DESIGN AND VERIFICATION OF PICK AND PLACE ARM MODEL BY USING PETRI NET

LOH MUN LOONG

BACHELOR OF MECHATRONICS ENGINEERING

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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LOH MUN LOONG

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DECLARATION

I declare that this thesis entitled “DESIGN AND VERIFICATION OF PICK AND PLACE ARM MODEL BY USING PETRI NET is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : --

Name : --

Date : --

APPROVAL

I hereby declare that I have checked this report entitled “DESIGN AND VERIFICATION OF PICK AND PLACE ARM MODEL BY USING PETRI NET” and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

Signature : ....

Supervisor Name : ....

Date : ....

DEDICATIONS

To my beloved mother and father

ACKNOWLEDGEMENTS

Firstly, I appreciate for the spiritual supports from God Amitabha whenever I am having any struggles and despairs, leading me towards dawn and drive off my fears. Moreover, I feel grateful towards God for giving me strength and good in health throughout my internship and I hope that the followings would also give to people beside of me.

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ABSTRACT

In this era of modernization, demands for industrial robotics technologies like Articulated robots, Cylindrical robots, Cartesian robots and SCARA robots are increased from days to days to improve consistency, productivity, efficiency and safety of workforce, reduce complexity and human errors. The performance of pick and place robot arm is increasing with the implementation of model checking technique in its development stage. However, the state explosion problem will be happened during the system verification since the state variables grows exponentially as the degree of freedom of the pick and place arm system increases. The first objective of this project is to design the petri net models for the pick and place arm system by using Hierarchical Petri Net Simulator. Next objective is to identify the incidence matrix of the petri net models. The last objective is to identify the structural and behavior properties of the petri net models. 3 petri net models with different in state variables are designed through translating of the real-life pick and place arm mechanism. The incidence matrix of the petri net models show the releasing and accepting of the tokens from the places via activation of transitions. The structural properties which includes the invariants are identified for each petri net model. The behavior properties which includes reachability, deadlock, boundedness and reversibility are verified for each petri net model. Among 3 petri net models, model B is the best because it is deadlock-free, having the largest amount of reachable and reversible markings. Therefore, model B has the best performance compared to model A and model C. From the results, model B can be concluded that the risk for the breakdown to occur is the least among these 3 models.

ABSTRAK

Era modenisasi hari ini, permintaan untuk teknologi robotik industri seperti robot Artikulasi, robot silinder, robot Cartesian dan robot SCARA dinaikkan dari semasa ke semasa untuk meningkatkan konsistensi, produktiviti, kecekapan dan keselamatan tenaga kerja, mengurangkan kerumitan dan kesilapan manusia. Prestasi memilih dan meletakkan lengan robot semakin meningkat dengan pelaksanaan teknik pemeriksaan model dalam peringkat pembangunannya. Walau bagaimanapun, masalah letupan sesuatu keadaan akan berlaku semasa pengesahan sistem kerana pemboleh ubah keadaan tumbuh dengan pesat apabila tahap kebebasan dan sistem lengan memilih dan menempat meningkat. Objektif pertama projek ini adalah untuk merekabentuk model petri bersih untuk sistem lengan memilih dan menempat dengan menggunakan Hierarchical Petri Net Simulator. Objektif seterusnya adalah untuk mengenalpasti matriks kejadian model petri net. Objektif terakhir adalah untuk mengenal pasti ciri struktur dan tingkah laku model petri net. 3 model petri net dengan pemboleh ubah keadaan yang berbeza direka bentuk menerusi menterjemahkan mekanisme sistem lengan memilih dan menempat. Matriks kejadian model petri net menunjukkan pelepasan dan penerimaan tanda-tanda dari tempat melalui pengaktifan peralihan. Ciri-ciri struktur yang termasuk invarian dikenalpasti untuk setiap model petri net. Ciri-ciri tingkah laku yang merangkumi kebolehcapaian, kebuntuan, ketinggalan dan kebolehulangan ditentusahkan untuk setiap model petri net. Antara 3 model petri net, model B adalah yang terbaik kerana ia bebas daripada kebuntuan, mempunyai tanda-tanda yang boleh dicapai dan boleh diterbalikkan. Oleh itu, model B mempunyai prestasi terbaik berbanding model A dan model C. Dari hasilnya, model B dapat disimpulkan bahawa risiko pecahan proses berlaku adalah yang paling kecil di antara 3 model ini.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

HiPS	-	Hierarchical Petri Net Simulator
EOFM		Enhanced Operator Function Model
AlPiNA	-	Algebra Petri Net Analyzer
PEP	-	Programming Environment based on Petri Nets
Yasper	-	Yet Another Smart Process Editor

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, the industrial automation applications are growing rapidly in performance, size and complexity. Industrial automation can be defined as the ability to handle processes and machineries in an industry to replace the manpower with the use of control system like robots, sensors, actuators, processors or controllers. The growth of industrial automation can be explained by industrial revolution.

Industry 4.0 was introduced by representatives from various fields to empower the competitiveness of German in the manufacturing industry. Industrial revolution in different fields can be distributed into 4 stages so far which are field of mechanization (1st industrial revolution), field of intensive use of electrical energy (2nd industrial revolution), field of widespread digitalization (3rd industrial revolution), field of smart machine and product (4th industrial revolution which also called as "Industry 4.0"). According to the principle of Industry 4.0, there are 2 development directions can be followed for future project which includes huge application-pull and exceptional technology-pull.

Huge application-pull encourages a remarkable need for changes depends on different operative framework conditions. The project work should be made changes such as shorten the development periods, increase individualization of products, increase flexibility, reduce organization hierarchy and increase resource efficiency. In the other hand, exceptional technology-pull has been practiced our daily life like Apps, smartphones, laptops and 3D printer but these technologies are not widely spread into industry. Therefore, extensive approach in field of industry should be carried out. These approaches include mechanization and automation increment, digitalization and networking and miniaturization. Hence, Industry 4.0 has catalyzed the development of industrial robots [1].

Since the industrial world these days is facing many technological changes which has increased the demanding of premium quality products and services that can only be accomplished by a high level of productivity, therefore industrial automation is implemented in fulfilling the requirements of companies to face globalization and productivity task. Industrial automation is moving towards extraordinary productivity spurred by excellent in energy efficiency, suitable standards, and better structure. With the development of SCADA, DCS and Process Instruments have made automation more reliable and powerful. Industrial automation also contributes in reducing the cost from employee's salary and bonus. Cost to employ a robot is much cheaper when comparing the spend on the maintenance, energy and repair. With the higher production and lower production cost can produce more affordable goods for consumers [2].

Besides, the industrial automation also increases human safety by minimizing contribution of human being in dangerous working environment like hazardous chemicals, heavy objects, back-breaking labor, poor air quality and extreme temperature.

1.2 Motivation

In new era of globalization, the new development situation and tasks have made our industries extremely urgent to establish a new manufacturing system featuring standardization, modularization, network and intelligence. With the concept of Industry 4.0, global market of production nowadays has gone through a dramatically changes on the manufacturing system from manually into integrated autonomous machines [1]. These changes include shorter product life cycle, variation in the order income and customized products demanding which can lead to inclining in robot quality and declining in robot prices from years to years as shown in Figure 1.1 and Figure 1.2. Figure 1.3 shows that the demands of industrial robot are increased significantly from 2012 with prediction for future.

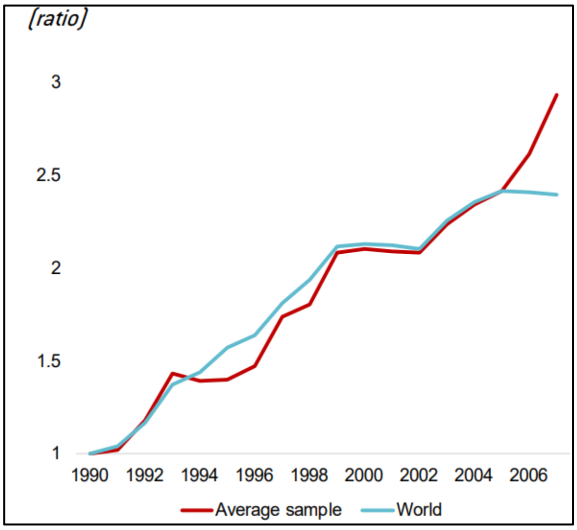

Figure 1.1: Quality of Robots Analysis 1990 - 2006.

