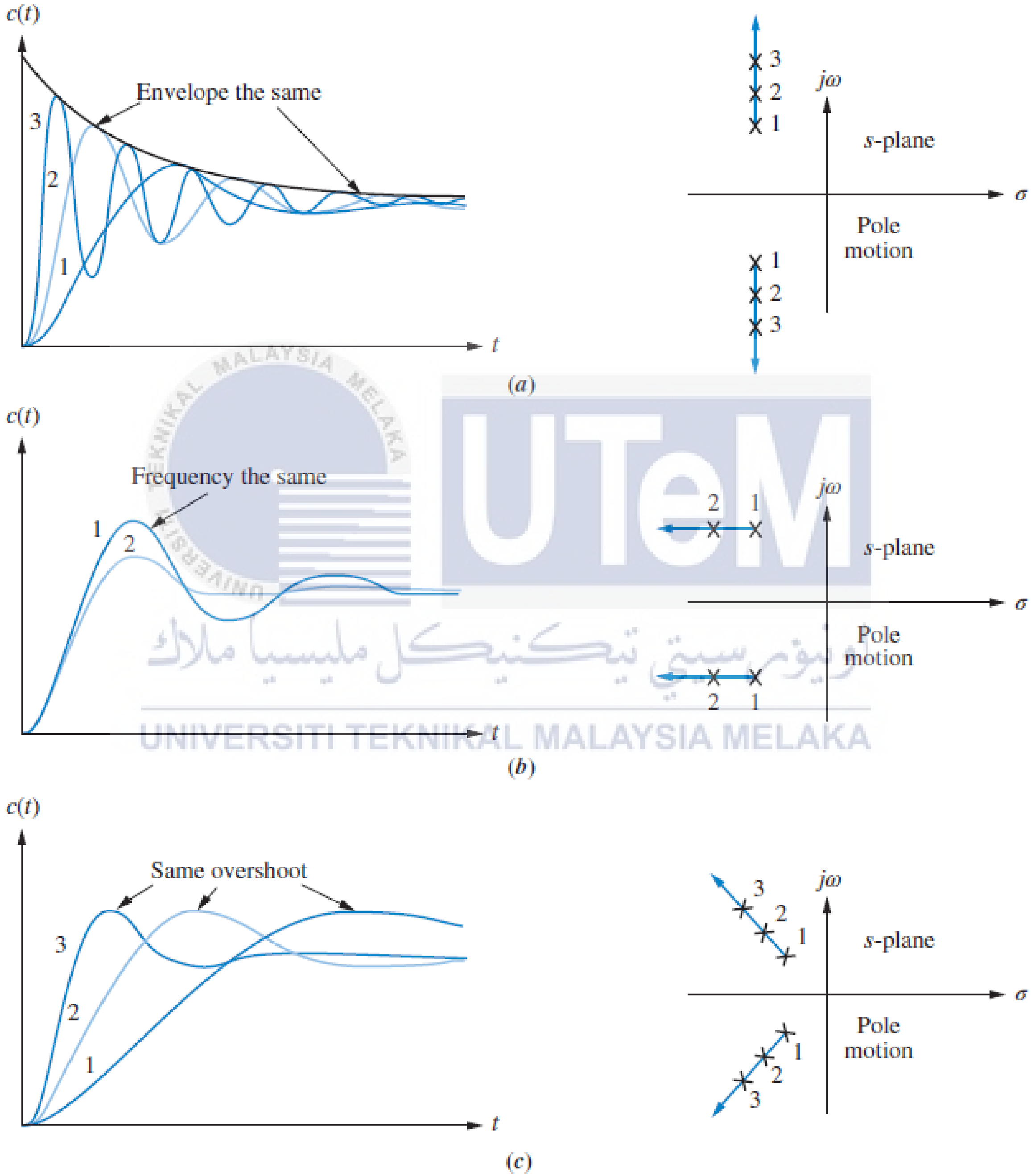

Figure 2.16: Step responses of second-order underdamped systems as poles move

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2.4.7 Influence of Zeros

Notice that throughout till now, the sections within Chapter 2 showed no significant influence of zeros towards a system. It is hereby clarified that most of the influences on the behaviour of the system are due to the poles. As for now, zeros are only known as a guide in providing the value of amplitude, or as a gain factor (Nise, 2015). The upcoming subsection which review about the addition of poles and zeros will show the influence of zero in transient step response. A system could have no zeros, but it must have the presence of pole (Scherbaum, 2001).

2.4.8 Addition of Poles and Zeros

Whitworth (2019) stated that addition of poles to transfer function has the effect of pulling the root locus to the right, making the system less stable. However, the best fit index increases with the increment of number of poles under MATLAB's SI. As the increment of number of poles basically increases the order of the system, a more accurate description of the system is provided. This is due to the fact that real system is usually found to be more complex and difficult to predict.

Meanwhile, addition of zeros to transfer function will pull the root locus to the left, making the system more stable. Statement made by Nise (2015) also supports the increase in stability via addition of zeros as adding a left-half-plane (LHP) zero to transfer function increase step response. Rise and peak time will decrease as overshoot increases. However, adding a right-half-plane (RHP) zero to transfer function will decelerate the step response as undershoot may take place.

2.4.9 Delay

Ljung (2003) gave an example of a most commonly used process model:

$$G(s) = \frac{K}{1 + sT_{p1}} e^{-sT_d} \quad (2.19)$$

whereas a model without delay ($T_d = 0$):

$$G(s) = \frac{K}{1 + sT_{p1}} \quad (2.20)$$

Therefore, delay could be represented to be e^{-sT_d} under mathematical expression. This statement could be defended as Nise (2015) defined time delay as the delay between the commanded response and the start of the output response. By having an example of a system with an input, $R(s)$, to a system, $G(s)$, yields an output, $C(s)$; while another system, $G'(s)$, delays the output by T_d seconds, has an output response of $c(t - T)$. By Laplace transforming $c(t - T)$, $e^{-sT_d}C(s)$ is obtained. Thus, it could be concluded that:

System without delay:

$$C(s) = R(s)G(s) \quad (2.21)$$

System with delay:

$$e^{-sT_d}C(s) = R(s)G'(s) \quad (2.22)$$

By dividing Eq. (2.22) with Eq. (2.21):

$$\frac{G'(s)}{G(s)} = e^{-sT_d} \quad (2.23)$$

Thus, system with time delay could be represented in terms of an equivalent system without time delay as follow:

$$G'(s) = e^{-sT_d}G(s) \quad (2.24)$$

Effect of adding time delay also reduces the phase shift and margin. By using second-order approximation, reduction in phase margin eventually reduce damping ratio of the system, and causes more oscillatory response. Along with a reduced gain-margin due to the reduction of phase, the system moves closer to instability due to the increase percent of overshoot.

2.4.10 Integrator

Ljung (2003) gave an example of a most commonly used process model as shown previously in Eq. (2.19), whereas a model with enforced integration (self-regulating process) is:

$$G(s) = \frac{K}{s(1 + sT_{p1})} e^{-sT_d} \qquad (2.25)$$

Notice that the enforcement of integration has increased the order of the system by the higher power of the *s* variable. As the order of the system is now higher, accuracy of model is increased during prediction as the model description suits better based on real cases. Event of overshoot could be eliminated with integration as the model reacts more accurately as denoted by the best fit index.

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2.5 Summary of Literature Review

The summary of the influence of pole, zero, delay, and integrator from the findings of literature review is shown in Table 2.1.

Table 2.1: Summary of influence of pole, zero, delay, and integrator

	Influence
Pole	- The higher the number of pole, the higher the order of the system - Location of pole determines the damping speed of the response of system
Zero	- Provides guidance on the value of amplitude or gain factor - Location of zero affects the stability of the system
Delay	- Reduces phase shift or margin - Reduces damping ratio in second-order approximation
Integrator	- Avoids overshoot of system - Increases the order of system - Reacts more accurately in trend

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2.6 Current Studies of Transfer Function

2.6.1 Development of Transfer Functions Relating Solid Oxide Fuel Cell Degradation to Operating Conditions

A research by Polverino (2021) tends to present an innovative model-based approach for the development of mathematical transfer functions to be applied on operating conditions by correlating Solid Oxide Fuel Cells (SOFCs) degradation rate. The transfer function is used for fuel cell lifetime prediction and Accelerated Stress Test (AST) protocols design. Evaluation of key operating variables, accelerating voltage decay over time is relied on multiscale modelling methodology and links local degradation to high level performance models. Thorough simulation analysis was conducted to convey the correlation among operating variables and degradation rate into the mathematical transfer functions. Case study of nickel agglomeration was conducted as well to better illustrate the overall design and application process of such functions. Multiscale modelling framework is applied to correlate microscale such as particles size change of nickel, and macroscale such as SOFC voltage reduction levels through the most affected mesoscale parameters. Voltage decay over time and link degradation rates are then simulated using the model towards the applied operating conditions. Investigation on the influence exerted by each operating variable on the degradation rate was conducted via parametric analysis to derive the transfer functions.

$$\xi(T, J_N) = a_1 e^{a_2 T} (e^{a_3 J_N} - e^{a_4 J_N}) \qquad (2.26)$$

2.6.2 Estimation of Non-Point-Source Solute Travel Times using Transfer Function Model

Research conducted by Bancheri (2021) had presented a new suitable fast and reliable transfer function model capable of simulating the spatiotemporal distribution of non-point-source solutes along the unsaturated zone for large scales usage within a web-based Decision Support System. The model uses transfer functions of travel time probability density functions derived from the unsaturated hydraulic conductivity curve. The output concentration of solute is the convolution of transfer functions with the input concentrations to the system. Model sensitivity analysis carried out showed that saturated water content and the tortuosity parameter were the parameters that affected the mean travel time. Validation was made against the concentration experiments carried out on four large soil columns. The result of the comparisons produced a high correlation coefficient shows that the model is feasible for the groundwater vulnerability assessment.

$$- \frac{z\left[1-\left(1-s_e^{1/m}\right)^m\right]}{\dfrac{t^2 se^{-1}\left[\tau + 2s_e^{1/m}\left(1-s_e^{1/m}\right)^{m-1} - \tau\left(1-s_e^{1/m}\right)^m\right]}{\theta_s - \theta_r}} \tag{2.27}$$

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CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter reveals the methodology for building a best-fit process model based on the influence of poles, zeros, delay, and integrator via MATLAB Toolbox. Flow chart of the process is provided in Figure 3.1. During the early stage of this project, the SI Toolbox Graphical User Interface (GUI) was explored and familiarised to figure out its related terms (best-fit, final prediction error, and mean square error) for future analysis and reporting in Chapter 4 and its operating procedures which is what Chapter 3 is focused on. Next, trial run was conducted for the process model estimation based on sample data as an exercise for familiarisation. The resulting process models are differentiated by the influence of poles, zeros, delay and integrator. The process model estimation is retrained with different specifications to achieve a best-fitted result of process model. The similar methodology would be repeated using different data set for the comparison and validation of the influence of poles, zeros, delay, and integrator, in order to prove that their influences are the same throughout all data sets. However, the methodology will only be shown via sample data set of dryer obtained from MATLAB SI Toolbox, as similar steps would be followed by other data set.

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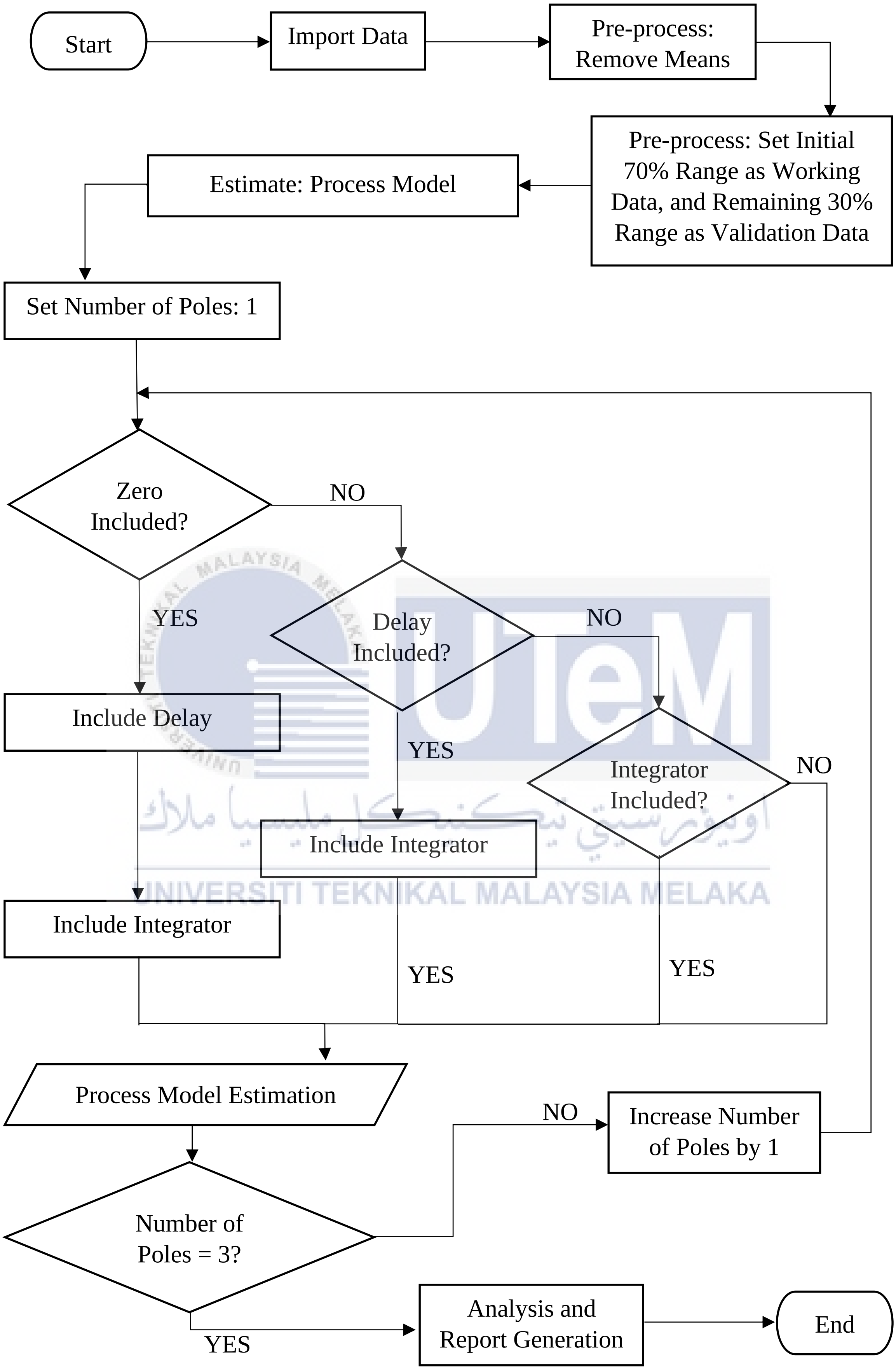

Figure 3.1: Flow chart of detailed methodology

3.2 GUI of MATLAB for System Identification

In this section, the GUI is separated into 3 parts consisting of data import, data pre-processing and the model estimation as shown in the Figure 3.2 and will be discussed accordingly.

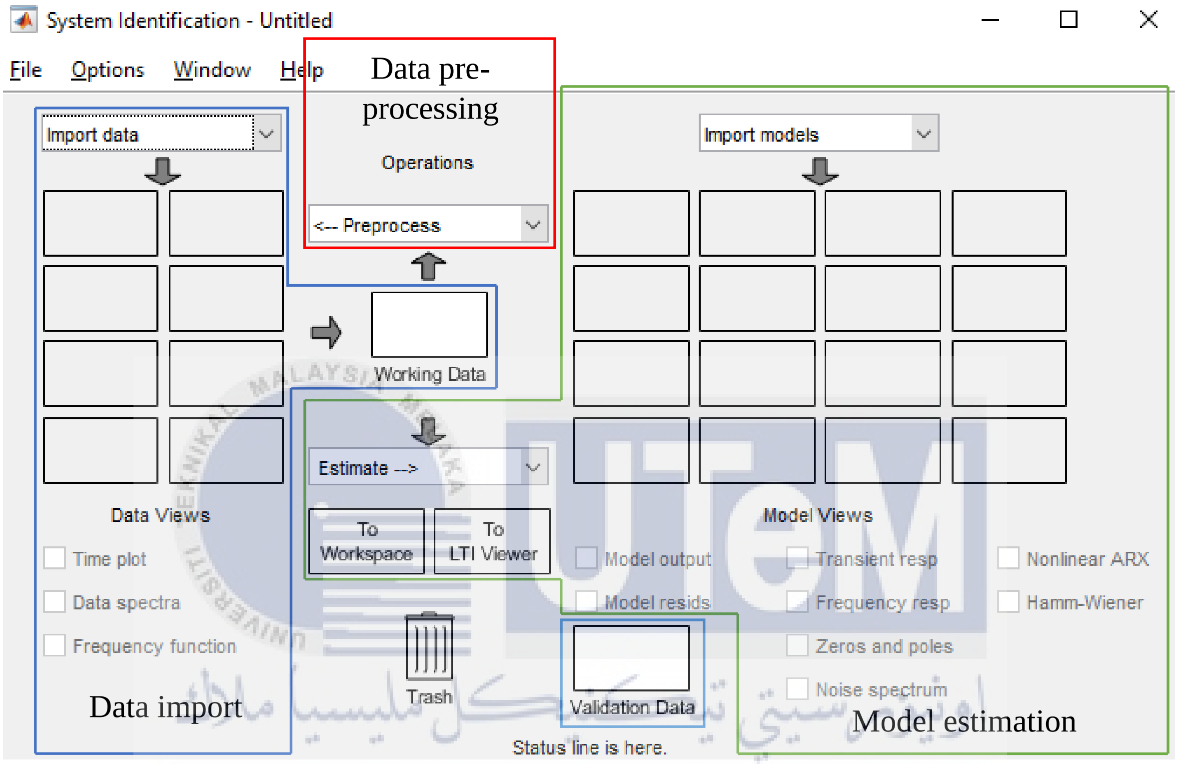

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Figure 3.2: Separation of GUI into different parts

3.2.1 Data Import

There are 4 types of data which could be imported into the GUI, which are the time-domain data, frequency-domain data, data object, and example data as shown in Figure 3.3.

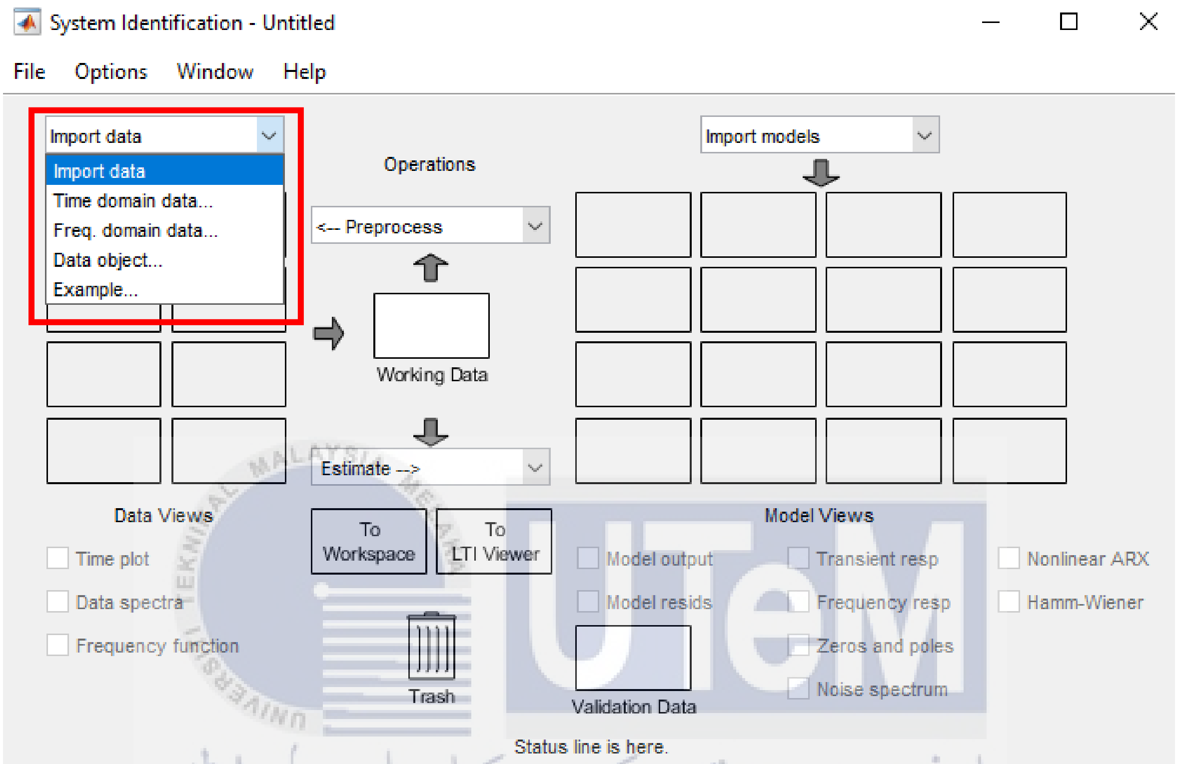

Figure 3.3: Types of data available to be imported

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- Time-domain data : Data with one or more input variables, with one or more output variables, sampled as a function of time.
- Frequency-domain data: Data with transformed input and output time-domain signals or system frequency-response sampled as a function of the independent variable frequency.

- Data object: SI iddata data with time-domain data or frequency-domain data, and has several properties that specify the time or frequency values; idfrd data with frequency-response data over a range of frequency values.
- Example : Sample data of dryer stored in MATLAB.

The imported data is displayed on the frame, while data view of time plot, data spectra, and frequency function of imported data are available to be viewed by users as shown in Figure 3.4. Comparison between different data sets could also be done by users by clicking on the frame.

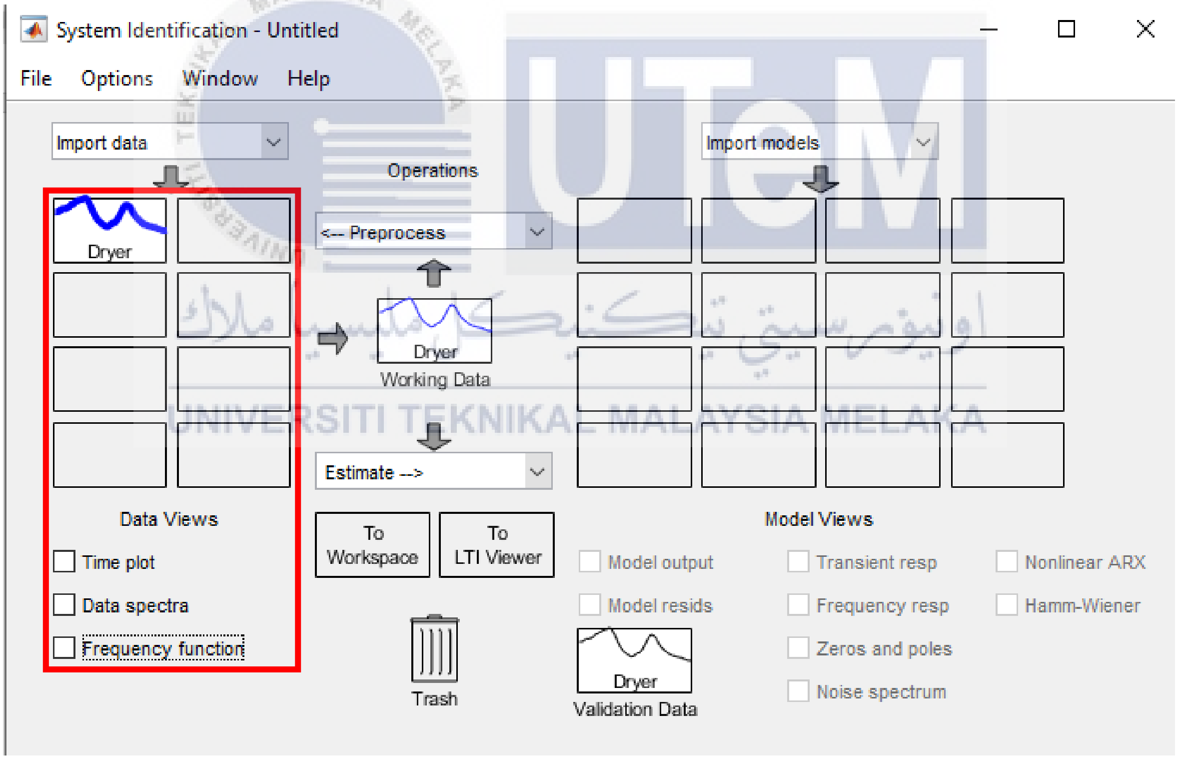

Figure 3.4: Displayed imported data and the available data views

Once data is imported, the data could be used as either working data or validation data by dragging into their respective frame as shown in Figure 3.5. Working data is the data used for pre-process and estimation purposes, while validation data is the data used for comparison with the data generated via model estimation to obtain its best-fit index.

Figure 3.5: Working data and validation data frame

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3.2.2 Data Pre-Processing

Potential restrictions on the accuracy of model could be avoided by pre-processing the data. Among the pre-processing features available in the GUI of SI include: channel selection, experiment selection, merging of experiment, range selection, removing of means, removing of trends, filter, resample, data transformation, and quick start as shown in Figure 3.6.

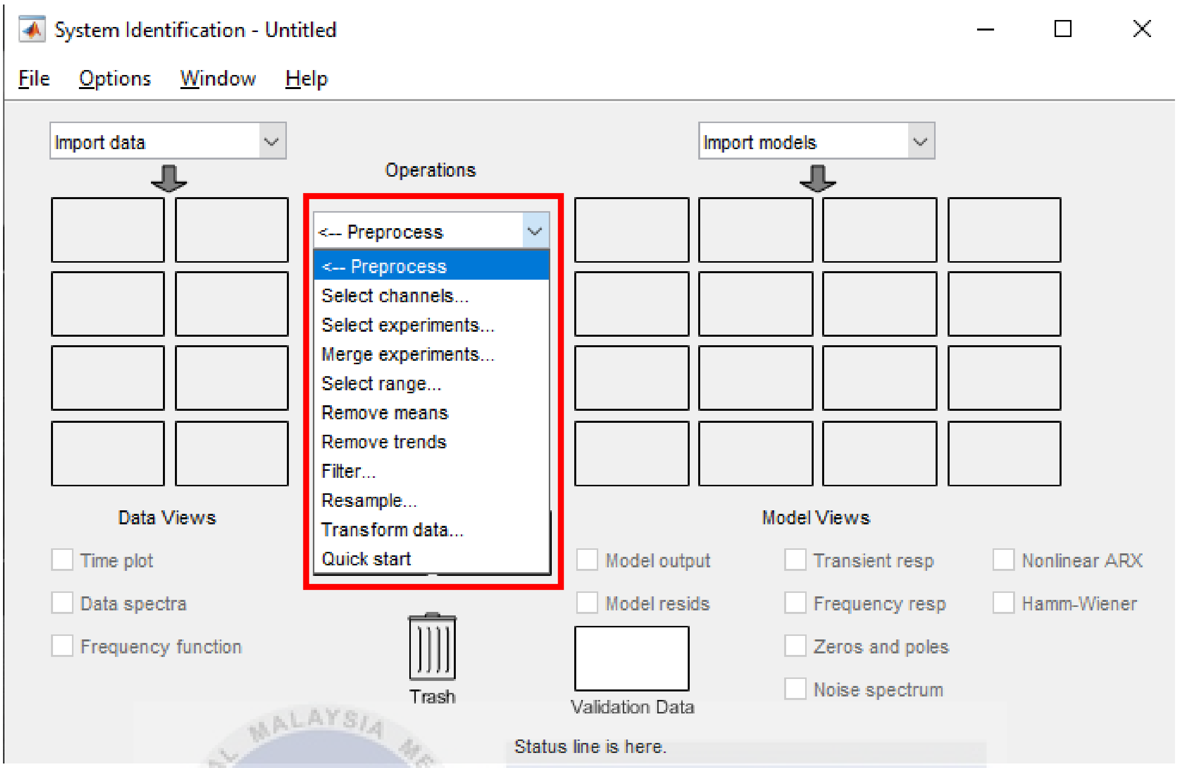

Figure 3.6: Types of pre-process available

- Channel selection : Subsets of input and output channels are extracted from an exisitng data set.
- Experiment selection : Specific experiment is extracted from a multi-experiment data set into a new data set.
- Merging of experiment: Multiple data sets are combined as one.
- Range selection : The beginning and the end of the value of data set are specified according to selection.
- Removing of means : Mean values from each input and output data signal are removed.
- Removing of trend : Linear trend is removed.

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- Filter : Time-domain data is filtered using a fifth-order Butterworth filter by enhancing or selecting specific passbands.
- Resample : Antialisaing (lowpass) finite impulse response (FIR) filter is added to the data to change the sampling rate of the signal by decimation or interpolation.
- Data transformation : Data domain is transformed into another data domain according to the prerference of user.
- Quick start : Shorcut of preprocess which perfrom substraction of mean value from each channel, and splittling of data into two parts whereby the first part is being set as working data, while the second part as validation data.

Data which had undergone pre-processing will be displayed as a new imported data on frame as shown in Figure 3.7.

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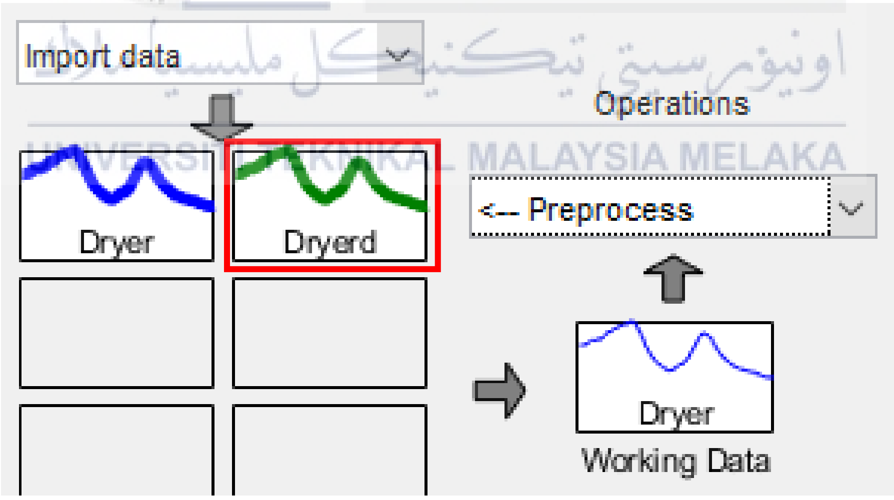

Figure 3.7: Data after being pre-processed

3.2.3 Model Estimation

Among the available model estimation of the GUI for SI are:

- Transfer function model
- State space model
- Process model
- Polynomial model
- Nonlinear ARX model
- Hammerstein-Wiener model
- Spectral model
- Correlation model

However, in this project, the focus will be on process model estimation only. Selection of estimation of model could be found in the GUI as shown in Figure 3.8.

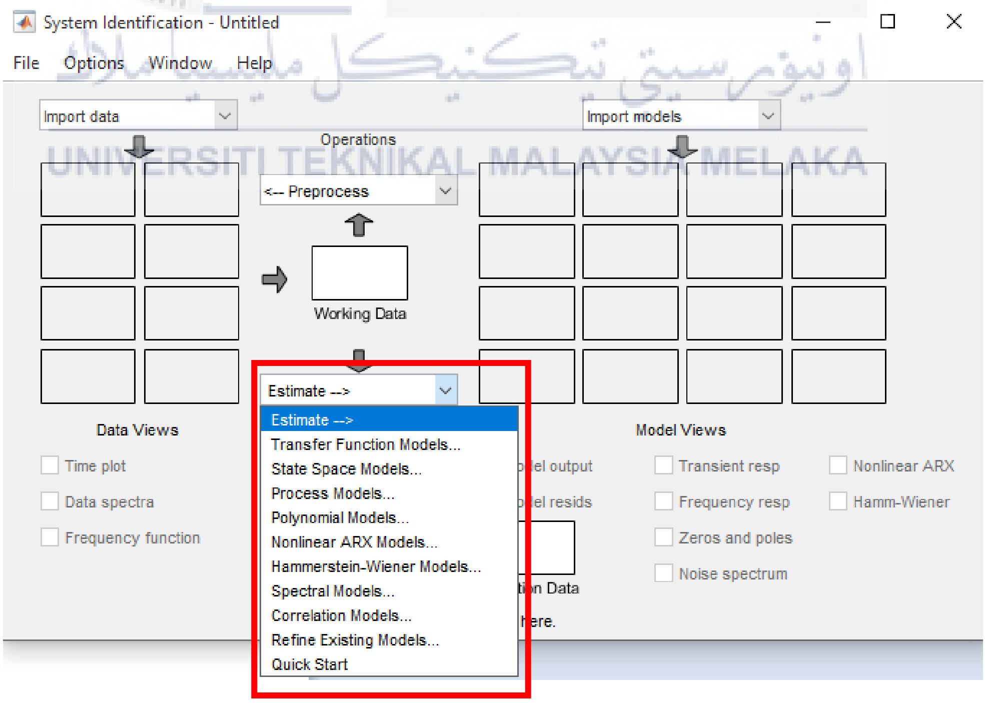

Figure 3.8: Model estimation selection in GUI of SI

The estimated process model is displayed on the frame, while model view of transient response, frequency response, zeros and poles, noise spectrum, nonlinear ARX, Hamm-Wiener, model output, and model residues of the estimated model are available to be viewed by users as shown in Figure 3.9. Comparison between different estimated models could also be done by users by clicking on the frame.

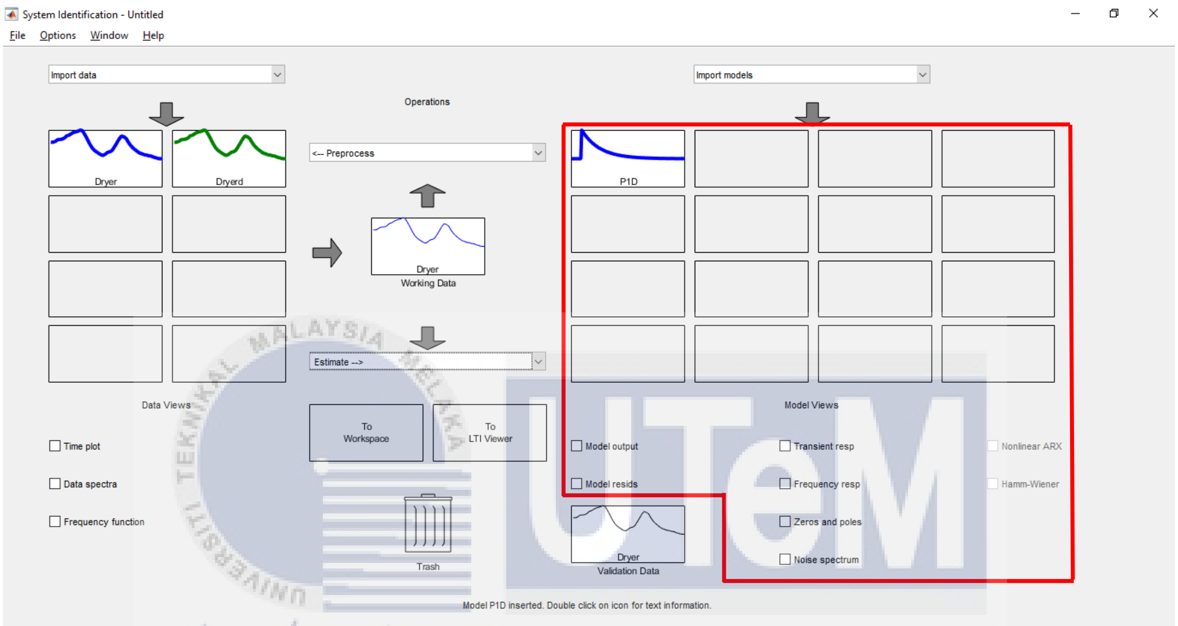

Figure 3.9: Displayed estimated model and the available model views

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3.3 Implementation of SI

The steps on implementation of SI in this project will be listed in this section. Section is divided into 3 parts, which are the data import and pre-process, process model estimation, and the obtained result of process model. Note that, in this section, demonstration of implementation of SI is based on the MATLAB sample data of dryer. The same implementation will be conducted on other data sets for the analysis of result and discussion on the upcoming Chapter 4 during PSM 2.

3.3.1 Data Import and Pre-Process

MATLAB sample data of dryer along with its default settings was imported into the GUI as shown in Figure 3.10.

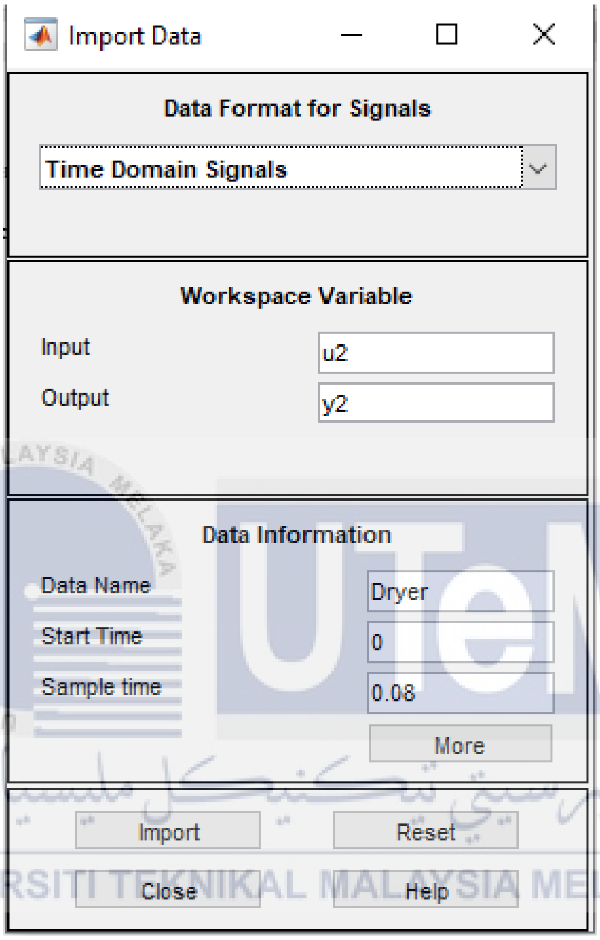

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Figure 3.10: Settings of MATLAB sample data of dryer

The working data of dryer was pre-processed by removing the means in order to remove the constant levels in the data sequence. A new data set will appear after the pre-process of means removal was conducted. The new data was then dragged into the working data frame as shown in Figure 3.11.

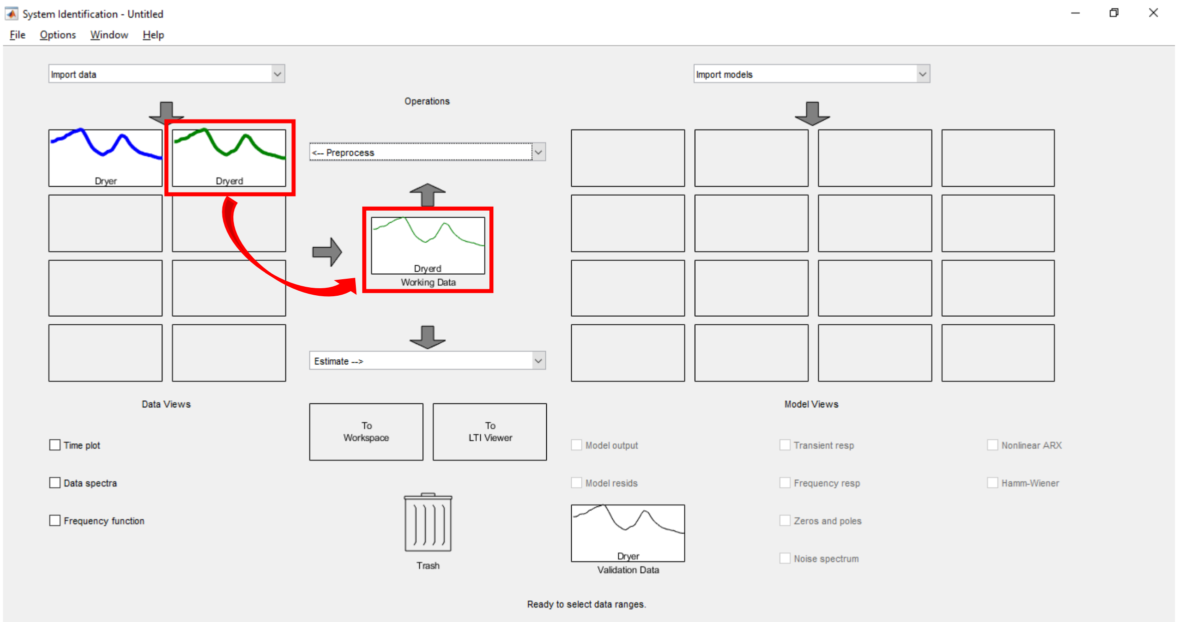

Figure 3.11: Update on working data after pre-process of means removal

By using the updated working data, further pre-process was carried out by extracting the initial 70% range of the data under range selection as shown in Figure 3.12.

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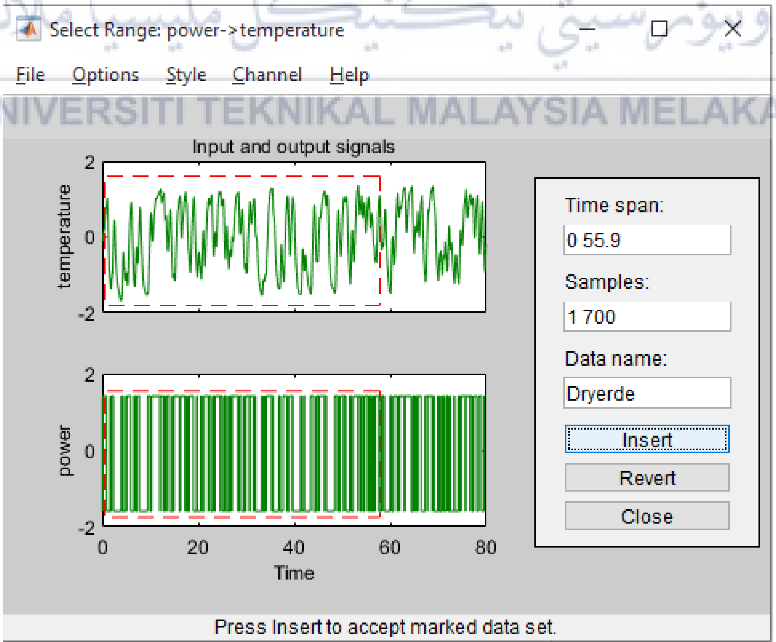

Figure 3.12: Initial 70% range selection of working data

The remaining 30% range of the working data was again extracted using range selection as well. The new data sets due to pre-process of initial 70% range selection and remaining 30% selection were dragged to the working data and validation data frames respectively as shown in Figure 3.13.