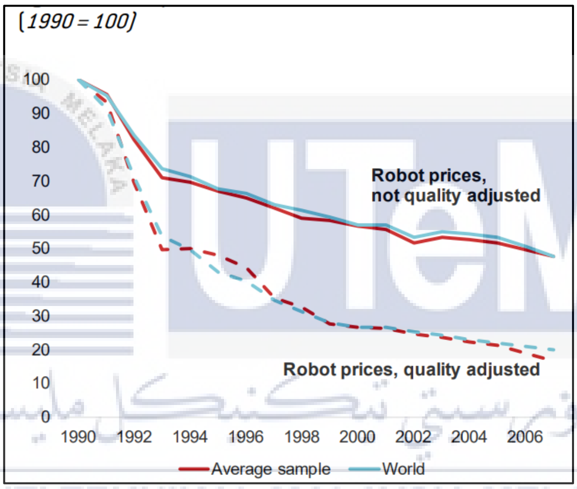

Figure 1.2: General Price for Robots 1990-2006.

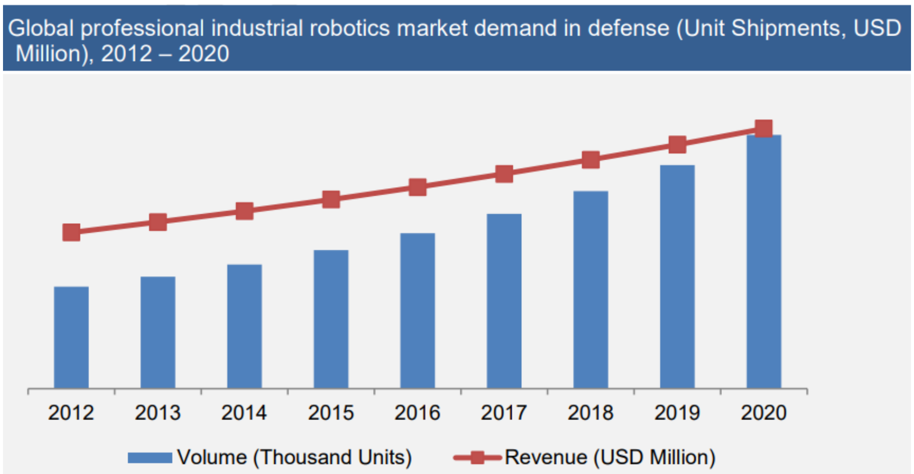

Figure 1.3: Global Professional Industrial Robot Market Demand in Defense 2012-2020 [3].

Along the growth of industrial robot, pick and place robots play important roles in process like assembly, inspection, quality controlling, packaging and sortation. This causes the pick and place robots become more competitive on the market. Since the assigned tasks for the autonomous pick and place robots increase, the complexity of the application for the pick and place mechanism also increases. This can cause the errors occur in the mechatronics control system which controlled by LLD due to more suitable to sequential control but not logic control rather than PN. In pick and place application, there are few commons errors may cause failure to the operation of robot includes:

- Underestimation of payload and inertia requirements.
- Overtasking to an industrial robot.
- Underestimation of cable management issues.
- Neglection of some application element before choosing a robotics system.
- Misunderstanding on the accuracy and repeatability factors.
- Choosing a robotics system based solely on control system rather than mechanical system.

As the results of occurrence of these errors, the industrial production and safety of employees may be influenced. This may lead to high losses from penalty on the project completion time delays. Moreover, higher maintenance fees on the machine may be applied to the company and this also can cause deficit in a company's account. Instead to develop a high-quality industrial robot with lesser errors, verification and validation steps must be taken seriously on its development process.

1.3 Problem Statement

State space approach, the most common way in modeling a large degree of freedom system may lead to state explosion problem since its tuple size for the combinations of state variables are grew exponentially [4, 5].

The large degree of freedom in a pick and place system cause the verification process of the system become challenging since there are a huge number in the possible combinations of actuators motions. Hence, petri net approach is introduced in this paper to prevent the state explosion problem of the pick and place arm system with multiple degree of freedoms.

1.4 Objectives

The objectives for this project are:

1. To design the petri net models for the pick and place arm system by using Hierarchical Petri Net Simulator (HiPS)
2. To identify the incidence matrix of the petri net models by using Hierarchical Petri Net Simulator (HiPS).
3. To identify the structural and behavior properties of the petri net models by using Hierarchical Petri Net Simulator (HiPS).

1.5 Project Scope

In this project, I model the process of the pick and place arm system by converting each of the state variables from real life pick and place mechanism into petri net. In modeling, I designed 3 models of the pick and place arm system with different amount of states. The incidence matrix for each model is identified to understand on the process sequence of the system from the petri net model. Then, the structural and behavior properties are identified for the 3 models. Lastly, the best model among the 3 models is chosen with proper facts.

1.6 Outlines

Chapter 1 discussed on the definition, revolution and importance of industrial automation to operators and industrial machines which can improve productivity and machine efficiency, increase human safety and product quality and reduce company expenses. By motivation from the quality demands of the manufacturing industry, this project is carried out to implement the modeling process of pick and place arm system via petri net approach. The state explosion problem can be solved through this approach. With the ease of using software HiPS, the verification and validation on the properties of the petri net models can be carried out. Chapter 2 will discuss on the theoretical backgrounds and literature reviews by referring to the past research papers, journals and books. Chapter 3 describes the flow of project and tasks to be accomplished by using suitable methods. In Chapter 4, the results obtained are recorded with analysis, synthesis and evaluations. In Chapter 5, conclusion and future works are discussed based on this project.

CHAPTER 2

LITERATURE REVIEW

2.1 System Modeling

Engineered systems nowadays integrate heterogenous of complex subsystems. For example, a pick and place arm system may consist of several combinations of motions which performed with the contributions of software, mechanical and electronics parts. Hence, there are numerous of transducers like limit switches, ultrasonic sensors, reed sensors or photoelectric sensors and actuators like electrical actuators, pneumatics actuators, hydraulic actuators or supercoiled polymers are used to accomplish loading and unloading tasks assigned by programmer. System development and enhancement for the pick and place mechanism are challenging because its complex combinations of motions which can span manifold engineering disciplines. This may cause engineers to have difficulties in specifying, designing, simulating and analyzing the system via design tools. The iterations of motions become much more insufficient to be constructed by simple mathematical equations [6]. The general development lifecycle of an engineering system can be illustrated as in Figure 2.1 [7].

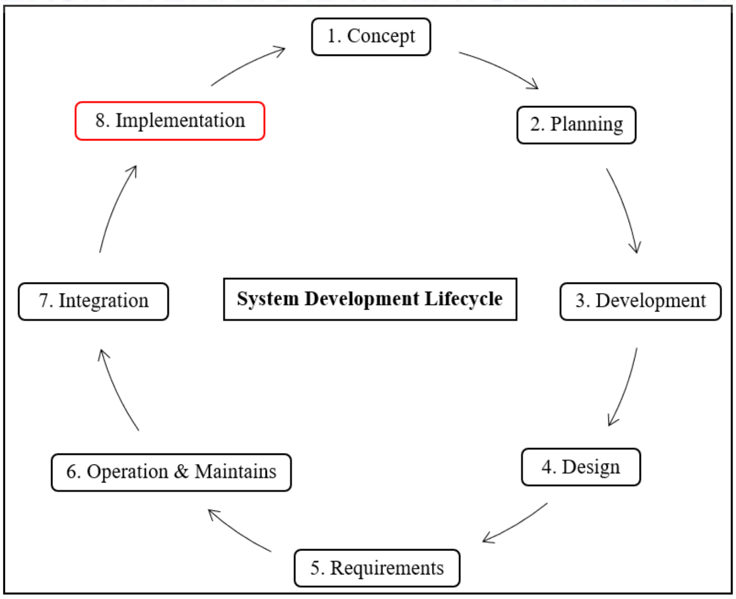

Figure 2.1: Engineering System Development Lifecycle.

There are 3 major parts of implementing process in system development which are modeling, design and simulation. Modeling is the abstract model development of a system where different perspective of that system is presented by each model. In modeling, a system is represented by using graphical notation based on Unified Modeling Language. Models define and show the properties of the system. Design is creation of artifacts according to the desired functionality. Simulation demonstrates the behavior of a system model in a particular environment. Simulation is a basic design analysis step that tend to attract insight on the design properties and to approach testing of the system design. We can understand a system deeper through dissection or partitioning into smaller and more readily analyzed compartments.

Models can be expressed in some modeling language either has strong semantics or a weak semantics. A modeling language with strong semantics has a clear and unambiguous meaning while modeling language with weak semantics has only adopted with block diagram notations without specific meaning. This means a weak semantics model is hard to analyze but it is commonly used to informally link design concept with human beings. Among modeling languages of engineering system design, mathematical modeling and graphical modeling are frequently used to describe the process of the system. The models can be classified as deterministic model and stochastic model. Deterministic model will come out with the same outputs from a given inputs. However, stochastic model will come out with a distribution of possible outputs[8].

Mathematical modeling is a deterministic way that often used to understand the internal mechanisms of a real system via translate the processes involved into mathematical operations [9]. According to Bellomo and Preziosi[10], a mathematical model can be defined as a set of mathematical expression which can be used for calculating the time-space evolution of a physical system. In mathematical modeling, the system can be expressed as differential equations, integral equations, difference equations, Boolean expressions, interpolation or linear equations.

On the other hand, graphical modeling is a stochastic method where a family of probability distributions are represented in terms of direct or indirect graph. With the use of graphical modeling, humans can understand clearer into a system compared to mathematical modeling. This would help the nonknowledge-based users easily to build rather than recognize every process in the system. The graphical approaches that frequently used are Bayesian network and Markov network. However, Bayesian network and Markov network methods require mathematical knowledge base in probability distribution of statistical operations [6, 7, 8]. Therefore, petri net modeling, a graphical modeling method is introduced in this paper.

2.2 Petri Net

Petri net is a graphical modeling tool (named after Carl Adam Petri) that usually used to model various field of system instead of engineered system such as business flows and biological networks. It is widely used for the designation and investigation of concurrent, deadlock, asynchronous and allocated dynamical system. A Petri net structure is a four-tuple with mathematics expression: Net, N = $\{P, T, I, O\}$ where $P = \{p_1, p_2, \ldots, p_n\}$is a finite set of places ○, $n \geq 0$. $T = \{t_1, t_2, \ldots, t_m\}$ is a finite set of transitions □, $m \geq 0$. Meanwhile, the set of places are disjointed with the set of transitions, $P \cap T = \emptyset$. $I: T \rightarrow P^{\infty}$ is the input function, a protraction from transition to the places. $O: T \rightarrow P^{\infty}$ is the output function, a protraction from transition to the places. Places can be symbolized as states, resources or conditions that need to be available before an action can be implemented. Transition can be symbolized as actions. A petri net graph is a depiction of a petri net structure as a bipartite directed multigraph such that each arc is coordinated from a component of a set (either place or transition) to a component of other set (either place or transition). However, the exchange on the sequence among places and transitions can lead to totally different net. The net is worked like data flow diagrams when its primarily is based on motions which represented by transitions. On the other hand, the net is worked like automata when its primarily is based on conditions which represented by places. System developers are always slotting the elements that representing a single system component on a cycle which would help to understand the net.

In petri net, a marking is to assign a number of tokens to the respectively place where a token is an original concept which can be allocated and expected to occupy in the place of petri net. The marking, M also defined as an n-vector, $M = (M_1, M_2, \ldots, M_n)$, where $n = |P|$. The quantity of tokens in place, p_i is M_i, $i = 1, \ldots, n$. On a petri net graph, tokens are illustrated by small dots ● in the places of a petri net [9, 10].

According to the firing rule of petri net, a transition fires by eliminating tokens from its input places. Then, it creates the new tokens and allocated into its output places. After a transition is enabled, the tokens can be fired. The transition is activated when there are tokens in either one of its input places. Multiple input arcs need multiple tokens for transactions of tokens. Enabling tokens are tokens which are functioned to enabling a transition. When a transition is enabled, the marking, M of the petri net will be changed into a new marking M'. The firing process of transition will remain the positive quantity of tokens in each place. Because there is only enabled transition can be fired. If there are insufficient quantity of tokens in any input place of a transition, the transition is not enabled and cannot be fired.

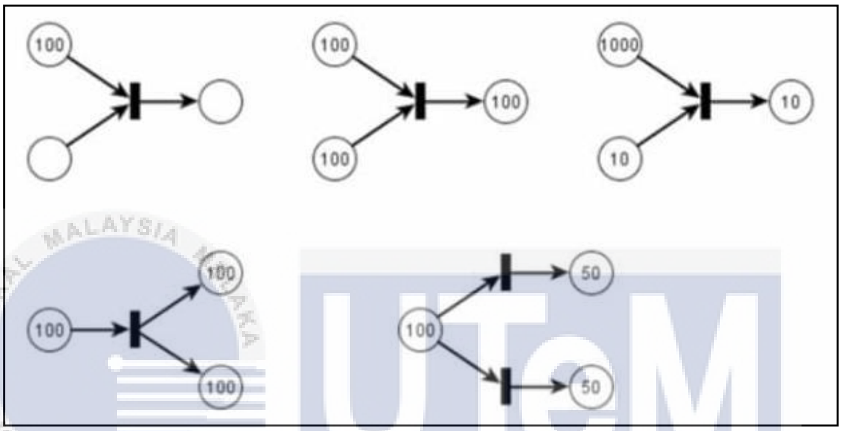

Figure 2.2: Firing rules through transitions in petri net.

Figure 2.2 shows the firing principle of petri net through transitions. A transition is acted like an AND gate which is only activated when both of its input places are containing tokens. The number of tokens in the output places are determined by the number of tokens present in the input places where the maximum number of tokens in output places will not exceeds the number of tokens in input places. The lower number of tokens will have the higher probability to be transferred to the output place. The output place will duplicate the number of tokens if there is 1 input place and multiple output places. The tokens in the input place will be shared if the process flow through 2 transitions [16].

The structure of a pure place and transition net can be mathematically represented by an incidence matrix. Let $N = \{P, T, F, W, M_0\}$ be a petri net. Its incidence matrix $C: P \times T \rightarrow \mathbb{Z}$ is the matrix whose rows are represented as places and columns are represented as transitions. Column $t \in T$ signifies effect of firing of the transition to the marking of the net: *C (t, p) = W (t, p) − W (p, t)* [17] [18]. Figure 2.3 shows that the petri net can be represented by an incidence matrix.

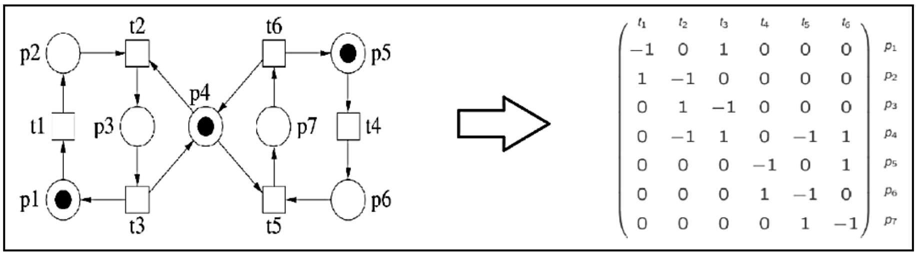

Figure 2.3: Conversion of petri net into incidence matrix.