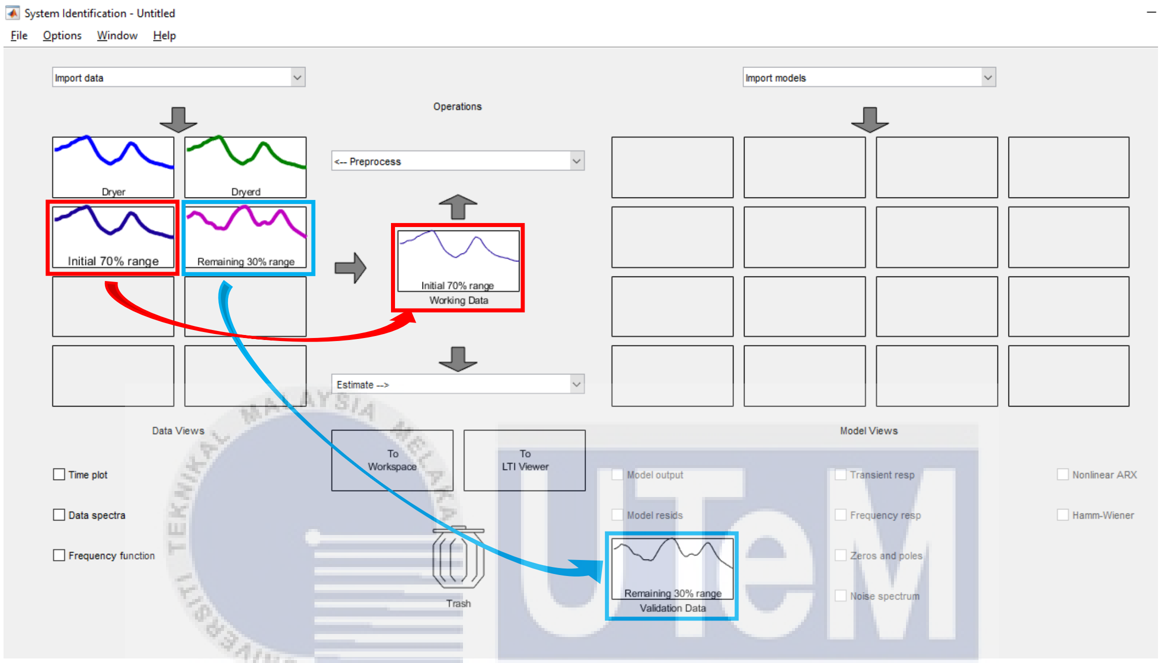

Figure 3.13: Update on working and validation data after pre-process of range selection

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3.3.2 Process Model Estimation

In process model estimation, the main focus will be on the number of poles, along with the presence of zero, delay and integrator. The settings of remaining features available under process model estimation will be remained as default. Meanwhile, poles are set to be all real throughout the entire process model estimation of this project. Features of process model estimation under the concern of alteration by user are shown in Figure 3.14.

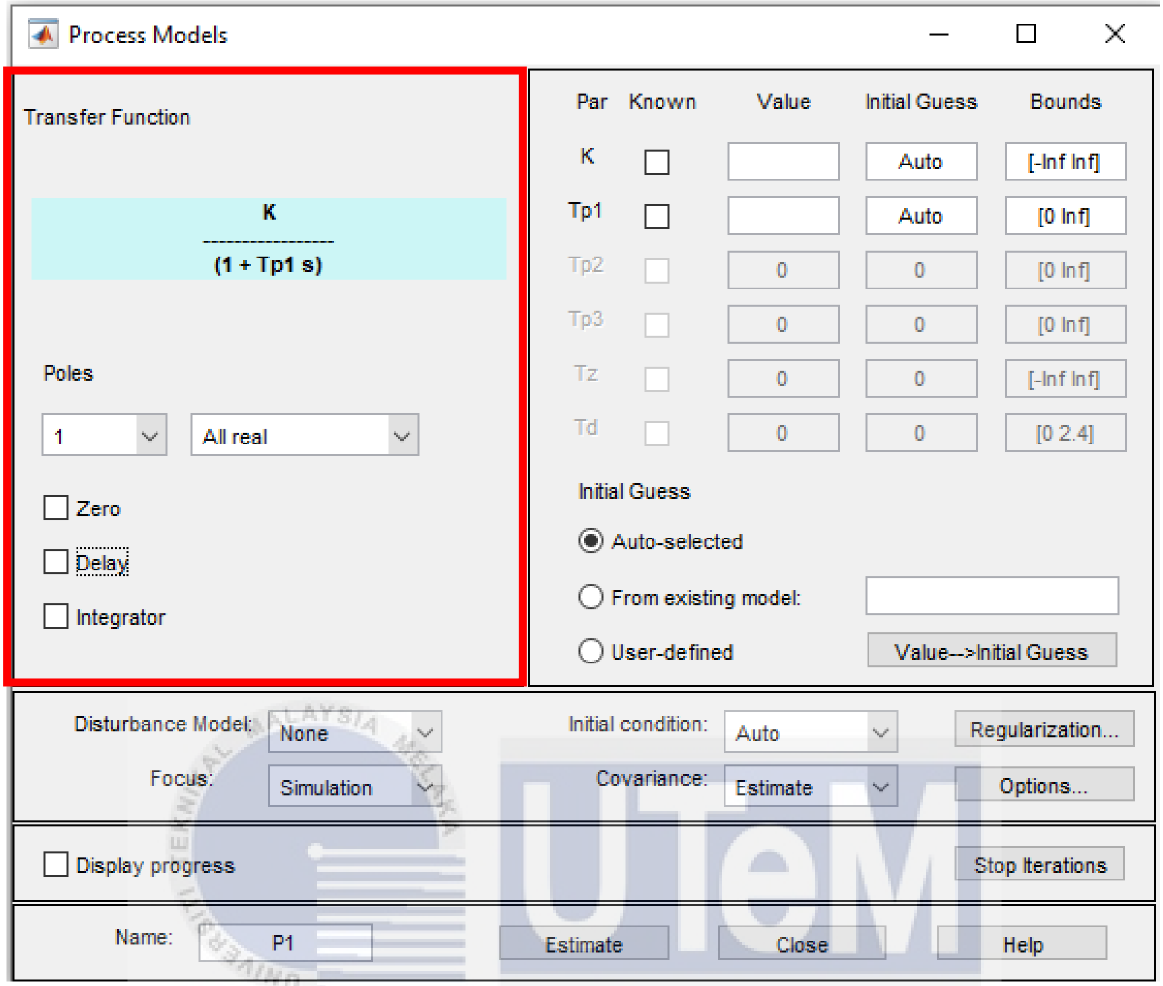

Figure 3.14: Concerned features of process model estimation

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Steps on process model estimation, starting with 1 number of poles:

1. The process model without the presence of zero, delay, and integrator was estimated.
2. The process model with the presence of zero only was estimated.
3. The process model with the presence of delay only was estimated.
4. The process model with the presence of integrator only was estimated.
5. The process model with the presence of zero and delay was estimated.
6. The process model with the presence of zero and integrator was estimated.
7. The process model with the presence of delay and integrator was estimated.

Steps 1 to 7 were repeated by increasing the number of poles by 1, until the maximum number of poles of 3 capped by the GUI of SI was achieved. Each process model estimation was named accordingly as shown in Figure 3.15 under default by the following sequence:

$$P(\#)DIZ$$

whereby, *P* represents poles; *Z* represents zeros; *D* represents delay; *I* represents integrator; and # represents the number of poles.

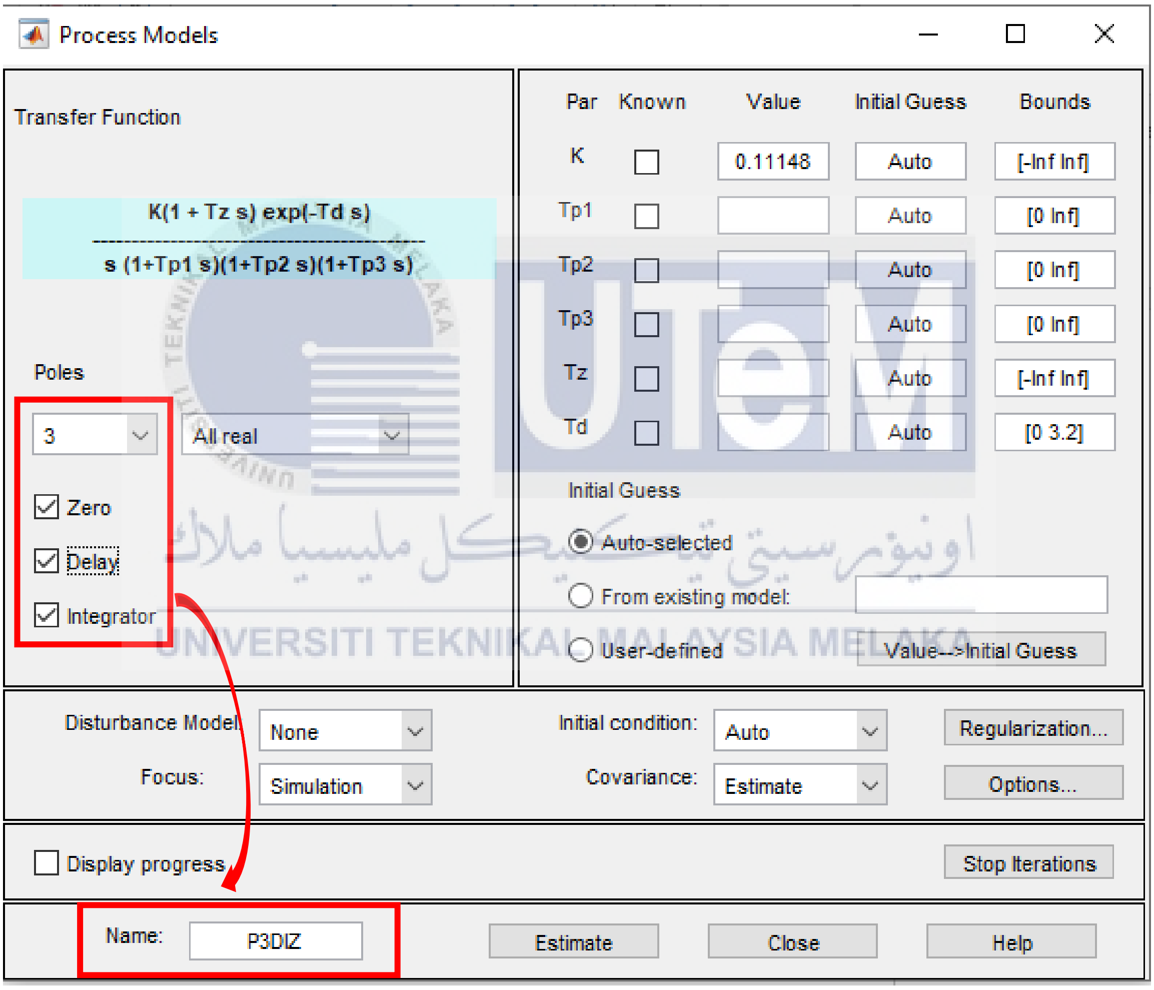

Figure 3.15: Default naming sequence of process model estimation

3.3.3 Obtained Result of Process Model

Estimated process models based on working data will be displayed at the model frame as shown in Figure 3.16.

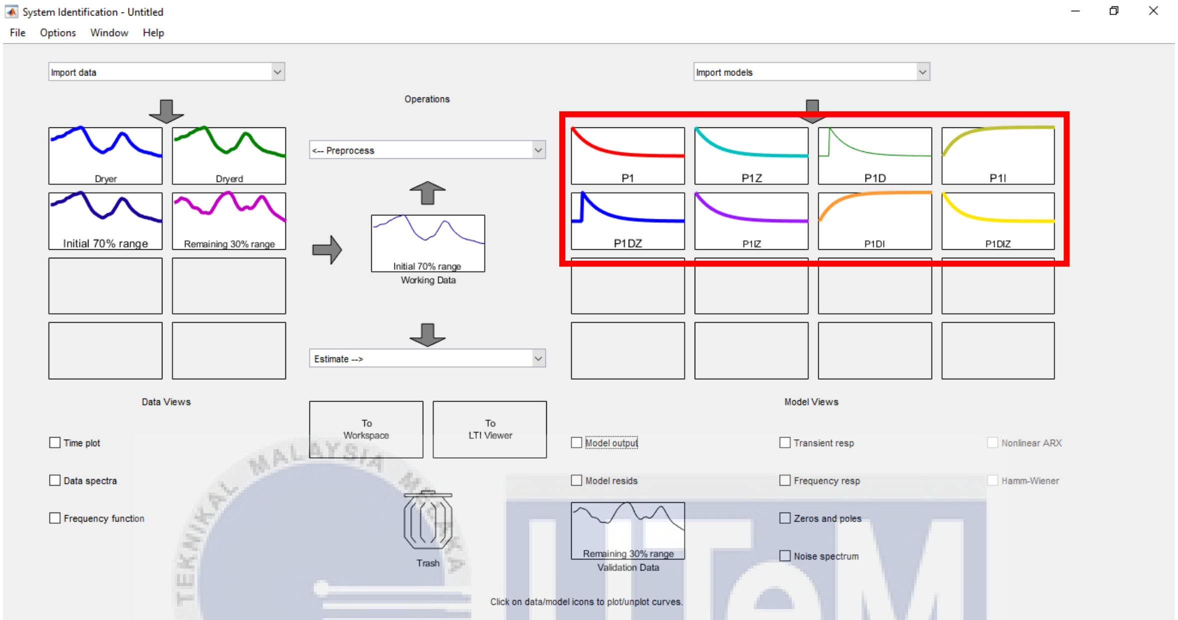

Figure 3.16: Displayed estimated process models based on working data

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In this project, the best-fit index, final prediction error (FPE), and mean squared error (MSE) were retrieved for future analysis on the influence of poles, zeros, delay, and integrator towards building a process model. The FPE and MSE value as shown in Figure 3.17 were obtained by double clicking the displayed figure on the model frame. A lower value of FPE and MSE are preferred as they indicate a better measure of model quality respectively, and a closer estimate or forecast of the actual value respectively.

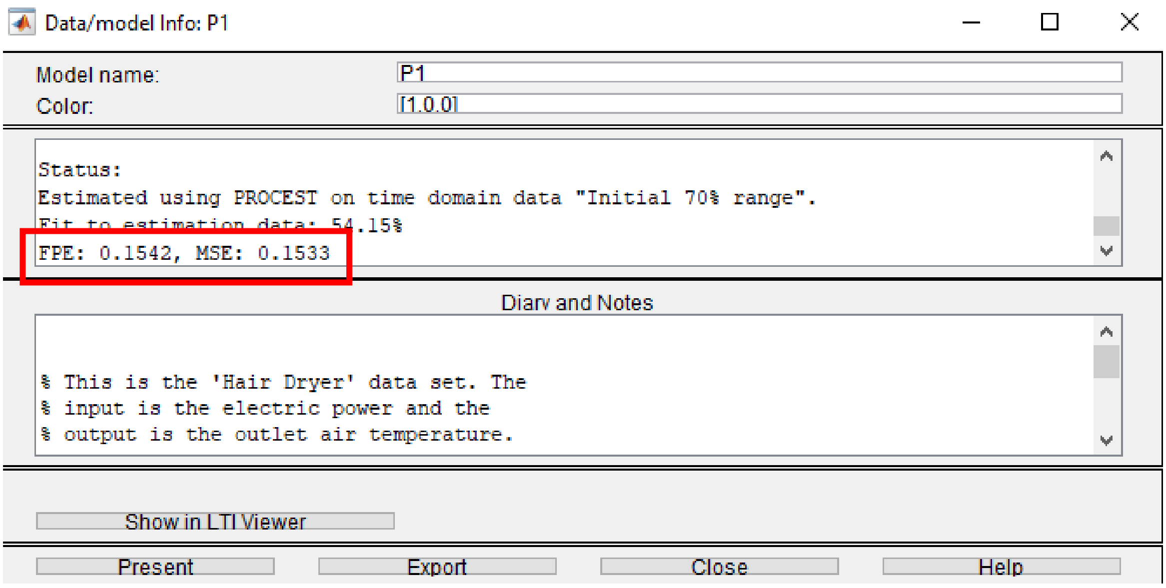

Figure 3.17: FPE and MSE value of an estimated process model

Meanwhile, best-fit index could be viewed as shown in Figure 3.18 by checking the 'model output' box under the model views selection list. Best-fit index represents the accuracy of a process model in estimating its value when being compared towards the actual value of the original model. Therefore, a process model with higher best-fit index will be preferred.

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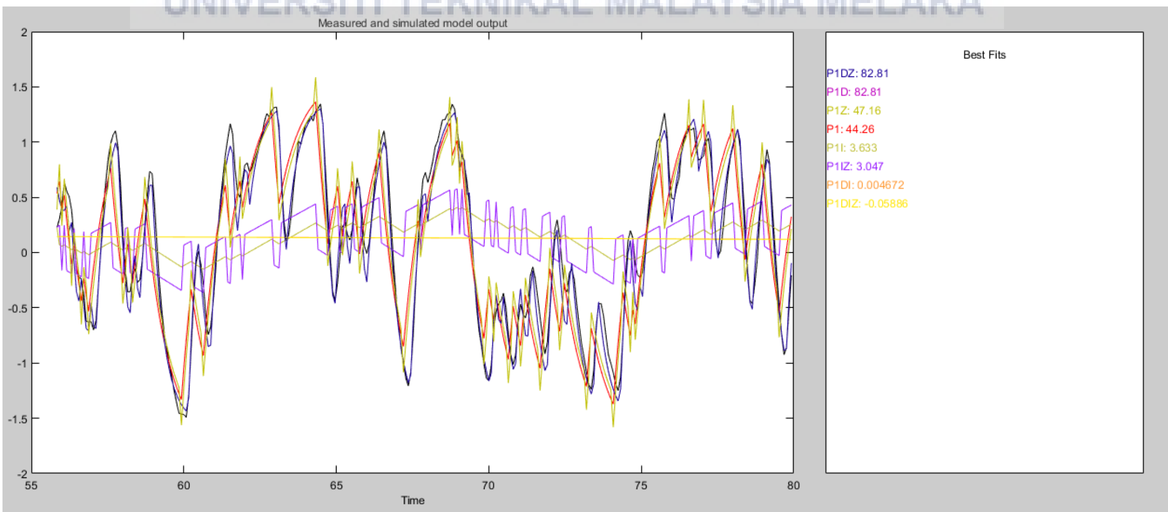

Figure 3.18: Best-fit index of respective process model

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

A program with 3 different transfer function were written which simulates 500 data of system according to its respective function. The system also includes random disturbances of 1% to replicate the imperfection of system in real life. The inputs are randomized discrete values, that may be considered as steps, from the range [-1, 1]. All 3 systems with different transfer function were labelled as System A, System B, and System C respectively, while process model estimation was carried out separately to compare the understanding on its influence of poles, zero, delay, and integrator. A real industrial data of an air compression system is then being tested out via process modelling to discuss and relate the significance of pole, zero, delay and integrator with the general understanding of how the system works.

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System A,

$$y(t) = 5\left[1 - \exp\left(-\frac{t}{5}\right)\right] \tag{4.1}$$

$$Y(s) = \left(\frac{5}{s} - \frac{5}{(s + 0.2)}\right) U(s) \tag{4.2}$$

System B,

$$y(t) = 5[1 - \exp(-5t)] \tag{4.3}$$

$$Y(s) = \left(\frac{5}{s} - \frac{5}{(s + 5)}\right) U(s) \tag{4.4}$$

System C,

$$y(t) = 5[1 - 1.005 \exp(-0.01t) \sin(0.1t - 1.471)] \tag{4.5}$$

$$Y(s) = \left(\frac{5.129s^2 - 0.40101s + 0.0505}{s(s^2 + 0.02s + 0.0101)}\right) U(s) \tag{4.6}$$

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4.2 System A

4.2.1 Process Model Estimation with 1 Pole

Table 4.1: Summary of findings of process model estimation with 1 pole of System A

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P1	$G(s) = \frac{-0.24442}{1 + 0.048035s}$	0.3126	8.908	8.807
P1Z	$G(s) = 4.9463 + \frac{1 + 1.0014s}{1 + 1.038s}$	**95.33**	**0.05567**	**0.05472**
P1D	$G(s) = \frac{0.53164}{1 + 0.045356s} \times \exp(-0.3144s)$	-1.178	8.918	8.766
P1I	$G(s) = \frac{-7.3031}{s(1 + 77.254s)}$	0.0666	8.795	8.695
P1DZ	$G(s) = 0.75028 \times \frac{1 + 0.20714s}{1 + 0.058917s} \times \exp(-0s)$	**47.82**	**2.637**	**2.577**
P1DI	$G(s) = \frac{-1683.9}{s(1 + 9559.4s)} \times \exp(-0s)$	0.1191	8.806	8.657

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Table 4.1, continued

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P1IZ	$G(s) = -1.3992 \times \frac{1 + 0.98511s}{s(1 + 34.227s)}$	0.06191	8.906	8.755
P1DIZ	$G(s) = -1951.2 \times \frac{1 - 0.46304s}{s(1 + 10000s)} \times \exp(-0.16s)$	0.05695	8.861	8.661

A model of P1, which represents a model of 1 pole without any inclusion of zero, delay, and integrator will be the initial baseline of estimation, as it represents the most basic structure of the model in first order. Based on Table 4.1, it is shown that P1 has a best fit index of 0.3126%. Therefore, any other models with best fit index which is lower than 0.3126% will be disqualified as the quality of the model had been degraded.

There are only 2 models having a higher best fit index than P1, which are the P1Z representing a model of 1 pole with zero, and the P1DZ representing a model of 1 pole with delay and zero. Both P1Z and P1DZ have a best fit index of 95.33% and 47.82% respectively. Further analysis and discussion will be focused on P1Z and P1DZ for better understanding. All of the model output best fit index with 1 pole were shown in Figure 4.1.