The marking of a petri net is generally defining its state. The firing of a transition descripts the state changes in petri net by a marking changes in the net. The state space of a petri net with n places is the set of all markings. Firing a transition which causes change in state is defined by a change function δ called as the next-state function. In a marking, M, a set of transition will be enabled and may fire. The result of firing a transition in a marking M is a new marking M'.

We can call *M'* as immediately reachable from *M* which means that we can get to state *M'* intermediately from state *M*. In situation that *M'* is immediate reachable from *M* and *M''* is immediate reachable from *M'*, we can say that *M''* is reachable from *M*.

The general equation for the marking can be expressed as shown in (2.1).

$$M' = M + C^T U \tag{2.1}$$

Where M' represents the next step marking of the petri net, M represents quo step of the petri net, C^T represents the adjacent of incidence matrix and U represents the firing count vector [19].

In petri net modeling, there are various types of approaches can be implemented such as standard petri net model, resource-oriented petri net model, colored petri net model and Fuzzy petri net model.

A standard petri net model can be divided into discrete petri net and continuous petri net. Referring to SS Peng and MC Zhou [20], they presented that petri net can be used to model a discrete system. In discrete system, there is a relationship between discrete petri net and ladder diagram which allows developers to make conversion between both of them. This approach suits for modeling a system with simple variants of characteristics such as lighting system with “On” and “Off” applications. On the other hand, Jorge and René [21] have modelled a predictive control of macroscopic traffic system by using continuous petri net. This model describes the continuous variables of the system like density, average speed and flow rate.

NQ Wu and MC Zhou [22] have presented resource-oriented petri net modeling technique in flexible assembly systems. According to their research, the system is modelled where single place is only allowed to link to single transition. With the help of resource-oriented petri net modeling, the system is verified as deadlock-free.

Tony [23] has model activity diagram of Unified Modeling Language Second Version (UML2) into colored petri net. With the aid of colored petri net, the model of UML2 activity diagram with more detailed specifications is constructed. This thesis shows that the colored petri net is a higher-level petri net model that is suitable to construct system model which contains several characteristics but not only for simple logic controlling of engineered system [24].

The other type of petri net approach is fuzzy petri net which combining fuzzy logic into the colored petri net model. According to work from Sanjin et al. [25], fuzzy petri net was used to model train delays estimation system. This model can make corrections from the historical data. Hence, the fuzzy petri net is suited for a system with artificial intelligent such as fuzzy washing machines.

Among the comparison between the petri net approaches, discrete petri net approach is chosen as the modeling method to be studied in this project. This is because the mechanism for a pick and place arm system is based on discreate variables which has only logical high and logical low signal in the inputs and outputs of the system.

2.3 System Verification and Validation

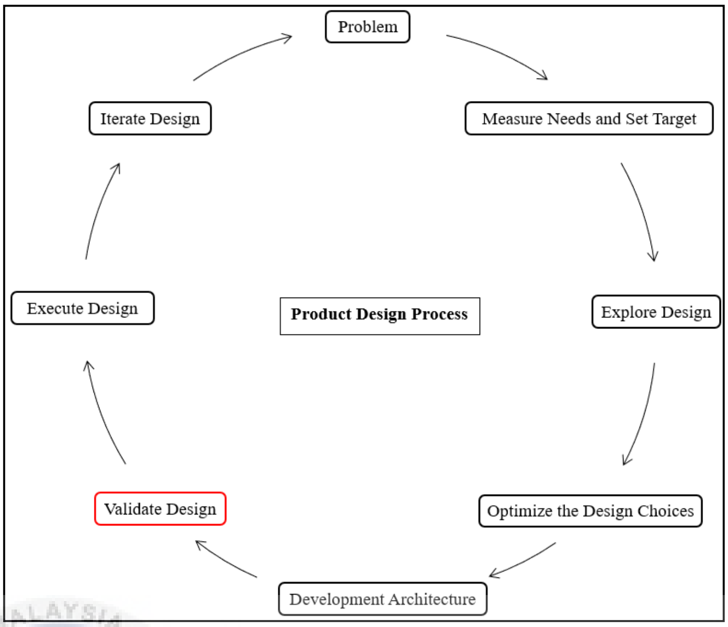

Figure 2.4: Product Design Process Lifecycle.

Figure 2.4 shows the product design process lifecycle in development of an engineered system. During the product design process, the draft of a design must be validated and verified before launched to the production line. Applying techniques of system verification into the system design process can make the system to be more reliable. System verification and validation aim to ensure that the product design is under consideration on certain properties like deadlock, boundedness, reversibility, reachability and safety. Deadlock is happened in a system when there is a terminal state, a state without any outgoing progression occurs in the simulation of the system. This problem happens due to:

1. Mutual exclusion where the resource cannot be shared, and the requests are delayed until the resource is released. The resource must be made as sharable to other transitions.
2. Preemption where the resource is released voluntarily into the undesired place. A path should be added to delay the preempted resource.
3. Hold and wait where thread holds one resource while waiting for another. The held resource should be released before requesting next one and all the resources must be acquired atomically at once.

4. Circular wait where the circular dependencies exist in a “wait-for” or a “resource-allocation” graphs. “Wait-for” graph denotes two places are waiting resources from each other. While “resource-allocation” graph denotes resource is held by a place and it wants to release the resource throughout a transition. Ranking should be provided to all resources that indicates the progression sequence [26].

Besides that, boundedness property denotes the amount of variations in term of combinations of possible outputs to represent the complexity of the system. The higher the number in bounded values, the more in the variants amount, hence the complexity of system is higher. Moreover, reversibility property describes the ability of the system to have some admissible process sequence to retrieve the initial step of all the process. A reversible system can return to its original state without concern on whatever processes is gone [19, 20]. For reachability property, it specifies the amount of possible combinations of outputs can be made throughout all the processes in a system [24, 25].

These properties that are going to prescribe the specifications of the system can be validated through model checking technique. The characteristics of these properties are as followed: The results obtained from the model checker are always used to prove satisfaction of a system to the selected property relative to a specification but not absolutely property of the system. The time spent on the verification is longer than on the construction of a complex system designing.

There are 2 techniques which are formal methods and model-based methods can be used to ease the verification process and improve their coverage at the same time. Formal method is the technique that used for modeling and analyzing system by applying mathematics expression. This technique can prove the system via mathematical rigor. According to Matthew, Radu and Ellen [31], they have presented a formal method of model checking in human-automation interaction by using task analytic models. In their thesis, they describe the system in Enhanced Operator Function Model (EOFM) language which is a form of mathematical modeling. Then, they translate these formal mathematical descriptions into model checker to verify on the system safety property. The limitations of the formal method of model checking is that it is described in mathematical cause difficulties in understanding for a beginner and it spends longer time in the model checking process.

On the other hand, model-based method also known as symbolic model checking is a technique that illustrates the system behavior properties in unambiguous and mathematically accurate manner. This technique executes algorithms which pass through all the states in the system to evaluate all the behavior properties of the given system model. According to research from Steve et al. (2011), a model-based method of model checking is implemented which is high-level petri net model checking by using Algebraic Petri Net Analyzer (ALPiNA). They modelled the system with a high-level petri net where its tokens have their internal structures. They perform reachability analysis and scale their system model up to large scale to understand the underlying this model checking techniques. As the result, this model checking technique provide higher usability and performance.

2.4 Overviews

In this project, a pick and place system is modelled in graphical model which is a discrete petri net approach so that the behaviors of the system can be visualized more obviously. Besides, the model checking method used is model-based technique since it is simpler and more suitable for beginner to model checking. This project only covers on the system properties specification which include reachability, deadlock, reversibility and boundedness of the petri net model.

CHAPTER 3

METHODOLOGY

3.1 Flow of Project

The flow for this project to be carried out is as shown in Figure 3.1.

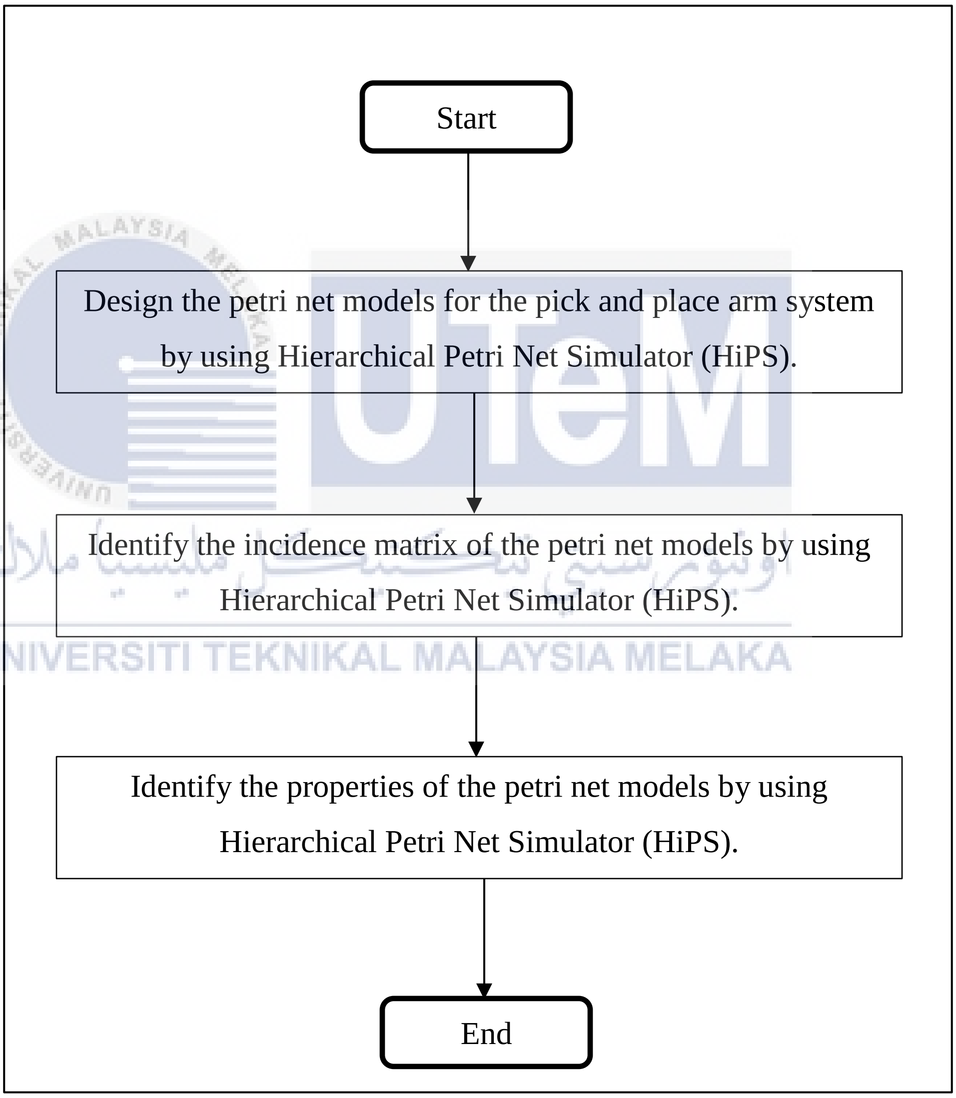

Figure 3.1: Flow chart of this project.

3.2 Design the petri net models for the pick and place arm system by using Hierarchical Petri Net Simulator (HiPS).

3.2.1 Pick and place arm mechanism.

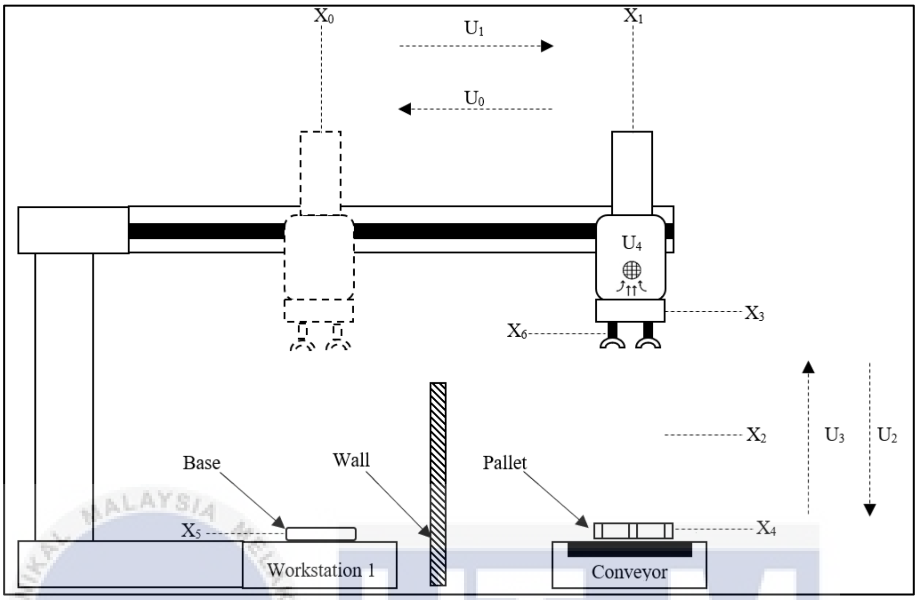

Figure 3.2: Structural model of the pick and place arm system.

An existing pick and place arm system, Souvenir Assembly Line of Computer-Integrated Manufacturing model which allocated in Centre of Robotics, Innovation and Automation (CERIA) laboratory of Universiti Teknikal Malaysia, Melaka is used as reference in this paper. Only the existing structural appearance model and process flows are taken to be the benchmark of the pick and place arm system in this project. From Figure 3.2, the components involved in the model are built up with pneumatics, electricals and electronics which includes short stroke double-acting cylinders, 3/2 ways directional control valves with solenoids, vacuum cup, diffuse-reflective sensors, reed sensors and vacuum suction sensor.

Table 3.1: List of inputs represented in the structure model of pick and place arm system.

Sensor	Type	Descriptions
X_0	Reed Sensor	Rear
X_1	Reed Sensor	Front
X_2	Reed Sensor	Bottom
X_3	Reed Sensor	Top
X_4	Photoelectric Sensor	Pallet
X_5	Photoelectric Sensor	Base
X_6	Vacuum sensor	Suction (ON)

Table 3.2: List of outputs represented in the structure model of pick and place arm system.

Actuator	Type	Description
U_0	Short Stroke Double-acting Cylinder	Backward
U_1	Short Stroke Double-acting Cylinder	Forward
U_2	Short Stroke Double-acting Cylinder	Downward
U_3	Short Stroke Double-acting Cylinder	Upward
U_4	Vacuum Cup	Suction

Table 3.1 and Table 3.2show the inputs and outputs to be represented in the structural model of the pick and place arm system as shown in Figure 3.2. Sensors as inputs are represented with “X” where X_0, X_1, X_2, X_3, X_4, X_5 and X_6 represent rear position, front position, bottom position, top position, presence of pallet, presence of base and suction is activated respectively. Actuators act as outputs with label “U” where U_0, U_1, U_2, U_3 and U_4 represent move backward, move forward, move downward, move upward and activation of vacuum suction respectively.

Besides, the process sequence of the pick and place system is as shown in Figure 3.3 and Figure 3.4. The initial position of the pick and place arm is in front and top positions. The pallet and the base must be present in their desired position to start whole process. As the base and pallet are present, the arm moves downward until it reaches at the bottom position. Then, the vacuum suction will be turned on and the sensor will ensure that the base is held by the vacuum cup. Next, the arm moves upward until it reaches at the top position. Then, the arm moves downward again until it reaches at the bottom position and the vacuum suction will be turned off. The sensor ensures the base is released. Next, the arm moves to its initial position. The process sequence is repeated unless breakdown is occurred.