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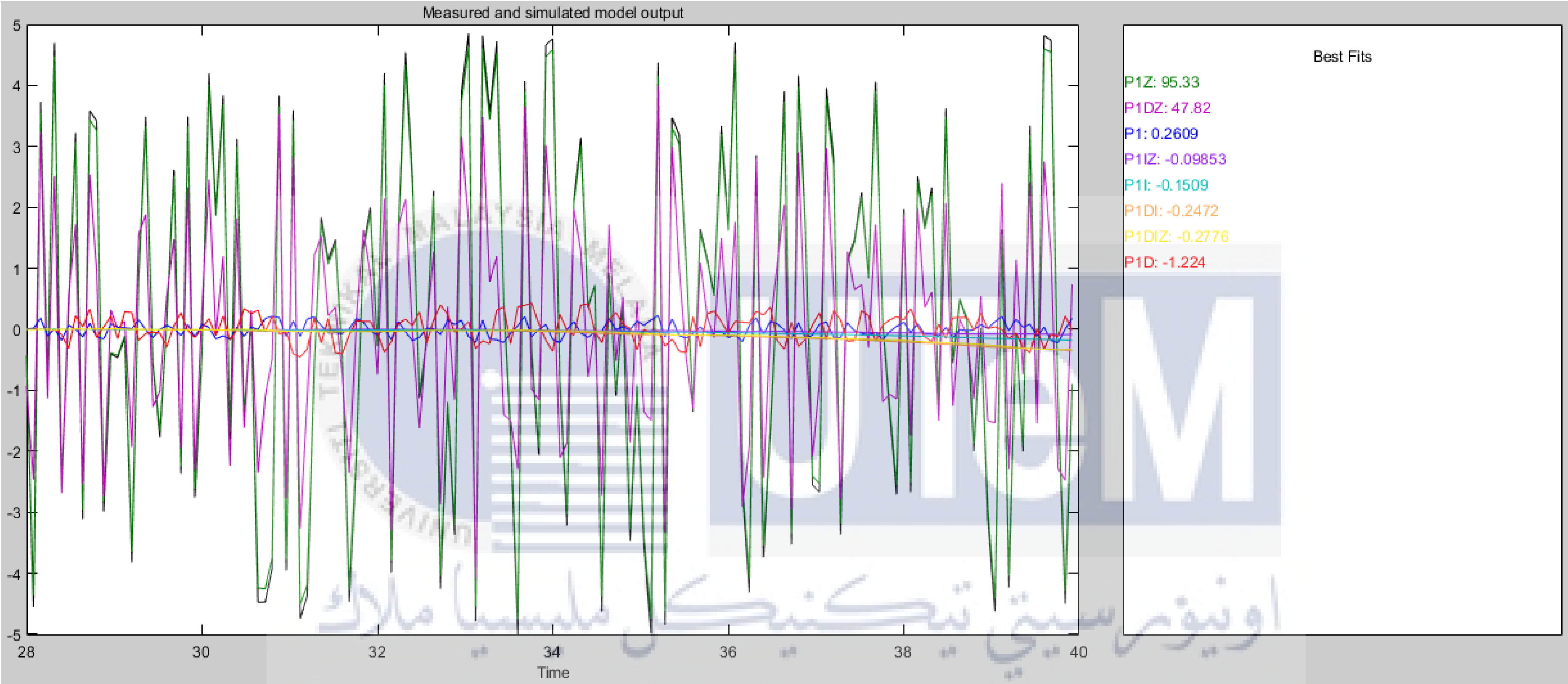

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Figure 4.1: Model output of all models with 1 pole for System A

4.2.2 Discussion on the Addition of Zero

Since both addition of zero via P1Z and P1DZ had increased the value of best fit index, this section hereby aims to prove the statements made by Nise (2015) to be correct. It was mentioned that addition of LHP zeros to transfer function increases step response and stability. Thus, contributing towards a higher best fit index compared to P1 alone. Similarly, both P1Z and P1DZ models are proven to have zeros in the LHP as shown in Figure 4.2.

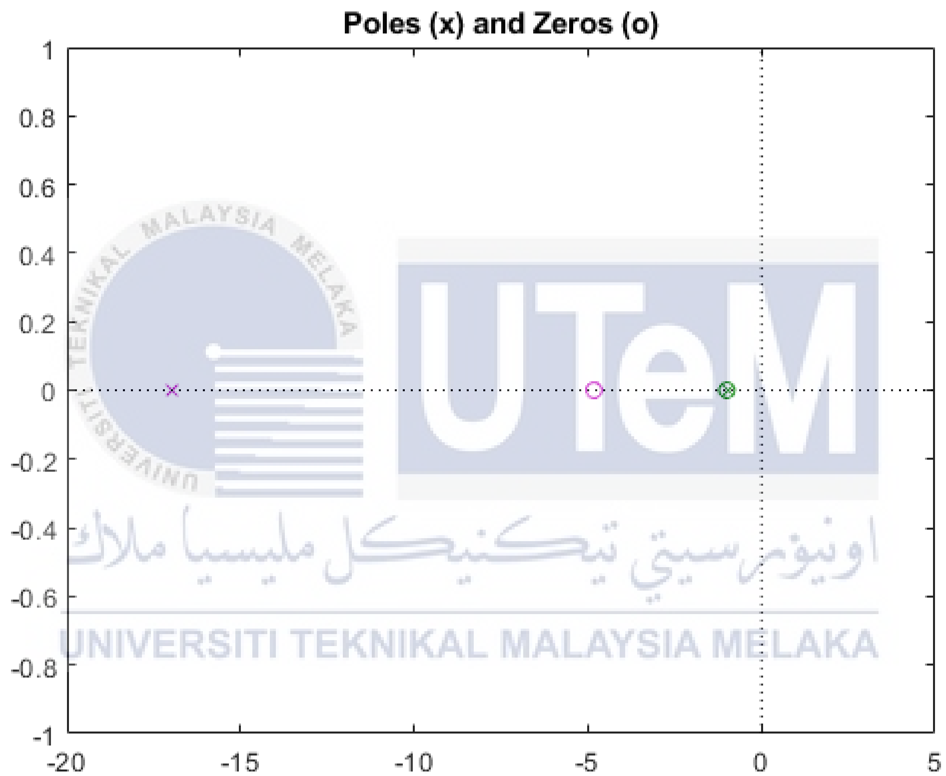

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Figure 4.2: Location of zeros of P1Z *(green)* and P1DZ *(purple)* in plane

4.2.3 Discussion on the Addition of Delay

As the best fit index of output model of a single pole with zero was decreased significantly after a delay was being included, attention was given to find out rational reasoning behind it. From the program simulating the data for process model estimation, it is known that there is no delay as it is not a data acquired from real life, such as the data of a combustion chamber, which requires a certain amount of time to heat up towards its ideal temperature. Hence, to prove that delay will downgrade the best fit index of the model, the bode diagram of both P1Z and P1DZ are compared as shown in Figure 4.3 and Figure 4.4. From both figures, results were distinguished as the magnitude in the model P1Z never hits zero. Meanwhile, the magnitude in the model P1DZ hits zero, the closed-loop stability is unknown.

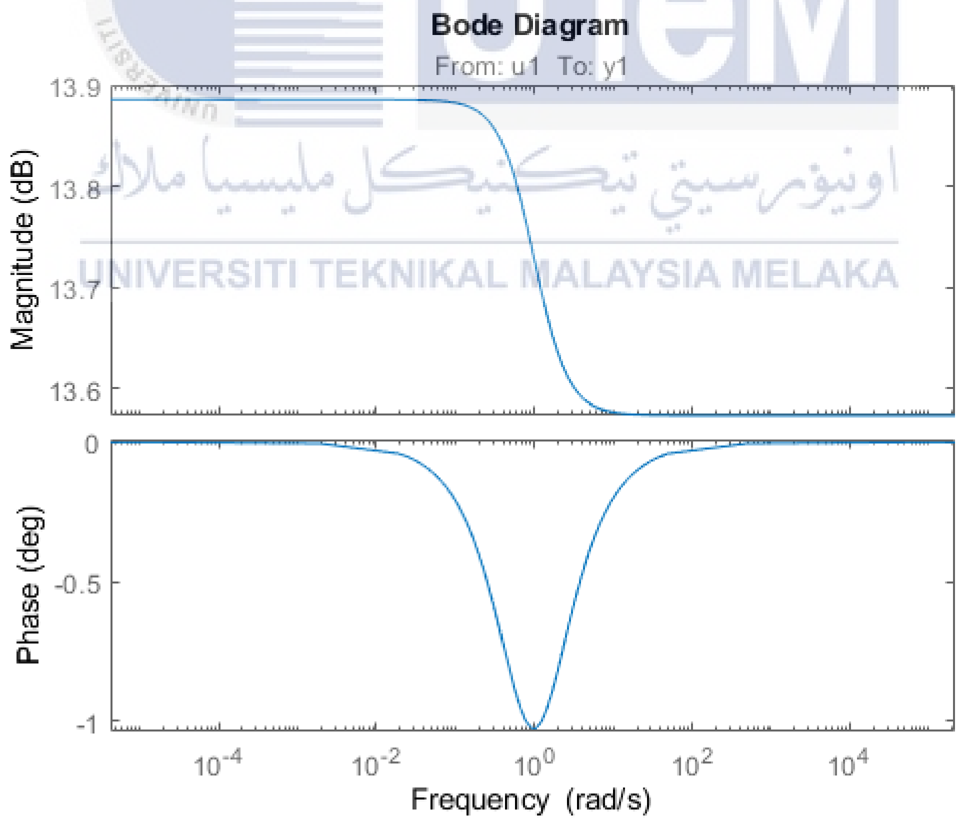

Figure 4.3: Bode diagram of P1Z for System A

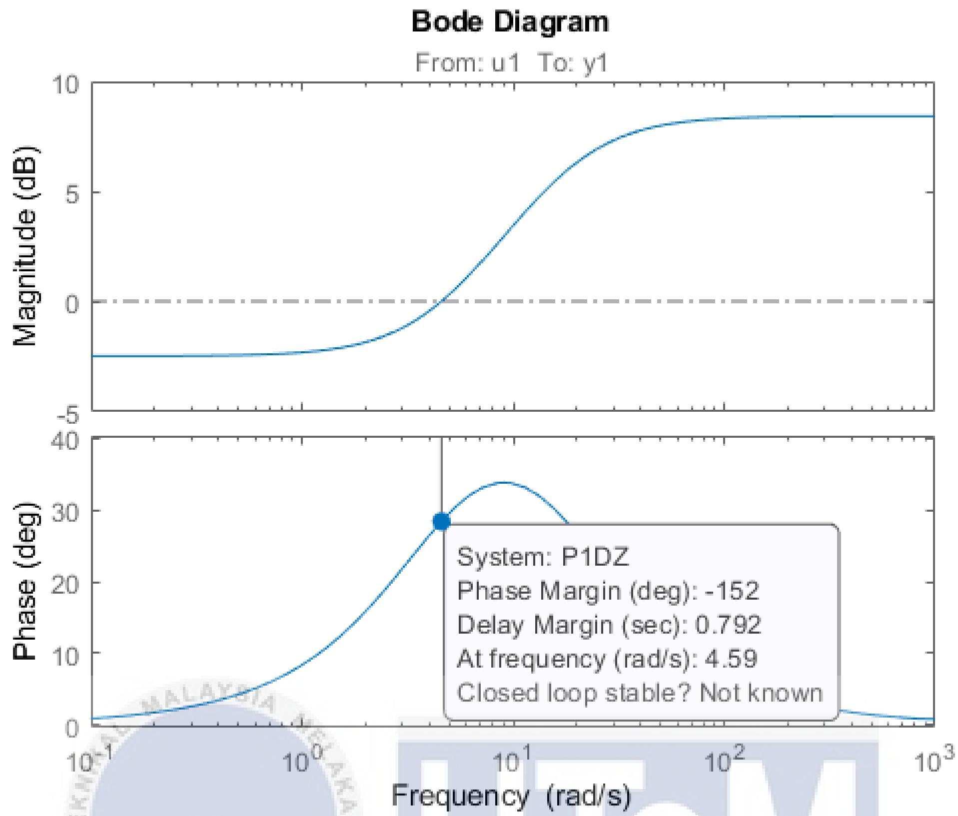

Figure 4.4: Bode diagram of P1DZ for System A

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Furthermore, based on the comparison of step response of P1Z and P1DZ as shown in Figure 4.5 and Figure 4.6 respectively, the original amplitude of 5 based on transfer function of the system was severely altered away in the case of P1Z with delay when compared with the amplitude of P1Z without delay. As the system originally has no delayed response due to the nature of the program, adding a delay will cause the input of process modelling estimation to be based on a wrongly guided past data according to its timeframe. Thus, the accuracy of process model estimation P1DZ was significantly lowered as compared to P1Z.

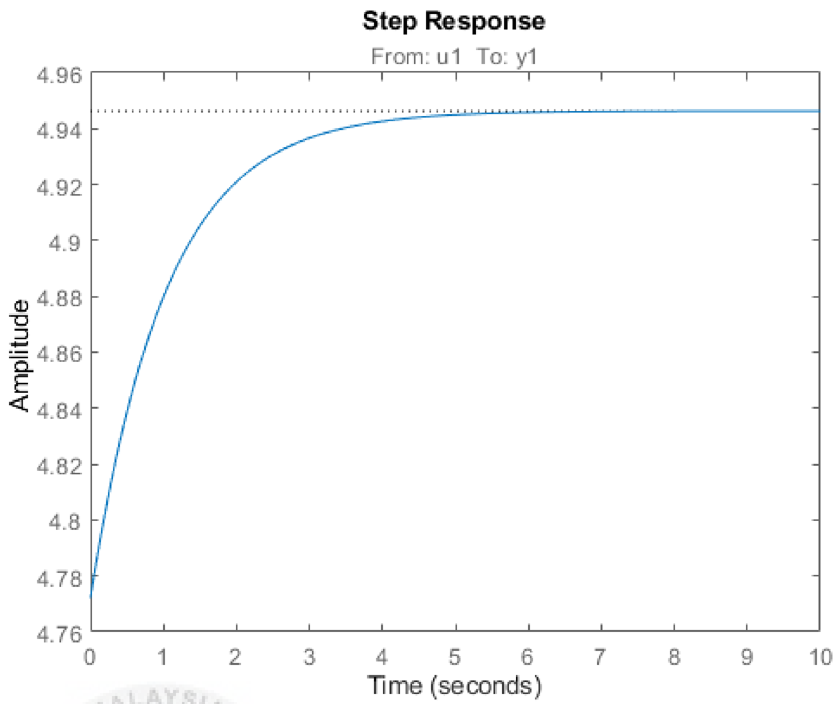

Figure 4.5: Step response of P1Z for System A

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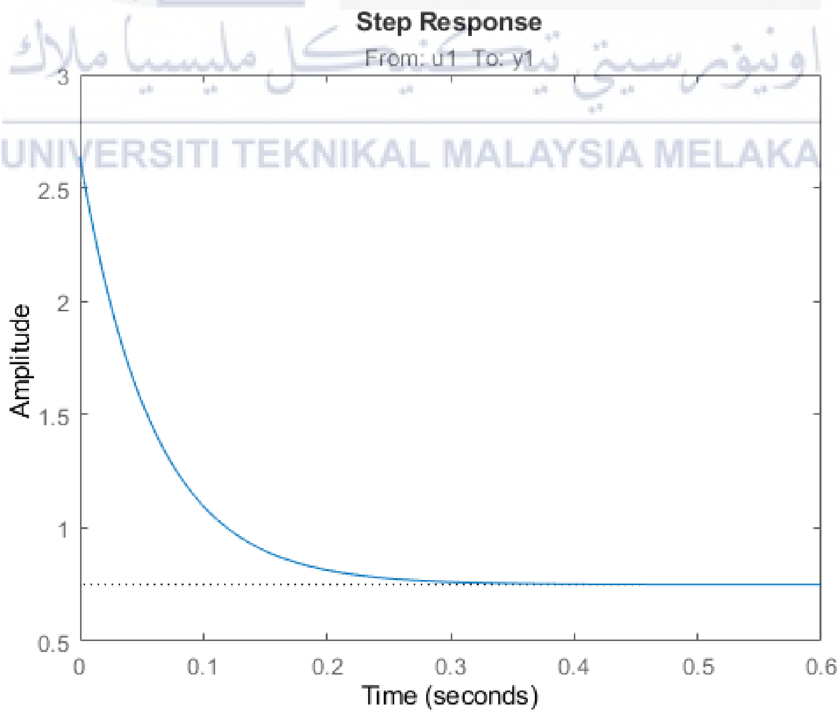

Figure 4.6: Step response of P1DZ for System A

4.2.4 Process Model Estimation with 2 Poles

Table 4.2: Summary of findings of process model estimation with 2 poles of System A

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P2	$G(s) = \frac{-0.29247}{(1+0.031351s)(1+0.031351s)}$	0.906	8.957	8.804
P2Z	$G(s) = -0.2034 + \frac{1-0.097749s}{(1+0.043724s)(1+0.0098879s)}$	0.6417	9.012	8.809
P2D	$G(s) = \frac{1.7594}{(1+1.0245s)(1+1.528e^{-5}s)} \times \exp(-2.1202s)$	-0.4269	8.978	8.775
P2I	$G(s) = \frac{-1761.6}{s(1+0.00038125s)(1+10000s)}$	0.1287	8.806	8.657
P2DZ	$G(s) = 0.56487 \times \frac{1-0.27718s}{(1+0.14024s)(1+0.0041998s)} \times \exp(-0.07912s)$	-0.4025	8.952	8.7

Table 4.2, continued

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P2DI	$G(s) = \frac{-2560.4}{s(1 + 2.7241e^{-5}s)(1 + 10000s)} \times \exp(-0s)$	0.1747	8.902	8.701
P2IZ	$G(s) = -16.506 \times \frac{1 + 323.59s}{s(1 + 10000s)(1 + 0.010645s)}$	0.4164	8.972	8.769
P2DIZ	$G(s) = -1493.1 \times \frac{1 + 3.3859s}{s(1 + 7.3779e^{-7}s)(1 + 9546.6s)} \times \exp(-3.2s)$	-0.131	8.903	8.652

Best fit index of all models with 2 poles were observed to be unacceptable as none of them scored a best fit index of 90% and above as shown in Table 4.2. Thus, addition in the number of poles outside the environment of an ideal case does not always increase in accuracy as the number of orders increase. As the quality of the model had already been degraded when the number of poles was added to 2, models with higher order of 3 poles will no longer be experimented. All of the model output best fit index with 2 poles were shown in Figure 4.7.

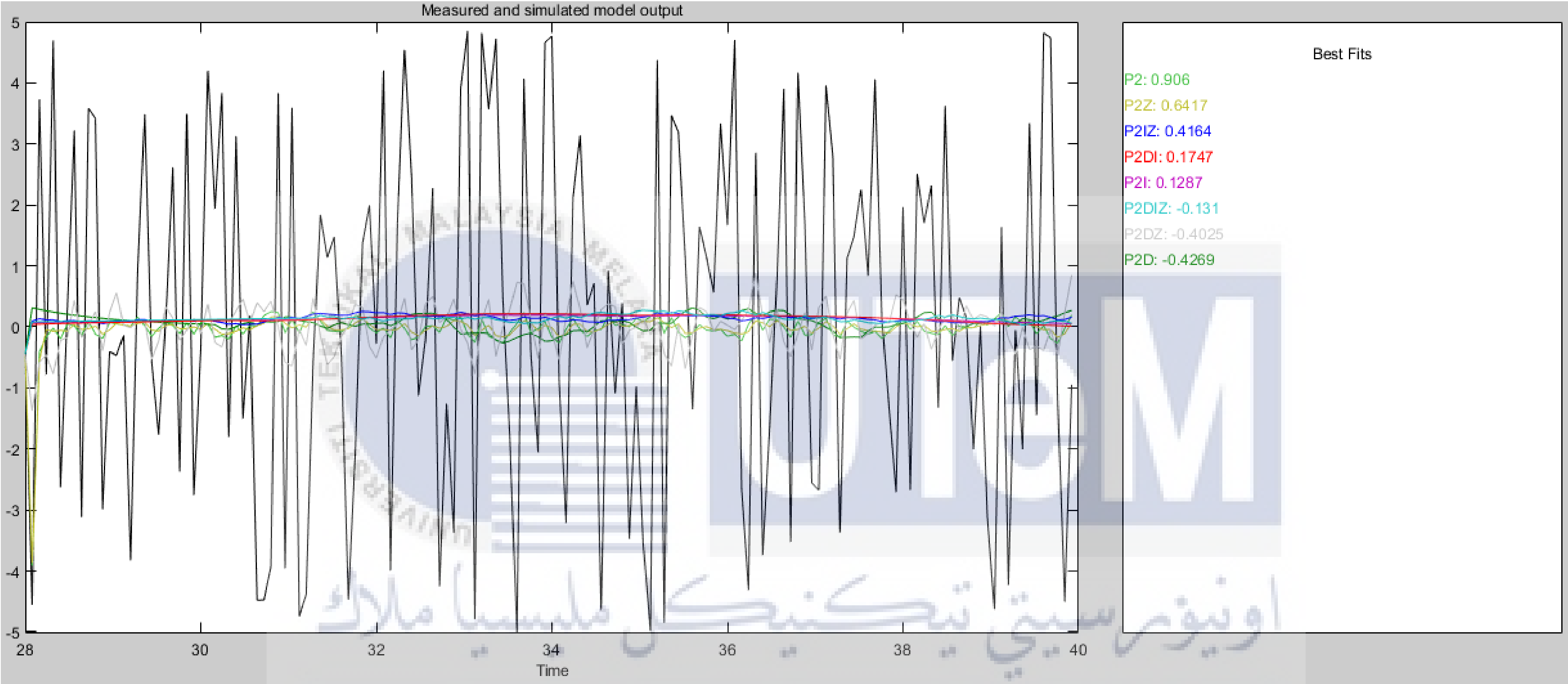

Figure 4.7: Model output of all models with 2 poles for System A

4.2.5 Discussion on the Addition of Poles

Both P1Z and P2Z are compared with the transfer function of System A. From mathematical aspect, comparison could be made by converting the s-domain transfer function into t-domain transfer function. The result of the conversion of P1Z and P2Z yield the following transfer function respectively:

P1Z,

$$y(t) = 4.77189 \ldots \delta(t) + 0.16802 \ldots e^{-0.96339 \ldots t} \tag{4.4}$$

P2Z,

$$y(t) = -0.2034\delta(t) + 95.62542 \ldots e^{-22.87073 \ldots t} - 321.71907 \ldots e^{-101.1337 \ldots t} \tag{4.5}$$

By comparing both Eq. (4.4) and Eq. (4.5) with Eq. (4.1), results were distinct whereby Eq. (4.4) yields an approximately close equation with Eq. (4.1), whereas Eq. (4.5) was a lot different from Eq. (4.1).