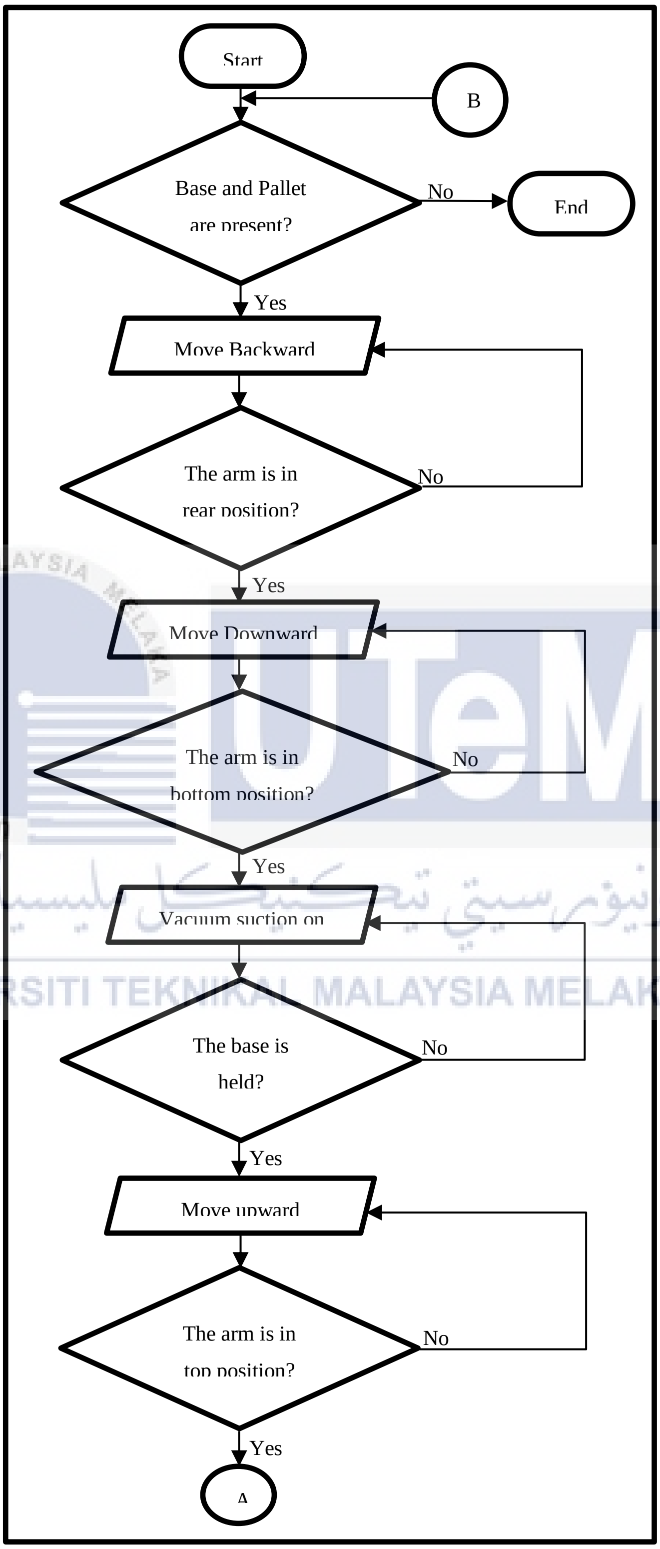

Figure 3.3: Flow chart of pick and place arm system (Part 1)

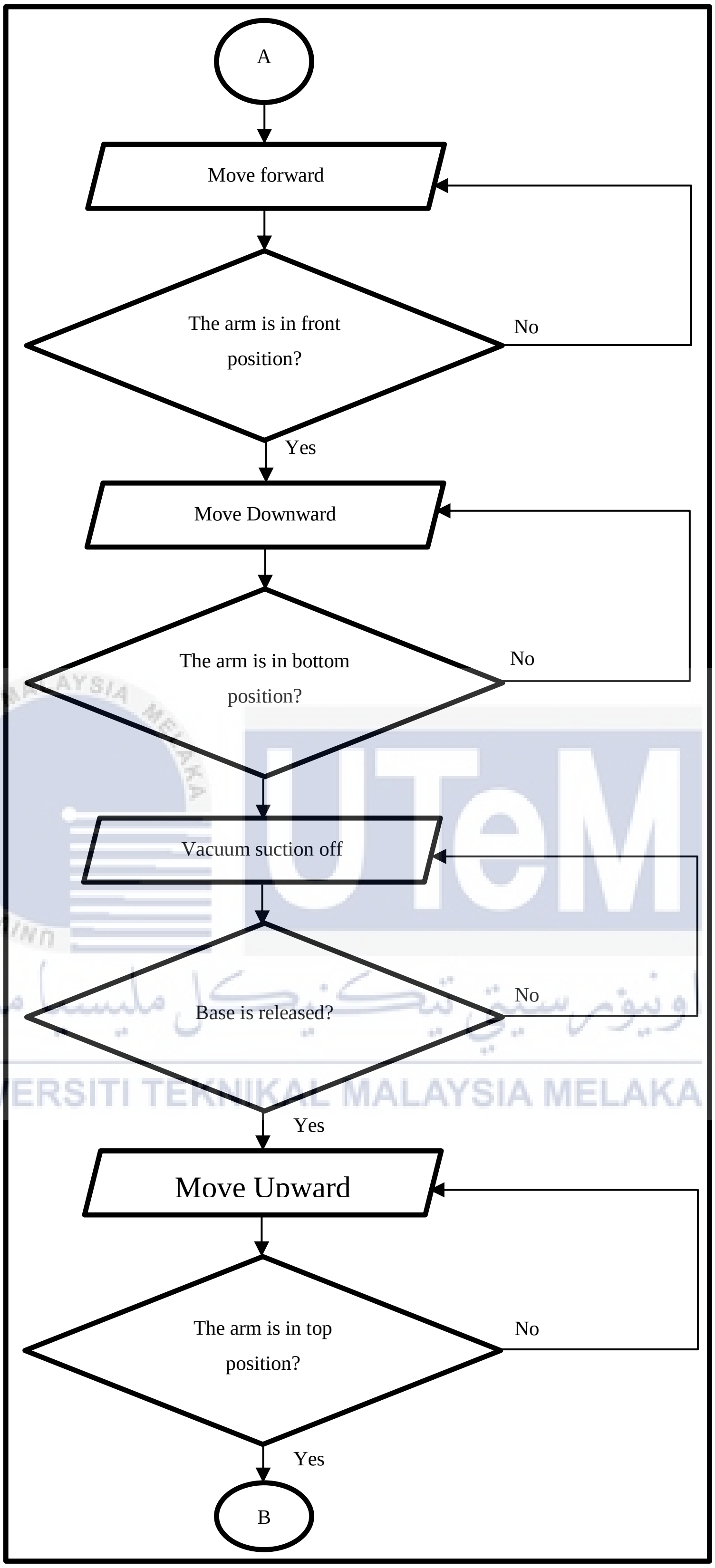

Figure 3.4: Flow chart of pick and place arm system (Part 2) .

3.2.2 Procedures.

1. A sample of pick and place arm system was chosen. The inputs and outputs, structural mechanism and sequence of process flow involved in the pick and place arm system were showed clearly in Table 3.1, Table 3.2, Figure 3.2, Figure 3.3 and Figure 3.4 respectively.
2. After having a clearly understanding on the existing pick and place system, discrete petri net modeling technique was applied to translate the process flow into petri net form by using HiPS software.
3. Three petri net models: model A, model B and model C with different place-transition assignations were designed.
4. The petri net models were snapshotted and recorded as pictures and the differences on their structure are compared.

3.3 Identify the incidence matrix of the petri net models by using Hierarchical Petri Net Simulator (HiPS).

3.3.1 Procedures.

1. The incidence matrix of the petri net model A was checked and transposed.
2. The transpose of incidence matrix obtained was recorded into matrix form.
3. To implement the incidence matrix check, “Tool” key was clicked and followed by “Incidence Matrix” and “old” as shown in Figure 3.5.

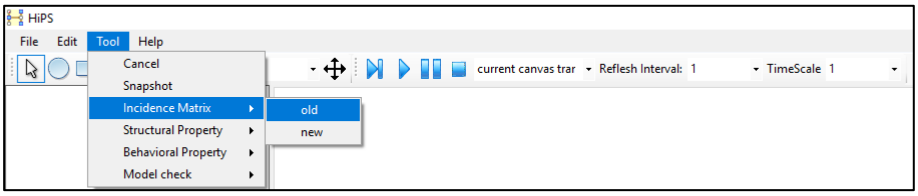

Figure 3.5: Incidence matrix check using HiPS.

4. Step 1 to step 3 were repeated for model B and model C.

3.4 Identify the properties of the petri net models by using Hierarchical Petri Net Simulator (HiPS).

3.4.1 Procedures.

1. The structure properties of model A which include T-invariant and S-invariant were checked subsequently, and the results were recorded. To implement the structurer properties check, “Tool” key was clicked and followed by “Structurer Property” as shown in Figure 3.6

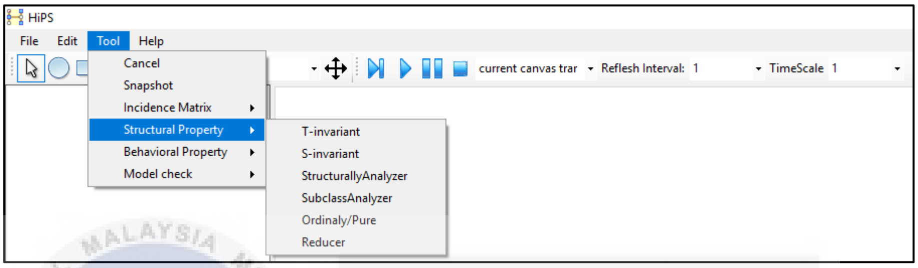

Figure 3.6: Structure properties check using HiPS.

2. The behavior properties which include reachability, deadlock, boundedness and reversibility were checked subsequently. To implement the behavior properties check, “Tool” key was clicked and followed by “Behavior Property” as shown in Figure 3.7. Then, keys “Reachability / Coverability Analyze (Auto)”, “Deadlock”, “Bounded” and “Reversibility” were clicked subsequently to check the reachability, deadlock, boundedness and reversibility respectively.

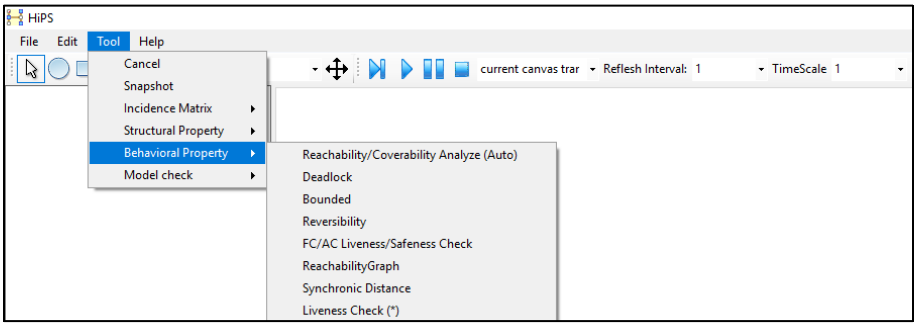

Figure 3.7: Behavior properties check using HiPS.

3. Step 1 and step 2 are repeated
4. The results obtained were analyzed and discussed accordingly.

3.5 Summary

There are numerous petri net simulators can be used for petri net modeling like Algebra Petri Net Analyzer (AlPiNA) [32], Programming Environment based on Petri Nets (PEP) [33], Yet Another Smart Process Editor (Yasper) [34], and Hierarchical Petri Net Simulator (HiPS). However, HiPS is a petri net simulator that integrates with the properties analyzer and model checking tool [4, 5]. Compared to AlPiNA and PEP, HiPS is the latest software built with multiple functions. HiPS has high performance since it provides a memory-saving technique and high-speed execution. Lastly, HiPS is simpler to use for a beginner in modeling and model checking compare to Yasper which should having programming skills to perform it well. In this project, there are 3 models will be designed and each model will be verified on structural and behavior properties by using petri net approach.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Design the petri net models for the pick and place arm system by using Hierarchical Petri Net Simulator (HiPS).

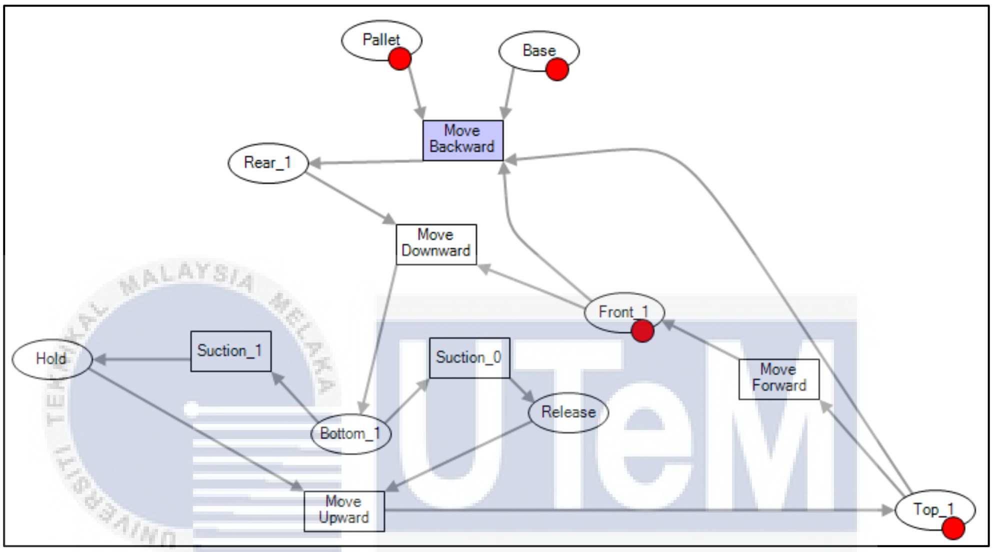

Figure 4.1: Petri net model A.

There are 8 places and 6 transitions in total for the model A as shown in Figure 4.1. Each place represents the activation of transducer. There are transducers that are functioned as positions detection of the pick and place arm which are reed sensors allocated on the actuators. Besides, there are transducers that are functioned to detect the presence of the base and pallet which are photoelectric sensors. There are vacuum pressure sensors which allocated on the vacuum cup for pressure detection. The vacuum pressure obtained will be compared to the benchmarks in determining the base is held or released. On the other hand, each transition represents the contraction-extension mechanism of the actuators which determining the directions of the pick and place arm moved. Table 4.1 and Table 4.2 shows the representative descriptions of places and transitions in model A to the real-life pick and place arm system.

Table 4.1: Representation descriptions of places in petri net model A to the real-life pick and place system.

Name in petri net model	**Representation in real system**
Pallet	Pallet is present
Base	Base is present
Rear_1	The arm is in rear position
Front_1	The arm is in front position
Top_1	The arm is in top position
Bottom_1	The arm is in bottom position
Hold	The base is held by the arm
Release	The base is released by the arm

Table 4.2: Representation descriptions of transitions in petri net model A to the real-life pick and place system.

Name in petri net model	**Representation in real system**
Move Backward	The arm is moving to backward
Move Downward	The arm is moving to downward
Move Forward	The arm is moving to forward
Move Upward	The arm is moving to upward
Suction_1	The vacuum suction is turned on
Suction_0	The vacuum suction is turned off

From the model A as shown in Figure 4.1, there are 4 places are assigned with initial markings which are “Pallet”, “Base”, “Top_1” and “Front_1”. These places are assigned with initial markings which mean that the initial position of the is at top and front position. At the same time, the slots for pallet and base are filled.