Comparison of zeros and poles plot between P1Z and P2Z as shown in Figure 4.8 also proved that the addition of pole had caused the response to damp out within 0.3 seconds (Figure 4.9) and become the main reason contributing towards instability of the model. The instability was then further amplified as the zero plot was located in the RHP which further contributes towards a larger downgrade towards the model.

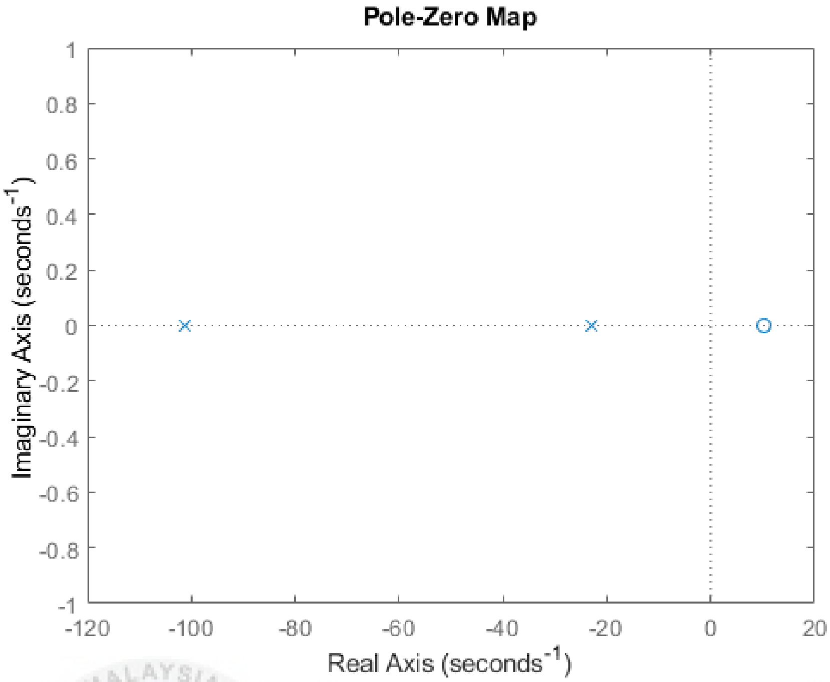

Figure 4.8: Pole-zero plot of P2Z for System A

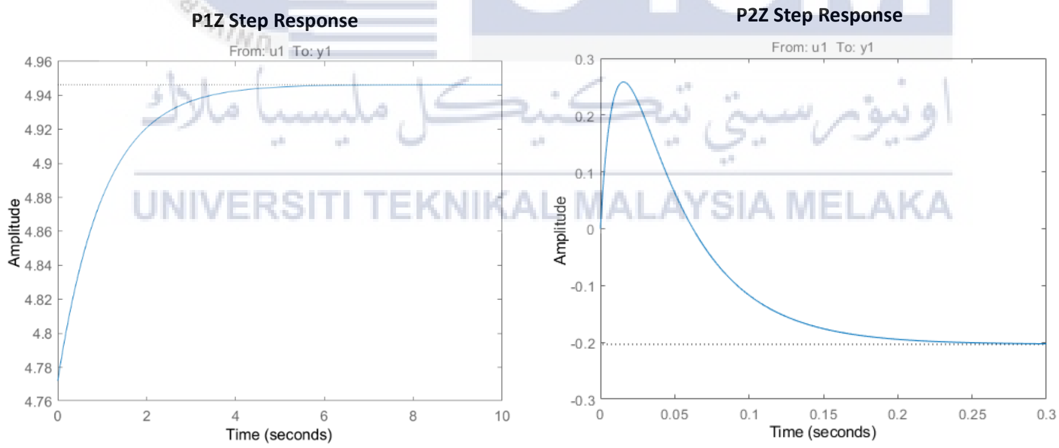

Figure 4.9: Step response of P1Z and P2Z for System A

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4.3 System B

The goal of process model estimation for System B is to validate the discussions made based on System A. As the difference between transfer function of System A and System B is mainly on the natural response being amplified by 25 times while maintaining the same forced response, the simulated data of System B should prove to yield a higher best fit model of 1 pole with zero via process model estimation of SI. The model P1Z must also be the best out of all other output models to prove the discussions being made upon the influence of zero and delay in the previous section.

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Table 4.3: Summary of findings of process model estimation with 1 pole of System B

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P1	$G(s) = \frac{-0.12731}{1 + 0.010092s}$	-0.5157	8.24	8.146
P1Z	$G(s) = 4.9864 + \frac{1 + 2.1246s}{1 + 2.119s}$	**99.79**	**3.516e-05**	**3.456e-05**
P1D	$G(s) = \frac{-2223.1}{1 + 10000s} \times \exp(-0s)$	0.05082	8.289	8.148
P1I	$G(s) = \frac{28.764}{s(1 + 7054.6s)}$	0.2495	8.14	8.048
P1DZ	$G(s) = -8544.8 \times \frac{1 - 4.0935s}{1 + 9595.6s} \times \exp(-0s)$	**72.65**	**0.6611**	**0.6461**
P1DI	$G(s) = \frac{-98.665}{s(1 + 10000s)} \times \exp(-0s)$	0.2451	8.194	8.054
P1IZ	$G(s) = 6.0869 \times \frac{1 - 6.5362s}{s(1 + 7.7352s)}$	1.916	7.883	7.749
P1DIZ	$G(s) = -93.596 \times \frac{1 - 6.092s}{s(1 + 8891.2s)} \times \exp(-0s)$	0.2073	8.223	8.037

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Based on the findings as shown in Table 4.3, results were within expectations as the model P1Z ranks highest with a best fit index of 99.79%, followed by the model P1DZ with a best fit index of 72.65%. Hence, discussions being made based on System A were validated via the data being simulated from an amplified natural response version of System B. All of the model output best fit index with 1 pole were shown in Figure 4.10.

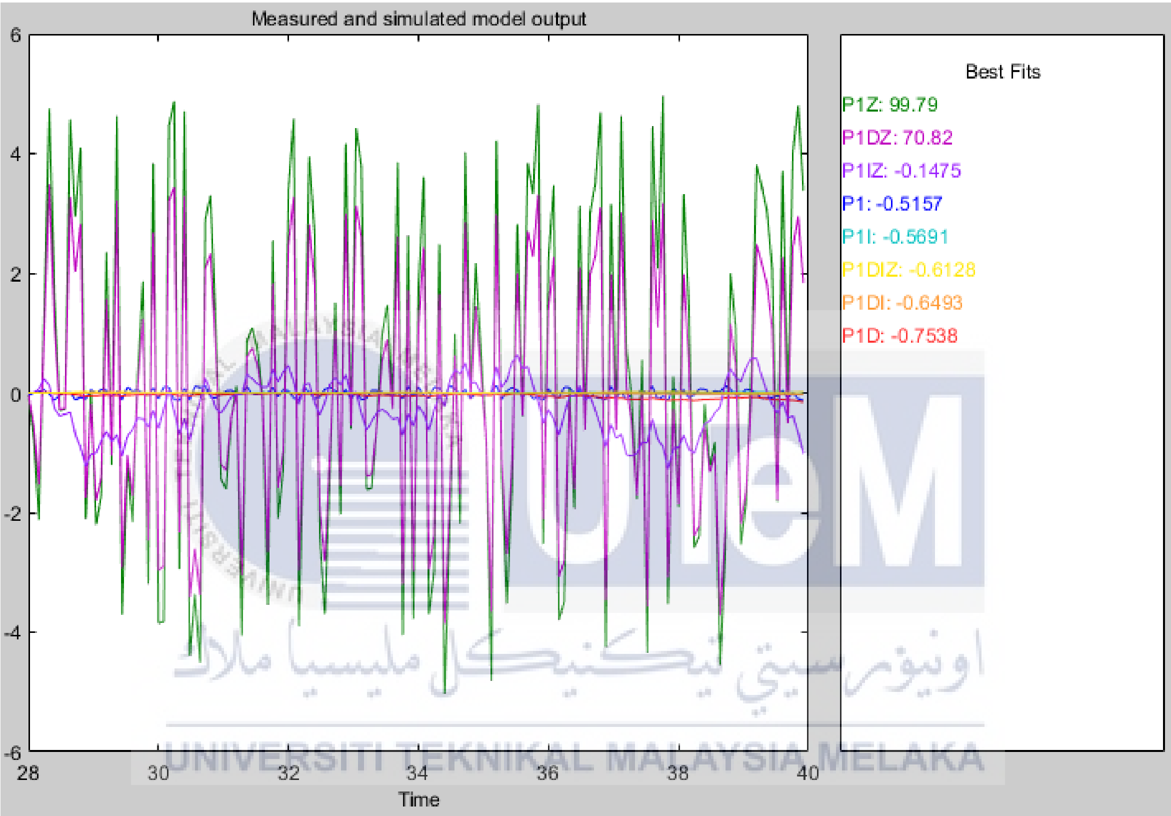

Figure 4.10: Model output of all models with 1 pole for System B

4.4 System C

The transfer function embedded in System C is a second-order transfer function which aims to analyse and discuss whether the influence of poles directly reflects upon the number of orders of the transfer function of a system. Process model estimation of 1 and 2 poles were carried out for the analysis and discussion of this subtopic.

Table 4.4: Summary of findings of process model estimation with 1 pole of System C

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P1	$G(s) = \frac{2.933}{1 + 1.7989s}$	-0.8636	8.667	8.568
P1Z	$G(s) = 5.3332 + \frac{1 + 0.053819s}{1 + 0.056633s}$	**95.22**	**0.57**	**0.5603**
P1D	$G(s) = \frac{0.78785}{1 + 0.077399s} \times \exp(-0.0384s)$	-0.6823	8.757	8.608
P1I	$G(s) = \frac{0.065715}{s(1 + 13.157s)}$	-0.9817	8.643	8.447
P1DZ	$G(s) = 0.79126 \times \frac{1 + 0.0062911s}{1 + 0.07764s} \times \exp(-0.04488s)$	-0.6832	8.807	8.608
P1DI	$G(s) = \frac{-3562.6}{s(1 + 10000s)} \times \exp(-0s)$	-1.523	8.534	8.294
P1IZ	$G(s) = -0.79163 \times \frac{1 - 24.166s}{s(1 + 1828s)}$	-0.9777	8.683	8.438
P1DIZ	$G(s) = -3547.4 \times \frac{1 + 5.499s}{s(1 + 9826.2s)} \times \exp(-0.15776s)$	-6.379	8.413	8.129

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Table 4.5: Summary of findings of process model estimation with 2 poles of System C

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P2	$G(s) = \frac{2.9387}{(1+1.8092s)(1+5.5561e^{-11}s)}$	-0.07726	8.716	8.568
P2Z	$G(s) = 2.9636 + \frac{1+0.35011s}{(1+2.4296s)(1+0.09452s)}$	0.4694	8.753	8.555
P2D	$G(s) = \frac{-253.36}{(1+1.8604e^{-6}s)(1+10000s)} \times \exp(-0.32s)$	0.9177	8.878	8.677
P2I	$G(s) = \frac{-526.32}{s(1+0.00010055s)(1+10000s)}$	1.652	8.796	8.646
P2DZ	$G(s) = 0.053887 \times \frac{1+13253s}{(1+1662.4s)(1+1.0384e^{-8}s)} \times \exp(-3.2s)$	0.1704	8.873	8.623
P2DI	$G(s) = \frac{-1183.2}{s(1+0.0092673s)(1+10000s)} \times \exp(-0s)$	1.666	8.52	8.186
P2IZ	$G(s) = 3.8461 + \frac{1-31.97s}{s(1+6524.9s)(1+51.549s)}$	0.9487	8.861	8.661
P2DIZ	$G(s) = -0.49127 + \frac{1+12321s}{s(1+10000s)(1+0.00028816s)} \times \exp(-3.2s)$	1.546	8.659	8.272

Based on the comparison of results as shown in Table 4.4 and Table 4.5, the increase of number of poles did not contribute towards a higher best-fit index. The rationale behind this occurrence is due to the fixed input, $u(t)$ of the system. Due to the narrow range of the input [-1,1], the second-order transfer function do not have sufficient range to stage its nature of oscillation within its time plot as shown in Figure 4.11.

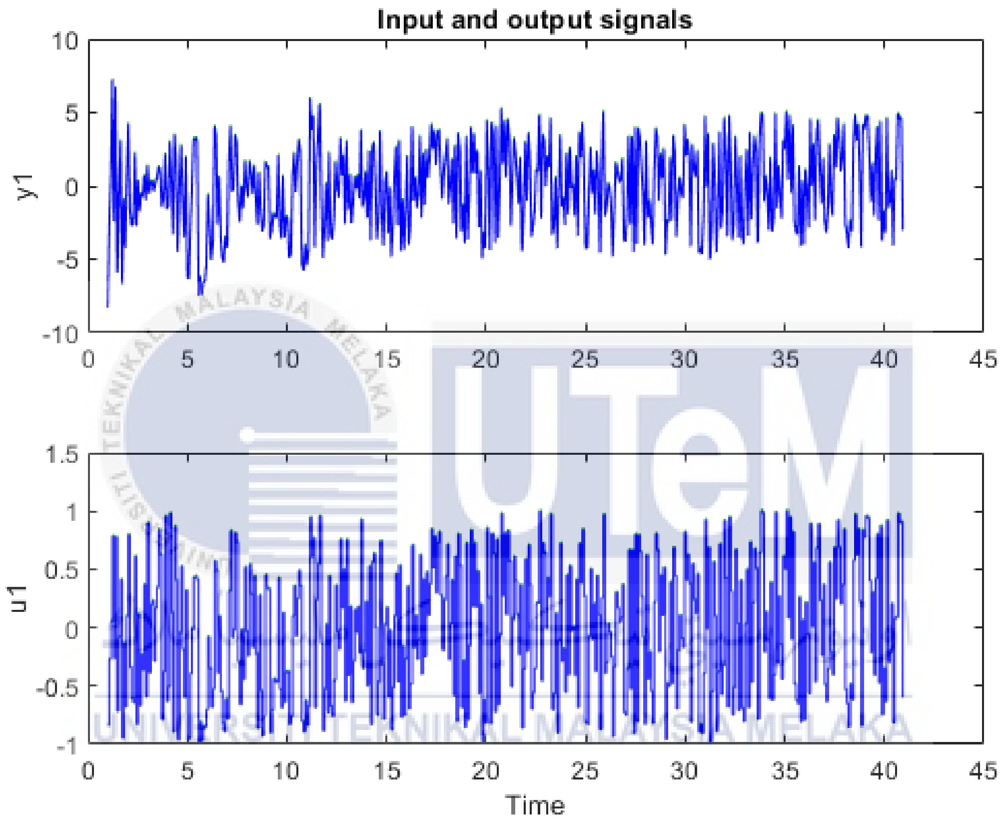

Figure 4.11: Input and output signals of System C

Therefore, due to the insufficient range for oscillation, the nature of the output had been decreased as if it was fast-forwarded towards the end stage of the output whereby the data had already begun to be stabilised. Thus, the best-fit index result of P1Z is higher than P2Z (Figure 4.12 and Figure 4.13) due to the oscillation of data was no longer distinguished enough to be taken into account by the process model estimation.

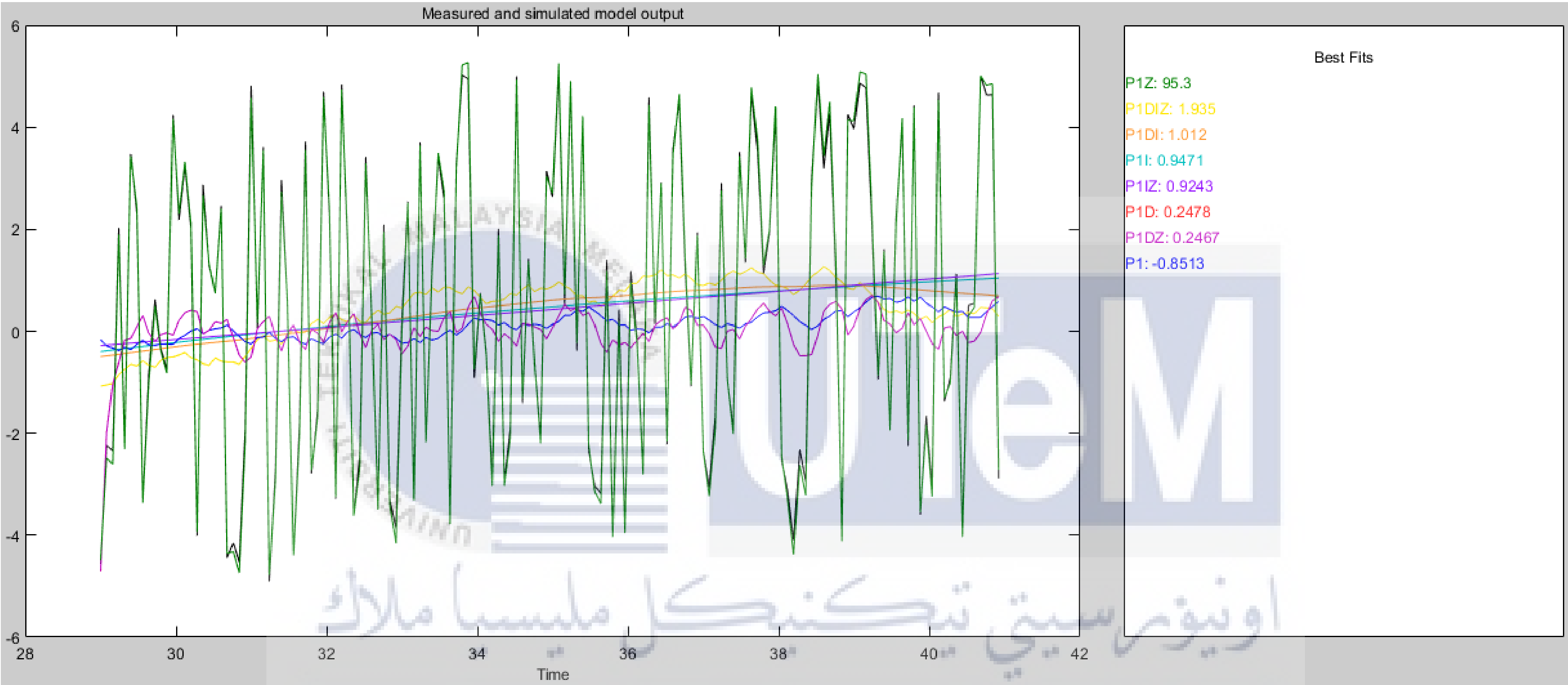

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Figure 4.12: Model output of all models with 1 pole for System C

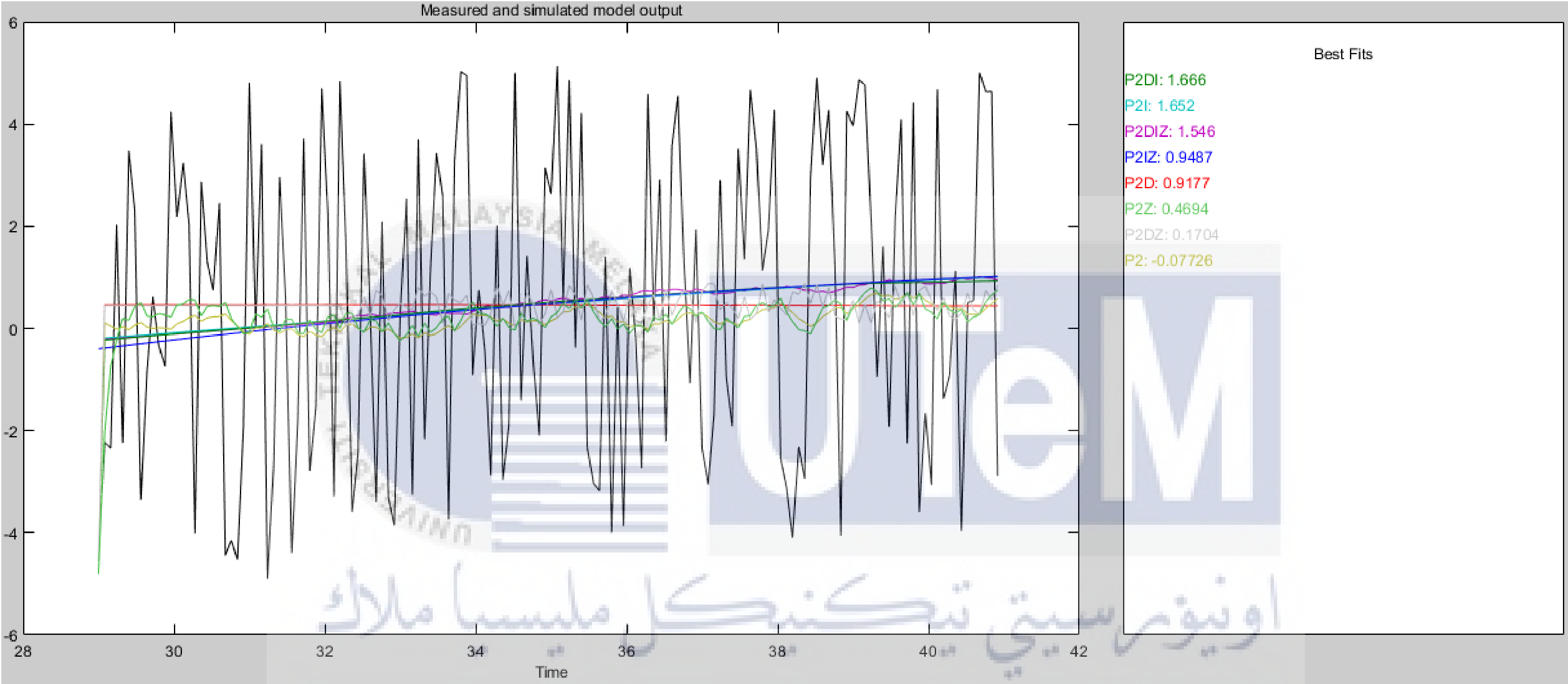

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Figure 4.13: Model output for all models with 2 poles for System C

4.5 Real Industrial Data of Air Compression System

An air compression system consists of two-lines, whereby the supply is labelled in red segment, while demand is labelled in blue segment as shown in Figure 4.14. The supply-line consists of components such as compressors and air treatment systems which include air dryers and filters. Meanwhile, the demand-line consists of secondary tank, end-user facility, and distribution system such as piping.

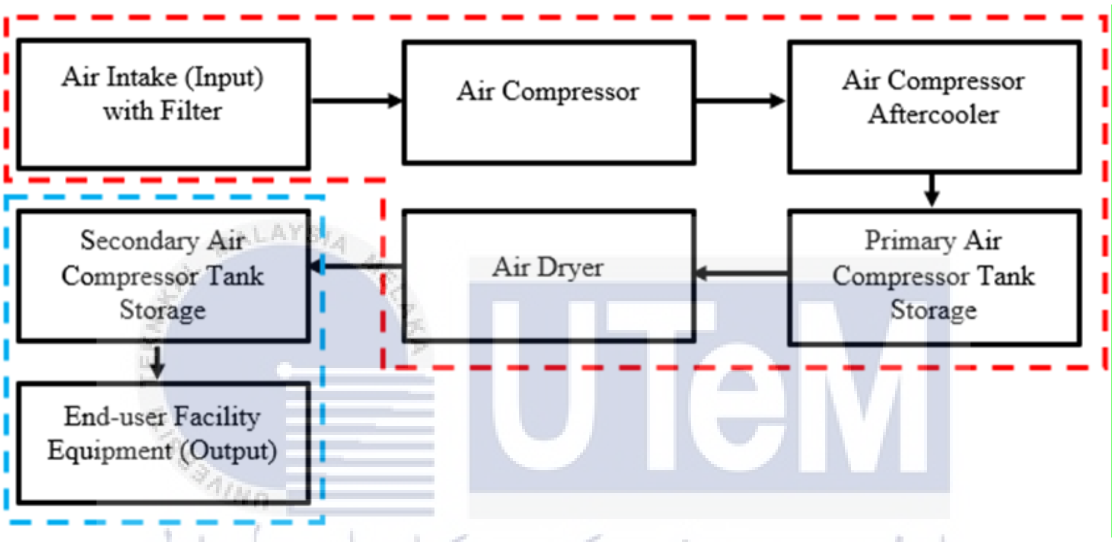

Figure 4.14: Typical air compression system block scheme

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Based on the data given, the input consists of the rate of electricity usage of the compressed dry air plant, while the output consists of the manufacturing plant compressed air usage. Both input and output were average value of continuous 24-hours data from the Supervisory Control and Data Acquisition (SCADA) system. The data acquisition period lasted from January 2018 to December 2018 (363 days) as shown in Figure 4.15.

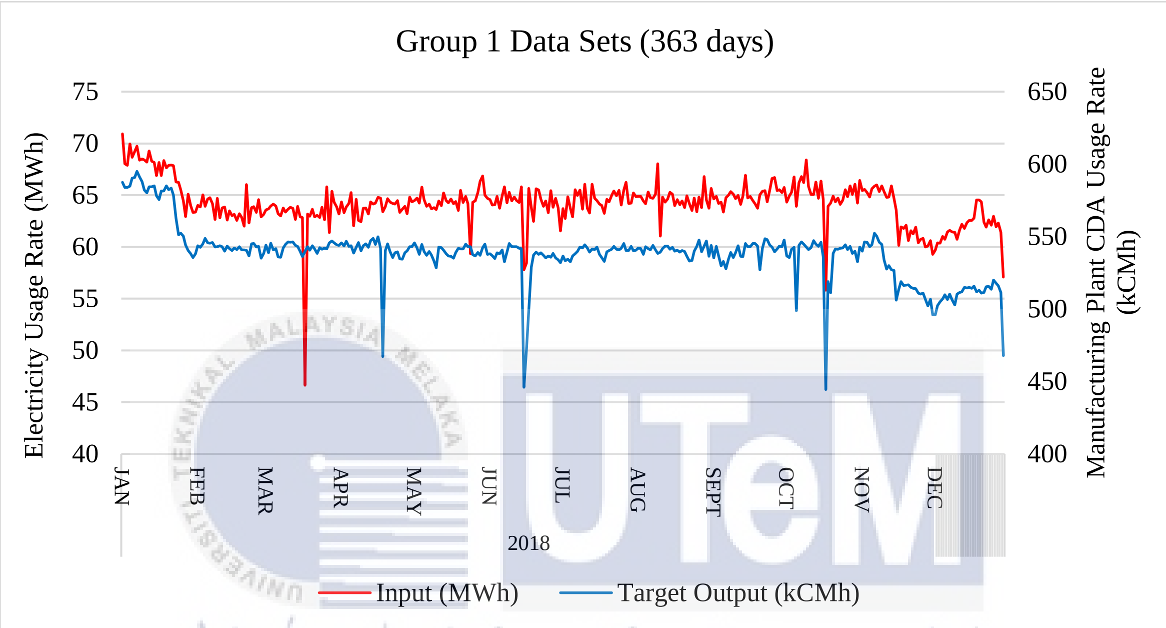

Figure 4.15: Input and output of an air compression system

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4.5.1 Process Model Estimation

Due to the unknown number of orders within the transfer function of the air compression system, process model estimation was carried out from 1 pole to 3 poles. Addition of zero, delay, and integrator were tested out for all number of poles for the analysis and discussion of their significance in comparison with the general behaviour of an air compression system.

Table 4.6: Summary of findings of process model estimation with 1 pole of air compression system

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P1	$G(s) = \frac{-1.4315}{1 + 75.662s}$	-1.452	257.8	251.8
P1Z	$G(s) = -0.16189 + \frac{1 + 1.6545s}{1 + 1.2263s}$	-19.84	121.4	117.7
P1D	$G(s) = \frac{-0.043218}{1 + 2.7836s} \times \exp(-3.9054s)$	-17.25	126.4	122.5
P1I	$G(s) = \frac{0.012644}{s(1 + 2.0461s)}$	15.18	116.8	113.2
P1DZ	$G(s) = -1.6919 \times \frac{1 - 1.3427s}{(1 + 2.259s)} \times \exp(-0s)$	-14.74	104.5	100.5
P1DI	$G(s) = \frac{-0.94314}{s(1 + 0.005859s)} \times \exp(-2.7725s)$	5.323	195.2	187.7
P1IZ	$G(s) = -6.0884 + \frac{1 + 38.753s}{s(1 + 2876.9s)}$	25.03	214.9	206.6
P1DIZ	$G(s) = -1.1024 + \frac{1 - 0.076359s}{s(1 + 0.048049s)} \times \exp(-2.4845s)$	6.069	190.7	181.9

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Table 4.7: Summary of findings of process model estimation with 2 poles of air compression system

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P2	$G(s) = \frac{1172.5}{(1+10000s)(1+3710.2s)}$	25.13	207.4	199.4
P2Z	$G(s) = -2.9019 + \frac{1-1.1558s}{(1+1.5322s)(1+0.40732s)}$	-19.01	101.9	97.18
P2D	$G(s) = \frac{7.2006}{(1+1.9483e^{-6}s)(1+0.19309s)} \times \exp(-0s)$	15.73	175.9	170.5
P2I	$G(s) = \frac{6.3729}{s(1+0.025954s)(1+10000s)}$	25.4	223	212.7
P2DZ	$G(s) = 107.15 \times \frac{1+146.68s}{(1+3629.4s)(1+1.8066e^{-7}s)} \times \exp(-0.0736s)$	23.7	210.5	202.4
P2DI	$G(s) = \frac{-1.1493}{s(1+0.0068089s)(1+0.0068065s)} \times \exp(-2.2811s)$	5.615	188	177.9
P2IZ	$G(s) = 0.051653 + \frac{1-118.18s}{s(1+6.2517s)(1+0.67996s)}$	24.27	115.9	109.7
P2DIZ	$G(s) = 6.8149 + \frac{1+461.58s}{s(1+10000s)(1+8894.6s)} \times \exp(-9.0989s)$	**25.76**	**153.4**	**144.1**

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Table 4.8: Summary of findings of process model estimation with 3 poles of air compression system

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P3	$G(s) = \frac{-14.545}{(1 + 0.011757s)(1 + 0.26042s)(1 + 9534.1s)}$	2.172	213.1	201.8
P3Z	$G(s) = -81.719 + \frac{1 - 100.09s}{(1 + 10000s)(1 + 0.0043482s)(1 + 3677.6s)}$	25.37	208.3	195.6
P3D	$G(s) = \frac{1.3138}{(1 + 1.1539s)(1 + 1.4113s)(1 + 4.0835s)} \times \exp(-1.8294s)$	8.833	114	107.1
P3I	$G(s) = \frac{2.0251}{s(1 + 169.15s)(1 + 0.049136s)(1 + 0.25164s)}$	**25.75**	**185.1**	**173.8**
P3DZ	$G(s) = 1.0566 \times \frac{1 + 0.12177s}{(1 + 0.048324s)(1 + 0.25919s)(1 + 6.6697s)} \times \exp(-3.0895s)$	-10.84	168.5	157
P3DI	$G(s) = \frac{9323.5}{s(1 + 10000s)(1 + 10000s)(1 + 10000s)} \times \exp(-9.652s)$	**27.24**	**132.2**	**123.2**

Table 4.8, continued

Name of Model	Transfer Function	Best Fit Index (%)	FPE	MSE
P3IZ	$G(s) = -8.7926 + \frac{1 + 1062.8s}{s(1 + 0.0029452s)(1 + 4046.8s)(1 + 9921.9s)}$	**25.87**	**153.4**	**143**
P3DIZ	$G(s) = 3.7464 + \frac{1 + 158.96s}{s(1 + 10000s)(1 + 0.0061174s)(1 + 10000s)} \times \exp(-9.9015s)$	**25.87**	**154.7**	**143**

Based on the results of Table 4.6, Table 4.7, and Table 4.8, the top 5 best fit index models placed in bold were P2DIZ, P3I, P3DI, P3IZ, and P3PIZ as shown in Figure 4.16. Discussion on the rationale of the models having a higher best fit index compared to the others is carried out on the upcoming subtopic.

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Figure 4.16: Model output for the top 5 models for air compression system

4.5.2 Discussion on the Top 5 Process Model Estimation Results

The data used for the process model estimation based on a real industrial air compression data is considered complex due to the occurrence of random disturbance of the environment. Thus, complexity of the system will contribute to a higher order of transfer function model as shown by the result of P2DIZ and P3DIZ, whereby the best fit index increases along with the number of poles from a best fit index of 25.76% to 25.87%.

As for the influence of delay in the top best fit model of P3DI (27.24%), the air compression system consists the component of air dryer which takes time to be heated up towards its optimum operational temperature. Inclusion of delay contributed towards a better process model estimation of the initial start-up of the system which took time for the air dryer to reach its optimum operational temperature, whereby a higher amount of rate of electricity and compressed air were used as shown in Figure 4.17.

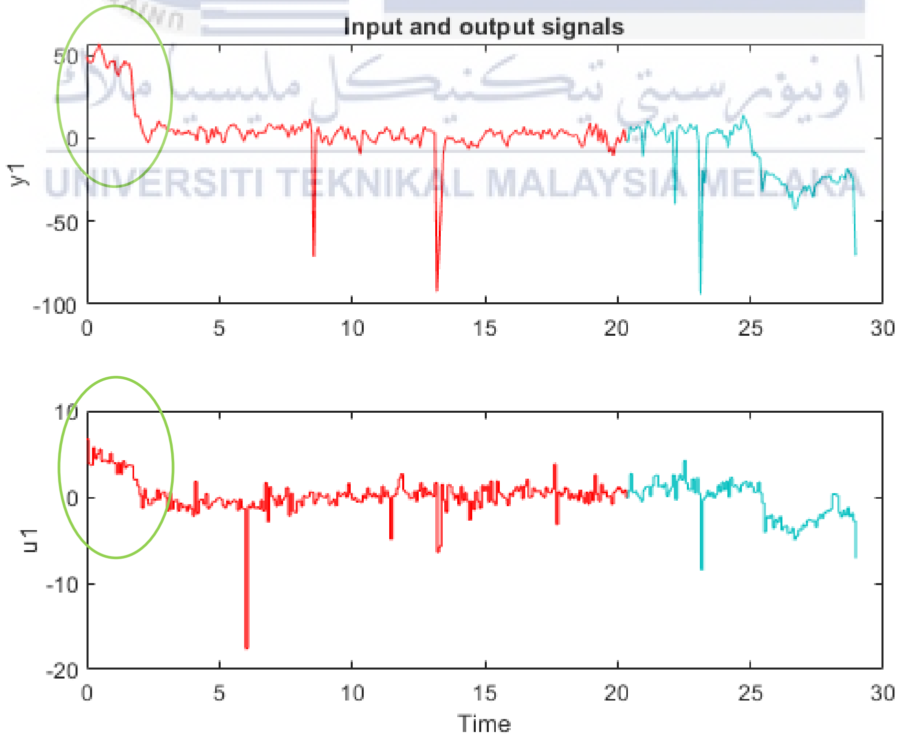

Figure 4.17: Input and output signals of air compression system

The top 5 models also possessed a similarity of the inclusion of integrator. As the data is based on discrete real time value of both input and output of the air compression system, process model estimation will be better in predicting the trend instead of its future discrete value based on past data. By achieving a best fit based on the trend instead of its discrete value, the model will serve better purpose in ensuring the estimation is not altered away from the wanted output or the purpose of the air compression system.

The exclusion of zero from a 3 poles model with delay and integrator contributed towards a higher best fit index as the zero is not located at the LHP as shown in Figure 4.18. The argument also aligns with the statement made by Nise (2015), whereby he mentioned that addition of LHP zeros to transfer function increases step response and stability. Therefore, the addition of zero in the case of P3DIZ did not significantly contributed towards a higher best fit index compared to the model P3DI without zero.

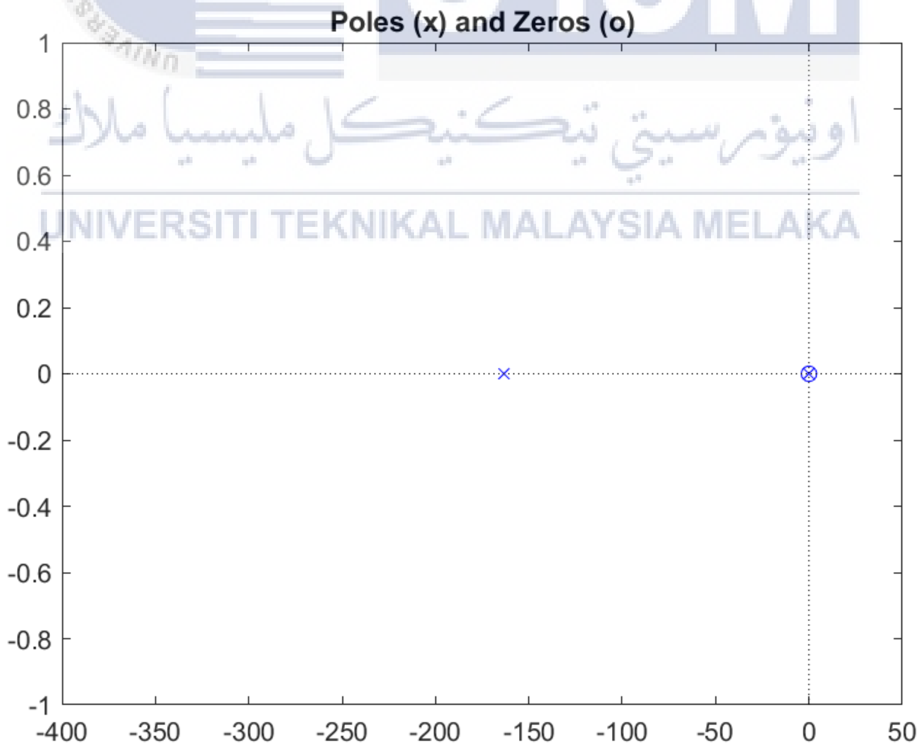

Figure 4.18: Location of zero of P3DIZ in plane

4.6 Summary of Result and Discussion

4.6.1 Poles

The order of a system is indirectly reflected by the number of poles within a model. However, effects such as response damping may be caused by the addition of poles, depending on the location of plot of the added pole. In real life system, increasing the number of order or poles do not always increase the best fit index of a model.

4.6.2 Zeros

Zeros are proved to be a guide in providing the value of amplitude, or as a gain factor. Stability and step response of a system are also increased when zero was added on a LHP of the transfer function. However, adding a right-half-plane (RHP) zero to transfer function will decelerate the step response as undershoot may take place. Inverse response might exhibit in such cases as well.

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4.6.3 Delays

Understanding of a system is needed before deciding on the inclusion of delay, as effects such as phase shift and margin reduction may cause a reduction in damping ratio of a system. This will provoke more oscillatory response along with reduced gain-margin, leading the system to move closer to instability. Such example was proven on the case of System A analysis as the system originally has no delayed response due to the nature of the program, adding a delay will cause the input of process modelling estimation to be based on a wrongly guided past data according to its timeframe.

4.6.4 Integrators

As overshoot was not included within all the tested systems, results shown that integrators being added will degrade the best fit index of the model. The reasoning behind the degradation is similar with delay, as process model estimation is based on previous data, adding an integrator into a system which does not undergo overshoot will only cause the input of process modelling estimation to be based on a wrongly guided past data according to its timeframe. Thus, the accuracy of process model estimation was significantly lowered.

However, in the case of real industrial data of air compression system, integrators do contribute in trend prediction even though overshoot did not exhibit. The nature description of integrator is somehow similar with the effect of having a damper, whereby it restricts the range of model estimation from going out of track, thus ensuring that the trend curve is kept within the desired range and direction of the system as shown previously in Figure 4.16.

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CHAPTER 5

CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

In this project, system identification was performed using process model estimation to investigate the significance of different number of poles, zero, delay, and integrator in process model. Analysis on the behaviour of simulated data of System A, B, and C were carried out to grasp a better understanding on the aspects in effects of pole, zero, delay, and integrator before leaping into a real industrial data of air compression system to analyse and discuss whether the significance of aspects remain the same in the process model estimation of real world condition. The order of a system is indirectly reflected by the number of poles within a model, while zero affects the stability and step response of a system. Delay is dependent on the nature of the system whereby a time lag exhibits to reach an optimum operating level, whereas integrator contributes in trend prediction of a system by restricting the range of model estimation from going out of track. An overall understanding of the real system will indeed be needed to relate the rationale behind the significance of pole, zero, delay, and integrator in order to understand its contribution towards a better prediction model. Furthermore, best fit index may not always be that satisfying due to the 70:30 settings of working and validation data, as the validation data extracted from the system may have unwanted condition such as disturbance. Lastly, recommendation of research in estimated process model via SI could be tried out in the real world to test whether the estimated range of model is able to alert whenever a process began to go off track from the trend of the

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process model to ensure its purposed functionality is preserved for a better reliability of a system.

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APPENDICES

APPENDIX A: Gantt Chart for PSM 1

Week	**PSM 1**														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Literature Review															
MATLAB's Toolbox Familiarisation															
Trial Run in MATLAB															
Discussion on Trial Run Result															

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APPENDIX B: Gantt Chart for PSM 2

Week	**PSM 2**													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Data Acquisition	■	■	■	■										
Simulation of System Identification using Process Model			■	■	■	■	■	■						
Analysis and Discussion									■	■	■	■		
Conclusion and Recommendation													■	■

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APPENDIX C: Input Data Set of System A (By Rows)

0.4897	-0.5148	-0.5499	-0.4258	-0.8974	-0.6742	-0.6649	0.9987	-0.9058	-0.2043
-0.5408	0.3664	-0.1241	-0.9883	0.6022	0.8649	0.6529	0.5852	-0.5531	0.169
-0.4191	0.7241	0.9824	0.6544	-0.5021	-0.2018	0.601	0.6429	-0.291	0.1445
0.4849	-0.2217	0.9127	0.6994	0.2446	0.9269	0.001	-0.8197	0.7688	0.5634
0.2396	-0.1087	-0.6076	-0.0334	0.597	-0.6819	0.4045	0.9474	0.2874	-0.1962
0.9705	0.8672	-0.0319	0.7753	-0.2093	-0.1953	0.8027	0.3063	-0.9278	0.1343
0.4922	0.0466	0.924	-0.9395	0.0394	0.7801	-0.5406	-0.3782	0.304	-0.4491
0.7601	0.5118	0.5665	0.9571	-0.8987	-0.3487	-0.5394	0.2063	-0.1031	0.0276
-0.7839	-0.0982	0.6108	0.7445	-0.5606	0.9171	-0.0963	-0.8818	0.0136	-0.1456
0.5034	0.8836	0.6581	0.0775	0.4533	0.7551	-0.4114	0.8526	0.1622	0.3025
-0.8881	0.0578	-0.5752	0.405	-0.1109	-0.8853	0.5924	-0.3094	0.0404	-0.8528
0.5501	0.5651	-0.6963	0.5697	-0.5444	0.6591	0.1414	-0.428	0.5925	-0.1076
-0.4419	0.8073	0.4944	0.3793	-0.753	-0.7085	-0.8533	0.4458	-0.0147	0.7802
-0.4356	-0.9271	0.946	-0.3817	0.8315	-0.3358	-0.0007	0.1663	-0.9413	-0.9359
-0.32	-0.5079	0.8754	-0.892	0.363	-0.7719	0.2357	-0.8614	0.5778	-0.5243
-0.7904	0.3964	0.3011	-0.3472	-0.7649	-0.9605	0.9407	-0.0652	-0.4196	0.1162
-0.4656	0.7968	-0.1863	-0.4891	0.9095	-0.4998	-0.8628	0.1832	0.2718	0.0034
0.5919	0.2017	0.0315	0.8416	-0.4448	0.8346	0.9484	-0.7776	-0.2072	-0.377
-0.8163	-0.4096	-0.7889	-0.4345	-0.9987	0.1016	-0.9155	-0.7381	0.6009	-0.7254
-0.1901	0.1504	-0.5711	0.9784	0.3897	-0.9304	0.6029	-0.8334	-0.2663	0.0495
0.6338	-0.7526	0.2758	0.7919	0.089	0.5209	-0.2343	0.4677	0.6795	0.6564
-0.741	-0.9118	0.4675	-0.2403	-0.202	-0.6864	-0.3719	-0.506	-0.1823	-0.7127
-0.8337	-0.9392	0.4001	0.3598	0.7014	0.8035	-0.2837	-0.4881	-0.0665	-0.1376
-0.1953	0.7125	-0.2528	-0.562	-0.1332	-0.8591	0.3598	0.7168	0.2147	-0.6754
0.543	-0.1579	0.1715	0.4572	-0.4939	0.5164	-0.8624	0.4741	0.554	-0.149
0.7115	0.0472	0.4079	0.1354	0.6859	0.878	-0.9973	-0.8251	-0.9544	-0.3179
0.8523	-0.3238	-0.319	0.0156	-0.2314	0.2558	-0.0528	-0.833	-0.106	0.7553
-0.1252	-0.0642	-0.067	-0.0251	-0.8289	0.7768	0.7232	0.7456	-0.7206	0.9611
0.7928	-0.9718	-0.5378	0.45	0.1767	-0.5117	-0.9796	0.916	-0.9288	-0.5061
0.6298	0.7597	-0.2949	0.1704	0.2961	-0.7205	-0.5164	0.7147	0.9442	0.6708
-0.9003	0.8863	0.6129	0.5792	-0.9009	0.3069	0.9457	0.1357	-0.4878	-0.1064
-0.8033	-0.9447	0.7999	-0.7596	0.4122	-0.9303	0.9142	0.2765	-0.5671	0.4462
0.1649	-0.8159	-0.0177	-0.3205	-0.6582	0.3953	0.3327	-0.1334	-0.6136	-0.462
0.8896	0.3584	0.5507	0.896	-0.4626	0.5444	0.3618	-0.2397	-0.2341	-0.0554
0.9517	0.6926	-0.076	0.9824	0.8509	0.1349	0.649	0.2927	-0.0469	-0.9703
-0.0569	-0.8806	0.7793	-0.1245	0.9705	-0.4925	0.09	0.674	-0.5926	0.7499
0.7127	-0.5643	-0.0516	-0.0612	0.0055	-0.7354	0.2059	0.7296	-0.0845	-0.322
0.054	0.5567	-0.4424	0.7293	-0.5202	-0.0412	0.8694	0.4178	0.7994	-0.3282
0.6562	-0.2677	0.0697	-0.8633	-0.8633	-0.7532	0.7979	-0.7596	0.7501	-0.9162
-0.8468	-0.0869	0.3985	0.2574	0.3247	-0.065	-0.8637	-0.384	0.3048	0.4302
-0.024	0.872	-0.7657	0.3698	0.9403	0.5207	-0.1941	-0.0087	0.4874	-0.8208
-0.2208	-0.6413	0.8103	0.9996	-0.9262	0.9952	0.747	0.9751	0.1285	-0.3243
-0.9727	0.8454	-0.0522	-0.3821	0.964	0.9852	-0.1479	-0.6135	0.4533	0.6582
0.1039	0.1756	-0.8956	0.2171	-0.1874	0.1106	-0.6616	-0.1637	-0.6803	-0.9642
0.9043	-0.9382	0.7254	0.6685	0.2579	-0.2406	0.3607	0.2639	0.1428	0.6994
0.3649	0.9739	-0.4994	-0.8312	0.6012	-0.7167	-0.2992	0.1748	0.8107	-0.6741
0.8632	0.3714	-0.4794	-0.5025	0.8216	0.5892	-0.6423	0.254	0.3279	0.48
0.2007	0.8447	0.054	-0.2397	-0.5118	0.4253	-0.5022	0.5345	0.3706	0.4934
-0.2322	0.7549	-0.0778	0.1285	0.0634	-0.3704	0.0315	-0.591	-0.895	0.3571
-0.8169	0.0199	-0.3679	0.7012	-0.259	0.9951	0.981	-0.204	-0.8707	-0.1592

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APPENDIX D: Output Data Set of System A (By Rows)

0.4517	-0.856	-1.2435	-1.1639	-2.8344	-2.3489	-2.5046	3.9823	-3.7863	-0.8867
-2.3956	1.6749	-0.5654	-4.6389	2.8555	4.1537	3.157	2.8425	-2.7073	0.8364
-2.0659	3.5784	4.8566	3.2487	-2.4941	-1.0017	2.9838	3.2094	-1.4519	0.7246
2.4249	-1.1083	4.5587	3.4889	1.2239	4.6229	0.0054	-4.0882	3.8411	2.8093
1.193	-0.5364	-3.0413	-0.1703	2.9942	-3.4144	2.0197	4.7462	1.4441	-0.9785
4.8534	4.3402	-0.1568	3.8703	-1.0365	-0.9733	4.0233	1.5238	-4.6365	0.6807
2.4643	0.2283	4.6207	-4.6934	0.1883	3.897	-2.7107	-1.8962	1.5113	-2.25
3.7995	2.5612	2.8249	4.7926	-4.4942	-1.7409	-2.6954	1.0336	-0.525	0.1363
-3.9203	-0.4901	3.0581	3.7134	-2.804	4.5911	-0.4846	-4.4042	0.0619	-0.7347
2.5143	4.4085	3.2931	0.3905	2.2582	3.766	-2.0634	4.2543	0.8137	1.52
-4.4341	0.2931	-2.8751	2.0343	-0.5629	-4.424	2.9656	-1.538	0.211	-4.2699
2.7586	2.8214	-3.4746	2.844	-2.7255	3.3021	0.7083	-2.1358	2.9614	-0.5385
-2.2061	4.0448	2.4672	1.889	-3.7712	-3.541	-4.2599	2.2375	-0.0705	3.902
-2.1684	-4.6392	4.7274	-1.9161	4.1504	-1.6709	-0.0012	0.8353	-4.7061	-4.6727
-1.5932	-2.5377	4.3677	-4.4698	1.8168	-3.8538	1.1699	-4.3145	2.8808	-2.6264
-3.9446	1.9867	1.5056	-1.7329	-3.8314	-4.7931	4.6962	-0.3228	-2.0931	0.5797
-2.323	3.9883	-0.9229	-2.4451	4.5429	-2.4906	-4.3182	0.9099	1.3648	0.02
2.9542	1.0006	0.1644	4.2079	-2.2208	4.1732	4.7359	-3.8922	-1.0374	-1.8814
-4.0832	-2.0521	-3.9425	-2.1796	-4.9977	0.5155	-4.5694	-3.6836	3.013	-3.6269
-0.9569	0.754	-2.8551	4.8917	1.947	-4.6564	3.0113	-4.1666	-1.3269	0.2535
3.1629	-3.7566	1.3693	3.9599	0.4473	2.6115	-1.1796	2.3354	3.3949	3.2757
-3.6972	-4.5555	2.3365	-1.192	-1.0113	-3.4354	-1.8515	-2.5335	-0.9072	-3.5562
-4.1692	-4.691	1.9947	1.8002	3.508	4.0161	-1.4189	-2.4318	-0.3374	-0.6838
-0.9831	3.5642	-1.2698	-2.8096	-0.6609	-4.2886	1.7915	3.578	1.0743	-3.3866
2.7201	-0.7982	0.851	2.2868	-2.461	2.5897	-4.3183	2.3747	2.77	-0.7428
3.5611	0.2319	2.0373	0.6846	3.4375	4.3963	-4.9964	-4.1301	-4.7735	-1.5885
4.2577	-1.612	-1.6025	0.0851	-1.153	1.278	-0.2548	-4.1694	-0.5282	3.7757
-0.6209	-0.3137	-0.3349	-0.1311	-4.1531	3.8786	3.6202	3.7369	-3.6052	4.8085
3.9637	-4.8566	-2.6885	2.2521	0.8823	-2.5597	-4.896	4.5717	-4.6364	-2.5404
3.142	3.7906	-1.4725	0.8552	1.4789	-3.5974	-2.5791	3.5654	4.7115	3.3608
-4.5005	4.4281	3.0667	2.9022	-4.5087	1.5344	4.7335	0.6744	-2.4312	-0.5257
-4.0094	-4.7157	3.9998	-3.8044	2.0677	-4.6465	4.568	1.3793	-2.8296	2.2265
0.8227	-4.0888	-0.093	-1.6067	-3.293	1.9706	1.6621	-0.6735	-3.0656	-2.3087
4.4521	1.8014	2.7555	4.4712	-2.3031	2.7216	1.8073	-1.2042	-1.18	-0.2801
4.7596	3.4612	-0.3733	4.9125	4.2591	0.6837	3.2542	1.4611	-0.226	-4.8583
-0.2835	-4.3999	3.8885	-0.6267	4.8546	-2.4699	0.4566	3.3767	-2.962	3.7418
3.5715	-2.8298	-0.2511	-0.3078	0.02	-3.6697	1.0248	3.6392	-0.418	-1.612
0.2777	2.775	-2.2146	3.6451	-2.5993	-0.198	4.3535	2.094	3.9884	-1.6508
3.2811	-1.3438	0.3441	-4.3246	-4.3184	-3.7673	3.9865	-3.7968	3.7473	-4.5879
-4.2293	-0.4314	1.9939	1.2945	1.631	-0.332	-4.3144	-1.9167	1.5248	2.1512
-0.12	4.3575	-3.8337	1.8559	4.6957	2.6051	-0.9703	-0.0405	2.4331	-4.0974
-1.0986	-3.2141	4.0591	5.0052	-4.6303	4.9764	3.7265	4.8838	0.6412	-1.6171
-4.866	4.2278	-0.2612	-1.9013	4.8202	4.925	-0.7453	-3.0609	2.267	3.291
0.5139	0.8711	-4.4741	1.08	-0.9346	0.5456	-3.318	-0.8186	-3.398	-4.8284
4.5308	-4.691	3.6221	3.349	1.2798	-1.1947	1.8011	1.3144	0.7238	3.4925
1.8217	4.8609	-2.4907	-4.1551	3.011	-3.5846	-1.4966	0.867	4.0561	-3.3693
4.3218	1.8562	-2.3954	-2.5159	4.1157	2.9544	-3.2112	1.2783	1.6375	2.4064
0.9951	4.2147	0.2626	-1.1923	-2.5514	2.124	-2.5157	2.6634	1.8553	2.4764
-1.1657	3.7808	-0.397	0.6364	0.314	-1.8476	0.1635	-2.9515	-4.4691	1.7946
-4.0762	0.1018	-1.8477	3.499	-1.2927	4.9759	4.8996	-1.016	-4.3486	-0.7898

APPENDIX E: Input Data Set of System B (By Rows)

-0.4756	0.7567	-0.1182	0.1265	0.5361	0.1747	0.722	-0.2922	-0.4926	-0.4036
-0.2774	0.4118	-0.9875	0.803	0.1942	-0.75	0.6354	0.724	-0.3246	-0.3644
0.0965	0.6837	0.8062	0.4902	0.4349	-0.1084	0.061	0.3554	0.0625	-0.8666
-0.4367	0.3697	0.2163	0.7617	-0.7952	-0.6942	-0.6889	-0.0912	0.6626	0.4254
0.4172	0.0116	0.5796	-0.5314	0.2388	-0.7548	-0.4311	-0.1774	0.8702	-0.8956
0.4953	-0.0141	0.8785	0.08	-0.8081	0.639	-0.6086	0.3686	0.9808	-0.1515
0.167	0.3203	0.1137	-0.0242	-0.5724	-0.2387	-0.245	-0.5174	0.0459	-0.5644
0.722	0.2308	0.9097	-0.2304	0.5935	-0.6824	0.6955	0.1724	0.1502	0.6188
-0.0402	-0.4838	-0.5453	-0.6615	-0.6042	0.6474	0.6045	0.7188	-0.5924	-0.8128
-0.5696	-0.3206	0.0137	-0.2108	0.2131	-0.1969	0.841	-0.4288	-0.7145	0.2214
-0.2333	0.7746	-0.7236	-0.1565	0.9183	0.962	-0.8075	0.0005	0.9533	-0.1982
-0.478	0.9285	-0.4017	-0.9971	-0.1912	0.9012	-0.4247	0.1644	-0.8538	-0.426
0.4496	-0.3042	0.9071	0.5365	0.8378	0.4043	-0.2298	-0.9265	0.2901	0.0357
-0.405	0.7828	-0.5802	0.7758	0.9336	-0.6693	0.3114	-0.4973	-0.5332	0.2669
-0.5857	0.7727	-0.6822	-0.047	0.7514	-0.8054	-0.93	0.9771	-0.2466	0.527
0.4519	-0.0822	-0.3218	-0.2016	-0.5479	-0.3509	0.0253	0.8092	-0.234	0.3834
0.8491	-0.0347	-0.4942	-0.6074	0.0874	-0.2359	0.6784	-0.1662	-0.5718	0.3504
-0.3074	-0.657	-0.0147	0.5501	0.6897	0.6925	-0.2335	-0.0722	0.3906	0.0926
0.1418	0.7275	-0.6426	0.5036	0.9659	-0.6491	0.8188	0.1412	-0.6467	0.0969
-0.0122	-0.6024	-0.9474	0.066	0.2044	-0.7302	0.2811	0.3507	0.6844	-0.6963
0.642	-0.34	0.6126	0.9995	-0.149	-0.1994	-0.1514	0.9761	-0.2918	-0.417
-0.9543	-0.5127	0.0572	0.9479	-0.762	0.1871	-0.151	-0.8585	0.2842	0.4005
-0.8302	-0.5024	0.406	0.0946	0.2611	0.2686	0.8184	-0.3292	-0.1202	0.4405
-0.5745	-0.451	0.1187	-0.1394	0.3078	-0.678	0.0102	-0.0393	0.5543	0.4231
0.4584	0.0345	-0.5636	-0.8346	-0.9561	-0.6416	-0.6368	-0.5725	0.5367	0.8189
-0.1265	0.1301	-0.7478	-0.9958	0.5326	-0.7223	-0.6973	0.6173	0.3768	0.4586
0.2539	0.1466	0.8121	-0.3229	-0.0495	0.0616	0.419	0.3162	-0.5414	-0.6673
-0.5945	-0.9682	-0.9486	-0.4048	0.7247	-0.622	0.8825	-0.7841	0.4931	-0.8574
0.6998	-0.9912	0.7227	0.6907	0.4924	0.018	0.6622	-0.661	-0.2243	-0.4571
0.483	0.4193	-0.6518	0.2819	0.7067	-0.769	-0.2791	-0.5708	0.3094	0.5716
-0.0154	-0.7373	0.8515	-0.4812	0.0446	-0.0418	0.209	-0.0191	0.5453	-0.1142
-0.8244	0.3112	0.1141	-0.7792	0.622	0.7638	-0.9745	-0.6644	-0.7967	0.8665
-0.2781	-0.8641	-0.9208	-0.6998	-0.1459	0.4485	0.0805	-0.9899	0.8537	0.6493
0.9943	0.8391	-0.7894	0.5277	-0.7915	-0.5619	-0.3594	-0.4803	-0.6235	-0.9366
0.1337	-0.5749	-0.7091	-0.9743	-0.0295	-0.7179	0.3821	-0.0223	-0.7751	0.2771
-0.0028	-0.147	-0.4188	0.2667	0.9555	0.3235	-0.0524	-0.0488	0.9193	0.5955
0.8244	-0.4134	0.0083	-0.434	-0.3374	0.4748	-0.235	0.9305	-0.7359	-0.234
-0.4263	0.0704	0.3789	-0.6311	0.7701	-0.7637	-0.7595	0.8988	0.9797	-0.583
0.9467	-0.8729	-0.6675	-0.8956	0.5866	0.6641	0.2437	-0.2814	-0.3166	-0.0789
0.027	-0.8056	0.1796	0.2227	0.1515	-0.0005	-0.7019	0.5133	-0.4129	-0.2498
0.6836	0.9203	-0.7746	-0.0384	0.7955	0.5426	-0.4751	-0.7328	-0.2301	0.3058
-0.4	0.8379	-0.115	0.8906	0.7648	-0.3165	-0.3144	-0.094	0.1982	0.2988
-0.0134	0.7756	-0.8033	0.5281	-0.7494	0.3525	0.7269	-0.7331	-0.5948	0.5023
-0.9995	-0.4523	0.2025	-0.4314	0.8075	0.0106	0.4385	0.1499	-0.1549	-0.9547
0.8479	-0.2664	-0.6973	-0.2984	0.5681	-0.0704	0.7728	0.6703	0.9678	-0.4997
0.4565	0.6997	-0.7517	-0.6941	0.0213	-0.3788	0.6305	-0.1033	0.6068	0.7044
0.9414	-0.8429	0.6351	-0.0674	0.93	0.1491	-0.0091	-0.348	0.1166	-0.862
0.8949	0.4209	0.9969	-0.6998	0.0609	-0.3764	0.6695	0.2804	-0.5097	-0.4737
-0.0326	-0.2374	-0.1589	-0.9036	-0.5216	0.4046	0.2218	-0.5021	-0.3594	0.0711
0.7669	0.6955	0.614	0.4209	-0.3581	0.7464	0.0008	0.8086	0.9661	0.6813

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APPENDIX F: Output Data Set of System B (By Rows)

-2.3602	3.7743	-0.5995	0.6332	2.6752	0.8728	3.613	-1.4643	-2.4538	-2.0248
-1.3822	2.063	-4.9403	4.0113	0.9668	-3.7521	3.1865	3.6116	-1.6282	-1.8123
0.4875	3.4119	4.0231	2.4555	2.1674	-0.5419	0.3121	1.7834	0.3215	-4.3324
-2.1838	1.8428	1.0781	3.8011	-3.9667	-3.4779	-3.4527	-0.4524	3.3188	2.1266
2.095	0.0539	2.8928	-2.6577	1.1962	-3.7813	-2.1507	-0.8803	4.3491	-4.4765
2.4731	-0.0762	4.3924	0.3944	-4.0493	3.2005	-3.0351	1.8461	4.8945	-0.7577
0.8267	1.5926	0.5725	-0.1185	-2.8593	-1.2015	-1.2296	-2.5847	0.2275	-2.8149
3.6058	1.1595	4.5569	-1.1586	2.9598	-3.4146	3.4792	0.8703	0.741	3.0959
-0.2055	-2.4194	-2.7356	-3.3124	-3.0188	3.2432	3.0265	3.5994	-2.9522	-4.0607
-2.8534	-1.6092	0.0773	-1.0522	1.0697	-0.9775	4.2099	-2.1381	-3.5723	1.111
-1.162	3.864	-3.6106	-0.7843	4.5964	4.8046	-4.04	0.0041	4.7662	-0.9813
-2.3867	4.646	-2.0076	-4.9777	-0.9601	4.505	-2.1318	0.8149	-4.2674	-2.1326
2.2554	-1.5116	4.5298	2.6848	4.1913	2.0263	-1.1539	-4.633	1.4463	0.1735
-2.0219	3.9212	-2.9029	3.874	4.6704	-3.34	1.5579	-2.4959	-2.669	1.3443
-2.9233	3.8627	-3.4046	-0.2426	3.7599	-4.019	-4.659	4.8894	-1.233	2.6259
2.2633	-0.4094	-1.6157	-0.9997	-2.7423	-1.7627	0.1333	4.0506	-1.1741	1.9247
4.2371	-0.1807	-2.4632	-3.0448	0.4332	-1.1738	3.3954	-0.8279	-2.8568	1.7539
-1.5396	-3.2793	-0.0762	2.7453	3.4547	3.4597	-1.1605	-0.3595	1.9623	0.4659
0.7175	3.6311	-3.2181	2.5118	4.8336	-3.2385	4.1033	0.7073	-3.2331	0.478
-0.0604	-3.0095	-4.7405	0.3265	1.0191	-3.6425	1.4088	1.7582	3.4221	-3.4837
3.2036	-1.6909	3.0574	4.989	-0.7471	-1.0048	-0.7546	4.875	-1.4639	-2.0913
-4.7724	-2.5562	0.2944	4.741	-3.8017	0.9433	-0.7531	-4.2839	1.4129	2.0002
-4.1567	-2.5175	2.0351	0.4739	1.3154	1.3448	4.0933	-1.6367	-0.5987	2.2062
-2.8808	-2.2479	0.5929	-0.6915	1.5424	-3.3911	0.0484	-0.1994	2.7691	2.1152
2.3006	0.1806	-2.8106	-4.1738	-4.7745	-3.2146	-3.1801	-2.8664	2.6834	4.0858
-0.631	0.6571	-3.743	-4.9698	2.668	-3.6144	-3.4867	3.0892	1.8868	2.3004
1.2632	0.7263	4.0521	-1.613	-0.2415	0.3023	2.0878	1.5838	-2.7133	-3.3435
-2.9634	-4.8318	-4.7337	-2.0235	3.6313	-3.1067	4.4218	-3.9271	2.4565	-4.2874
3.5089	-4.9552	3.6217	3.4611	2.4542	0.0836	3.3197	-3.2975	-1.1237	-2.2781
2.414	2.1053	-3.2639	1.4155	3.5317	-3.8535	-1.3887	-2.8481	1.5374	2.8662
-0.0702	-3.6813	4.264	-2.4117	0.2211	-0.199	1.0537	-0.0968	2.7314	-0.5799
-4.1158	1.5465	0.5751	-3.9016	3.103	3.8275	-4.8749	-3.3211	-3.9926	4.3417
-1.3878	-4.3264	-4.6046	-3.4892	-0.7203	2.2441	0.4067	-4.9441	4.2588	3.2516
4.9659	4.1983	-3.9514	2.6445	-3.9581	-2.8009	-1.7896	-2.394	-3.1121	-4.6803
0.6662	-2.8687	-3.5458	-4.8778	-0.1409	-3.5848	1.9014	-0.102	-3.8706	1.3873
-0.0124	-0.7434	-2.0929	1.342	4.7696	1.6194	-0.2647	-0.2408	4.5882	2.9792
4.114	-2.076	0.0466	-2.1756	-1.688	2.374	-1.1667	4.6551	-3.6773	-1.16
-2.1276	0.3459	1.8854	-3.1647	3.8572	-3.8202	-3.7963	4.489	4.8957	-2.9115
4.7359	-4.3672	-3.3429	-4.4699	2.9304	3.3256	1.2165	-1.4154	-1.5823	-0.3916
0.1415	-4.0289	0.8919	1.1043	0.7641	-0.004	-3.5189	2.5726	-2.0721	-1.2425
3.4211	4.6103	-3.87	-0.2006	3.9777	2.7042	-2.3724	-3.6612	-1.1453	1.5268
-2.003	4.1884	-0.5759	4.4472	3.8144	-1.577	-1.5696	-0.4796	0.9928	1.491
-0.063	3.8691	-4.0134	2.6505	-3.7495	1.7598	3.6304	-3.6618	-2.9668	2.51
-5.0047	-2.2542	1.0089	-2.1584	4.0461	0.0555	2.1831	0.7403	-0.7753	-4.7824
4.2402	-1.3348	-3.4933	-1.4953	2.84	-0.3594	3.8674	3.3547	4.8488	-2.496
2.2824	3.4921	-3.7685	-3.4698	0.104	-1.904	3.1552	-0.5217	3.0403	3.5213
4.7138	-4.2198	3.1738	-0.3278	4.6554	0.7537	-0.0524	-1.7441	0.5743	-4.3169
4.4806	2.114	4.994	-3.49	0.2961	-1.8739	3.3377	1.4082	-2.5574	-2.3765
-0.1644	-1.1794	-0.7987	-4.5238	-2.6177	2.0133	1.1074	-2.5075	-1.8052	0.3489
3.8377	3.4827	3.0728	2.108	-1.7899	3.723	0.0027	4.0454	4.8321	3.4057

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APPENDIX G: Input Data Set of System C (By Rows)

-0.8414	-0.2754	0.0493	0.778	-0.2674	0.7724	-0.7157	-0.0814	0.4072	-0.9482
-0.1418	-0.6798	0.0954	0.7906	-0.342	-0.6079	-0.6453	0.6019	-0.8339	0.108
-0.6705	-0.2347	-0.3639	0.3638	-0.5893	0.8897	-0.3861	0.1951	0.2258	-0.2891
0.1687	0.3402	0.8396	0.6202	-0.7863	-0.3827	0.9513	-0.6355	-0.5079	0.9776
0.1243	-0.8937	0.8596	0.4033	-0.967	-0.046	0.5179	-0.1927	-0.5961	0.3159
-0.9685	-0.9502	-0.3972	-0.0137	0.4281	0.4358	0.4064	-0.9827	-0.8136	-0.968
-0.8617	-0.8457	-0.7081	-0.0818	-0.3527	-0.6841	-0.5301	0.5685	0.4851	-0.3914
0.0886	-0.5505	-0.8243	-0.891	-0.6204	-0.782	0.3149	0.8244	-0.0855	-0.0249
0.8054	0.7306	-0.2974	-0.658	-0.0226	-0.4453	0.5108	-0.0327	-0.2427	0.5354
0.2852	-0.1749	0.436	-0.2268	-0.858	0.2712	-0.5437	-0.9259	-0.7633	0.4483
0.3317	0.328	-0.8995	-0.7114	-0.4443	-0.4684	-0.4635	0.4208	-0.5307	-0.6906
0.1204	-0.6419	-0.3807	-0.3799	-0.8319	-0.7653	0.0939	0.3516	-0.0684	0.2431
0.4821	0.3542	-0.8066	-0.8915	-0.6285	-0.8394	-0.6783	0.9402	0.6075	0.7619
-0.6885	0.2314	0.5422	0.9503	-0.1406	-0.8845	-0.5273	0.0238	-0.7262	0.4367
-0.6771	-0.7586	-0.4549	0.3536	-0.0342	-0.1868	0.7497	0.1695	0.4945	-0.6316
0.7462	-0.4079	0.1751	-0.6438	-0.2911	0.1467	-0.0425	0.1723	-0.2153	0.9205
-0.3505	-0.2069	0.2139	-0.498	0.5181	-0.8307	0.5597	0.629	-0.001	-0.7507
-0.4649	0.7332	-0.3174	-0.7874	0.0244	0.1695	-0.5918	-0.029	-0.8733	-0.5153
0.094	0.4582	-0.4625	0.5281	-0.7699	-0.167	-0.7505	-0.2733	0.3479	-0.6986
-0.4851	0.7004	-0.1741	0.0954	-0.2734	-0.1025	0.6163	-0.4023	0.4083	-0.2461
0.4666	0.1057	0.3688	0.8401	0.5137	0.7763	0.2991	0.7279	0.8134	0.2737
-0.1919	0.2341	0.4392	0.7064	-0.2763	0.0305	0.4015	-0.5804	0.6014	-0.8016
0.7955	0.5271	-0.6872	-0.2908	-0.8548	0.7172	-0.7901	-0.1574	0.8306	0.1833
0.7228	0.1765	0.4758	-0.5665	0.1924	-0.9803	-0.6261	-0.8181	0.8495	0.2575
-0.8228	0.7987	0.6286	-0.7234	0.7474	-0.6578	-0.0658	0.9725	0.2742	0.8051
0.1105	0.8261	0.5667	-0.5053	0.0693	0.6	0.3952	0.1111	-0.2316	0.3597
-0.8566	-0.3572	0.5797	-0.1996	0.7048	0.361	-0.6983	-0.5636	-0.3536	0.2062
0.2112	0.9936	-0.457	0.7212	0.6352	-0.0052	0.4212	0.263	0.9669	-0.7054
-0.5716	0.1167	-0.9027	-0.1109	0.7193	-0.2913	-0.1867	-0.5553	0.446	-0.406
0.5229	-0.028	0.001	-0.4132	0.4058	-0.6846	0.7163	0.384	0.8371	0.2674
-0.8184	-0.8318	-0.0762	0.4946	-0.1035	0.199	-0.3756	0.4379	0.1066	-0.8707
0.2507	0.9634	-0.3939	-0.3038	0.0262	-0.0467	-0.2538	-0.9319	-0.335	0.2987
0.1684	0.0438	0.08	0.3604	-0.7305	-0.7525	-0.354	0.6607	-0.5256	0.6588
-0.9051	0.7962	-0.805	0.7886	0.6489	0.2608	-0.084	-0.8288	0.6144	-0.4425
-0.2123	-0.5477	-0.8218	0.2139	0.7972	0.661	-0.2074	0.4429	0.1089	0.5075
-0.9584	-0.4808	-0.5027	0.3867	-0.4779	0.6803	0.4408	-0.6996	-0.1966	0.0987
-0.0925	-0.1711	0.8161	0.4103	0.6183	0.3736	-0.8126	0.5402	0.2342	0.1211
0.4549	-0.8934	-0.8356	-0.908	-0.3976	0.9172	-0.012	0.6816	-0.9848	-0.552
0.5562	0.0937	-0.8877	-0.3809	0.7118	-0.5739	-0.3262	0.9106	0.4233	-0.68
0.942	0.3104	-0.7467	-0.5151	0.6629	0.0343	-0.7098	0.3977	-0.6954	-0.8079
0.0309	0.4917	-0.6846	0.7279	-0.466	0.214	0.6711	0.5002	-0.786	0.6392
0.9977	0.9815	-0.2096	0.1278	-0.1129	-0.6076	0.3823	-0.6195	-0.4061	0.9819
-0.3059	0.2613	-0.1482	-0.4431	0.605	0.5009	0.9977	0.0822	0.9398	-0.1005
0.8129	-0.4858	-0.6237	-0.6524	0.2532	-0.8122	0.0583	-0.7888	0.2081	-0.0624
-0.5656	0.8846	0.0064	0.552	-0.4639	0.6828	0.8808	0.2282	-0.2376	0.3623
-0.492	-0.6357	-0.3575	0.5543	-0.2152	-0.4063	0.6814	0.2448	0.914	0.6875
0.2038	0.3639	0.8378	-0.5345	-0.6537	-0.8491	-0.4901	-0.6191	0.5765	0.9673
0.623	0.8399	0.2146	-0.8438	0.8329	0.7743	0.9537	0.9355	0.4	-0.2135
0.2985	-0.4082	0.4156	0.7975	-0.472	0.8635	-0.7457	-0.3542	-0.634	0.9115
-0.3005	-0.2086	0.2	-0.8151	0.0754	0.0842	0.9725	0.8988	0.8993	-0.5967

APPENDIX H: Output Data Set of System C (By Rows)

-8.301	-2.6655	0.4668	7.1844	-2.3974	6.6558	-5.9086	-0.6464	3.0458	-6.7012
-0.945	-4.2039	0.5449	4.1955	-1.6646	-2.7081	-2.6063	2.1921	-2.7266	0.3065
-1.7373	-0.5427	-0.7478	0.6638	-0.9673	1.325	-0.5302	0.2471	0.2834	-0.3798
0.2145	0.4766	1.2609	1.0162	-1.4284	-0.7838	2.139	-1.5849	-1.4179	2.9937
0.4151	-3.295	3.4327	1.75	-4.4915	-0.2268	2.7266	-1.0837	-3.493	1.9461
-6.2178	-6.3184	-2.7318	-0.1059	3.0932	3.2221	3.0605	-7.4823	-6.2381	-7.4578
-6.6589	-6.5094	-5.4247	-0.6266	-2.6333	-5.0406	-3.8296	4.0281	3.3393	-2.6263
0.5744	-3.464	-4.9989	-5.1859	-3.477	-4.1835	1.6218	4.0258	-0.4005	-0.1028
3.4193	2.9592	-1.1543	-2.4407	-0.0804	-1.5123	1.678	-0.1067	-0.757	1.638
0.8597	-0.5345	1.3163	-0.69	-2.6463	0.8507	-1.7576	-3.0831	-2.6166	1.5845
1.2339	1.2493	-3.5937	-2.9591	-1.9108	-2.1061	-2.1567	2.0403	-2.6589	-3.5826
0.6402	-3.519	-2.1462	-2.1869	-4.9118	-4.6028	0.5842	2.1805	-0.4267	1.536
3.0923	2.2819	-5.2036	-5.7455	-4.0503	-5.3762	-4.3172	5.9399	3.7928	4.7077
-4.1911	1.3901	3.1907	5.4947	-0.797	-4.9071	-2.8656	0.1286	-3.76	2.2039
-3.3365	-3.6394	-2.1287	1.6141	-0.1535	-0.8104	3.2129	0.7198	2.041	-2.5819
3.0061	-1.6292	0.6981	-2.5328	-1.1388	0.5776	-0.1636	0.6908	-0.8576	3.7411
-1.4514	-0.8591	0.9119	-2.1579	2.2823	-3.7141	2.5603	2.9287	-0.003	-3.6249
-2.2856	3.6862	-1.6269	-4.0831	0.1278	0.9035	-3.2083	-0.1674	-4.8455	-2.8855
0.5368	2.6105	-2.6513	3.0377	-4.4373	-0.9654	-4.3361	-1.5738	1.9947	-4.0092
-2.774	3.9709	-0.9861	0.5378	-1.5104	-0.5561	3.327	-2.1406	2.1541	-1.2868
2.4026	0.5296	1.8445	4.1493	2.5083	3.7515	1.4349	3.4284	3.7868	1.2713
-0.8695	1.0533	1.971	3.1548	-1.2246	0.1374	1.7888	-2.5761	2.6686	-3.5665
3.5414	2.3711	-3.0874	-1.3141	-3.9056	3.2994	-3.667	-0.7317	3.9313	0.8755
3.4836	0.8511	2.3395	-2.8221	0.9581	-4.9589	-3.2083	-4.2114	4.4057	1.3541
-4.3449	4.2332	3.3582	-3.8796	4.0126	-3.5386	-0.3549	5.2529	1.4768	4.3657
0.5938	4.4587	3.0468	-2.7223	0.3703	3.1999	2.0928	0.5868	-1.2094	1.8764
-4.4425	-1.83	2.9648	-1.0034	3.5478	1.8047	-3.4734	-2.7784	-1.7423	1.0049
1.0222	4.7794	-2.1948	3.4311	3.0238	-0.0172	1.9904	1.2471	4.5508	-3.324
-2.6889	0.5467	-4.2478	-0.5265	3.3993	-1.3886	-0.8884	-2.658	2.1311	-1.9522
2.535	-0.1367	0.0101	-2.0226	1.9932	-3.394	3.5711	1.935	4.2185	1.3513
-4.168	-4.2389	-0.3856	2.5447	-0.5284	1.029	-1.9534	2.2813	0.5629	-4.5331
1.2995	5.0371	-2.055	-1.5874	0.1428	-0.2334	-1.3115	-4.8265	-1.7376	1.5505
0.8733	0.2228	0.4043	1.8332	-3.7048	-3.7947	-1.7782	3.3057	-2.6245	3.284
-4.4865	3.9274	-3.9691	3.8776	3.1859	1.2757	-0.4106	-4.0411	2.9872	-2.152
-1.026	-2.6607	-3.9803	1.0339	3.8595	3.2018	-1.0114	2.1474	0.5323	2.4704
-4.683	-2.3511	-2.4614	1.9054	-2.3608	3.3555	2.1859	-3.4744	-0.9829	0.5002
-0.4663	-0.8632	4.1185	2.0628	3.1234	1.9026	-4.1315	2.7493	1.1859	0.627
2.3318	-4.5626	-4.2696	-4.6444	-2.0366	4.6873	-0.0697	3.4876	-5.0219	-2.8227
2.845	0.469	-4.5179	-1.927	3.5992	-2.9119	-1.6428	4.5783	2.1228	-3.4067
4.7141	1.5548	-3.7144	-2.5632	3.2973	0.1683	-3.52	1.965	-3.4274	-3.977
0.1457	2.419	-3.3761	3.5844	-2.2945	1.0425	3.3073	2.4671	-3.8565	3.1472
4.9056	4.826	-1.0322	0.6302	-0.5639	-3.0001	1.8919	-3.0791	-2.0104	4.8786
-1.533	1.2993	-0.7407	-2.2174	3.0258	2.5144	5.0146	0.4055	4.7373	-0.4985
4.0958	-2.452	-3.1577	-3.2995	1.2794	-4.1142	0.3048	-3.9908	1.0588	-0.3228
-2.8541	4.4662	0.0282	2.7928	-2.3364	3.4418	4.4287	1.1419	-1.1967	1.8183
-2.4643	-3.1773	-1.7981	2.7823	-1.072	-2.0337	3.3959	1.2258	4.55	3.4205
1.0117	1.8105	4.1605	-2.6585	-3.2362	-4.2172	-2.4354	-3.0645	2.8461	4.7824
3.0793	4.1531	1.0684	-4.1803	4.1365	3.8455	4.7432	4.6481	1.9917	-1.0701
1.488	-2.0434	2.0657	3.9725	-2.3665	4.3079	-3.7216	-1.7832	-3.1828	4.5638
-1.4996	-1.0398	1.0051	-4.0876	0.3852	0.4274	4.8849	4.5138	4.52	-3.0068

APPENDIX I: Input Data Set of Industrial Air Compression System

70.928	68.041	67.896	69.969	68.66	69.218	69.746	68.367	68.489	68.418
68.196	69.28	68.289	68.147	66.908	68.162	66.8888	68.339	67.634	67.88
67.905	67.842	66.276	66.243	65.49	64.441	62.942	65.106	63.993	63.327
63.369	64.02	63.851	65.041	63.935	64.636	64.759	64.177	62.641	64.7
62.7988	63.773	63.848	62.594	63.48	63.023	63.161	62.569	63.221	62.859
62.001	66.017	62.315	63.801	63.899	63.329	64.562	62.889	63.152	63.593
63.666	63.961	64.128	63.947	63.2	62.985	63.756	63.359	63.64	63.819
63.733	62.661	63.929	62.907	62.833	46.628	63.181	62.972	63.635	62.899
63.048	62.828	63.82	62.613	65.822	61.372	65.364	64.318	63.856	63.18
64.36	63.315	63.868	64.203	65.266	62.019	64.597	62.57	62.437	63.736
63.77	63.182	64.356	64.141	64.242	64.803	64.726	63.409	63.898	64.673
64.3369	64.204	64.132	64.491	63.32	63.635	63.908	63.219	64.806	64.346
64.472	64.712	64.216	65.779	64.577	63.914	64.141	63.672	63.791	63.616
64.451	63.99	65.228	64.48	64.252	64.641	64.176	64.395	63.515	65.461
64.299	64.887	64.174	59.343	64.318	64.443	65.251	66.335	66.876	64.993
64.689	64.571	64.053	64.065	64.884	63.743	64.933	65.824	64.247	65.2822
64.4448	64.827	64.488	64.293	65.822	57.808	58.428	65.66	63.815	62.468
65.61	65.508	64.614	63.935	64.439	63.308	65.444	63.814	64.686	63.769
61.547	63.697	62.745	64.847	63.741	62.906	65.533	64.965	65.507	63.648
66.056	63.734	63.272	66.051	64.701	64.49	64.128	64.03	63.252	64.606
64.354	64.96	65.404	64.935	65.468	64.033	65.499	66.243	64.194	64.237
65.224	64.864	64.887	64.871	64.462	64.157	65.313	64.766	64.694	65.11
68.027	61.039	64.809	64.335	64.647	65.271	65.09	63.98	64.569	64.0611
64.4419	63.792	64.9524	64.1792	63.532	64.732	63.399	64.822	63.789	66.794
64.556	63.742	65.651	64.647	64.874	64.208	64.325	63.377	64.753	65.017
65.35	65.099	64.655	64.981	64.093	64.908	66.909	64.718	64.866	64.467
64.166	63.736	65.024	65.377	65.426	64.37	65.505	66.606	66.713	65.43
65.545	65.266	65.75	64.323	64.914	65.294	66.769	63.923	66.171	66.787
66.222	68.409	65.826	65.053	65.053	66.288	64.684	66.36	64.609	55.8
63.916	64.241	64.904	64.346	64.728	64.121	64.521	65.544	64.862	65.908
65.066	66.047	64.225	66.431	65.436	65.572	65.257	64.812	65.629	65.865
65.999	65.351	65.89	65.35	64.773	64.8327	65.888	64.685	63.559	60.135
61.947	61.772	62.101	60.613	61.574	61.246	61.909	60.379	60.743	60.834
59.996	60.087	60.6	59.283	59.69	60.397	60.374	60.997	60.748	61.453
61.59	61.431	61.425	60.73	61.635	62.177	61.79	62.35	62.558	62.55
62.77	64.539	64.534	64.363	62.407	61.912	62.609	62.085	62.952	61.9424
62.318	61.4062	57.0936							

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APPENDIX J: Output Data Set of Industrial Air Compression System

587.507	583.991	583.814	584.886	590.239	590.811	595.028	591.226	587.934	582.165
580.161	584.276	584.402	585.013	578.155	575.616	581.4494	581.449	585.016	582.387
583.405	578.521	562.618	551.198	552.25	550.345	544.026	540.434	538.052	535.514
538.259	543.772	542.603	545.094	548.77	545.6245	545.456	545.92	542.724	543.105
543.6766	543.054	540.018	543.494	541.633	540.269	542.068	541.01	543.084	540.707
540.774	540.669	536.597	545.084	545.141	542.87	543.286	535.027	538.261	544.089
538.8	545.4	540.791	541.709	535.923	535.729	542.05	544.628	546.231	546.1
546.417	543.793	543.145	539.772	536.217	539.631	543.061	540.609	543.706	541.555
538.461	542.286	541.174	542.027	541.378	545.613	547.056	545.661	544.27	543.85
545.699	543.429	546.679	543.337	543.603	538.652	542.61	545.987	540.102	543.64
544.967	542.601	547.298	548.739	544.46	549.891	541.946	467.112	540.44	545.021
539.4787	535.458	538.864	539.416	534.644	534.425	538.806	540.05	542.953	542.953
545.734	542.09	537.608	544.589	539.721	537.092	539.625	537.276	533.172	528.474
542.698	542.34	540.504	538.181	536.624	536.291	535.004	539.056	542.005	541.517
541.517	544.871	542.94	542.94	537.583	536.583	539.136	537.041	542.346	544.798
537.683	538.182	536.739	534.903	538.876	538.212	540.815	532.641	539.274	545.2563
542.9712	543.121	543.122	541.804	541.796	445.961	472.258	498.86	528.911	537.163
539.217	537.683	538.873	537.096	535.333	536.674	535.652	538.418	535.246	534.007
531.871	536.507	533.335	534.378	532.513	536.616	538.154	539.659	542.725	542.15
544.244	542.086	539.29	541.4	540.945	542.7	537.661	535.479	532.931	539.42
540.384	541.231	543.182	541.344	540.754	541.832	545.275	540.397	540.3216	543.343
540.188	540.506	542.043	541.681	537.762	543.009	541.755	540.794	543.916	540.742
538.292	539.156	541.613	543.388	543.544	541.206	542.523	540.01	540.553	539.3315
540.4162	539.738	536.33	533.0067	533.477	540.023	543.22	547.562	539.48	543.534
546.922	536.362	543.94	535.34	543.16	536.799	529.825	532.946	527.789	534.352
539.043	535.508	538.749	543.7	536.442	536.257	545.246	542.992	542.942	545.272
545.258	543.503	527.033	541.878	548.644	547.887	544.166	542.725	539.572	541.358
543.347	543.008	547.702	536.566	535.466	541.318	542.521	498.696	543.844	546.292
544.85	542.793	541.115	542.386	547.162	544.751	543.199	546.12	535.964	444.422
519.015	511.191	538.42	541.568	541.282	541.908	542.086	544.278	541.067	543.234
538.305	539.882	532.523	542.857	539.889	546.329	546.145	543.007	544.249	552.198
550.298	546.21	544.504	533.973	527.648	529.8894	526.991	526.746	506.194	513.568
518.854	516.347	516.517	516.808	514.976	514.198	513.958	510.889	510.221	510.907
506.768	502.081	506.683	495.836	495.927	502.438	504.996	506.909	509.839	506.478
510.386	506.167	502.694	510.326	511.383	511.948	514.99	514.6	514.938	514.355
515.889	511.811	512.95	510.958	511.355	515.434	515.652	513.639	520.124	517.8907
516.1002	511.3384	467.8173							

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