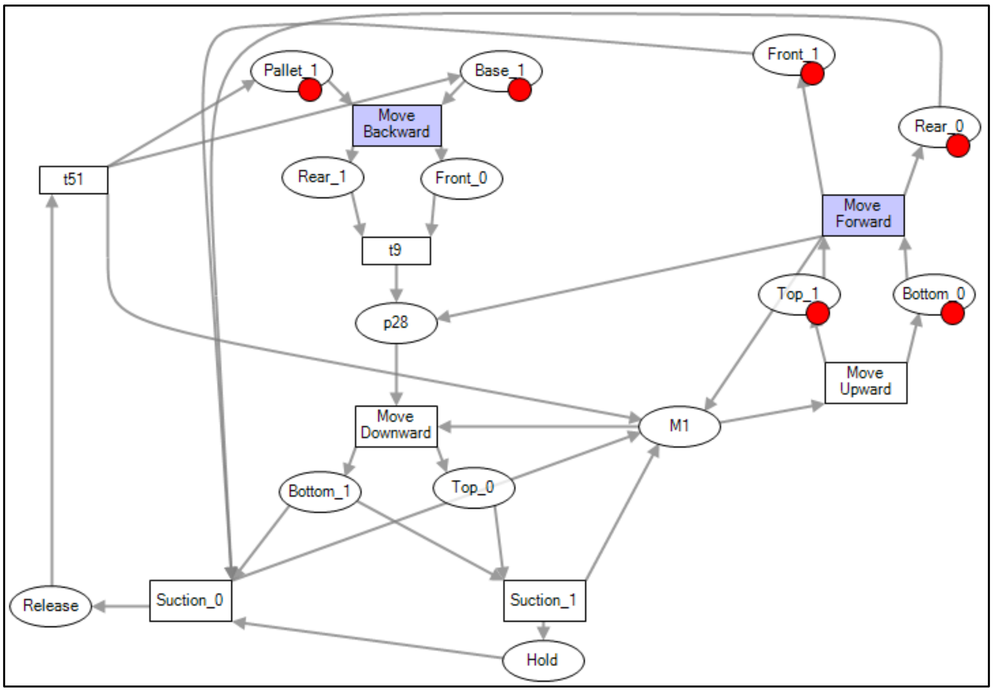

Figure 4.2: Petri net model B.

There are 14 places and 8 transition in total for the model B as shown in Figure 4.2. There are certain places can represent the activation of transduces while some of them are represented as contacts of relays in the real-life arm system. The role of place “p28” and “M1” are to apply the logical controls and to generate linkages from transition “Move Forward” to transition “Move Downward” and linkage from transitions “Suction_1”, “Suction_0”, “t51” and “Move Forward” to transitions “Move Upward” and “Move Downward” because petri net rule implies that place-place and transition-transition direct linkage is invalid. On the other hand, there are certain transitions can be represented by the contraction-extension mechanism of the actuators which determining the directions of the pick and place arm moved. However, there are also a few transitions are represented as coils of relays in the real-life arm system. According to the rules of petri net, transition “t9” and “t51” are added into the model is aimed to apply the logical controls and to make the linkage from places “Front_0” and “Rear_1” to place “p28” and linkage from place “Release” to places “Pallet”, “Base” and “M1” respectively. Table 4.3 shows the representative descriptions of places and transitions in model B to the real-life pick and place arm system.

Table 4.3: Representation descriptions of places in petri net model B to the real-life pick and place system.

Name in petri net model	Representation in real system
Pallet_1	Pallet is present
Base_1	Base is present
Rear_1	The arm is in rear position
Rear_0	The arm is not in rear position
Front_1	The arm is in front position
Front_0	The arm is not in front position
Top_1	The arm is in top position
Top_0	The arm is not top position
Bottom_1	The arm is in bottom position
Bottom_0	The arm is not in bottom position
Hold	The base is held by the arm
Release	The base is released by the arm
p28	Contact of relay
M1	Contact of relay

Table 4.4: Representation descriptions of transitions in petri net model B to the real-life pick and place system.

Name in petri net model	Representation in real system
Move Backward	The arm is moving to backward
Move Downward	The arm is moving to downward
Move Forward	The arm is moving to forward
Move Upward	The arm is moving to upward
Suction_1	The vacuum suction is turned on
Suction_0	The vacuum suction is turned off
t9	Coil of relay
t51	Coil of relay

From the model B as shown in Figure 4.2, there are 6 places are assigned with initial markings which are “Pallet_1”, “Base_1”, “Top_1”, “Bottom_0”, “Front_1” and “Rear_0”. These places are assigned with initial markings is to ensure the initial position of the is at top and front position with the presence of base and pallet. The reason for adding of 4 places “Bottom_0”, “Top_0”, “Front_0” and “Rear_0” in this model is to make sure the respective solenoid of the actuators is deactivated as the solenoid of its opposite direction is activated. This can prevent the awkward motions of the pick and place arm system.

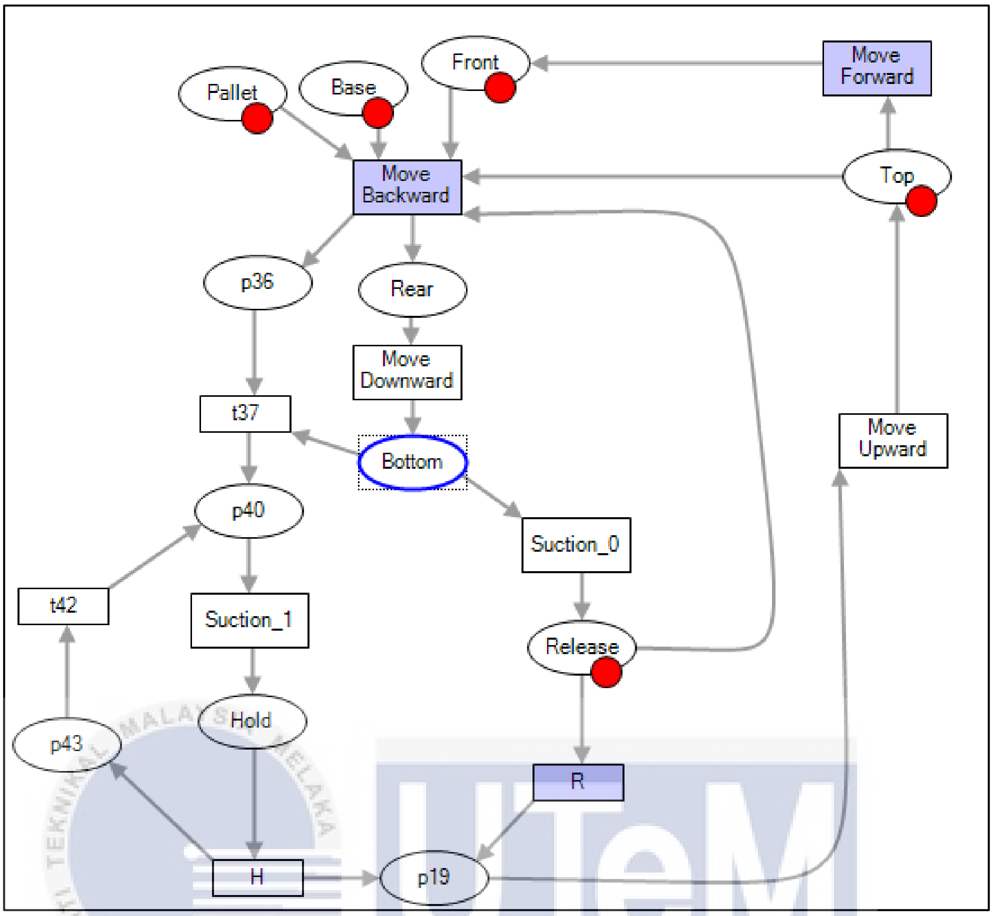

Figure 4.3: Petri net model C

There are 12 places and 10 transitions in model C as shown in Figure 4.3. Same as model B, model C is designed with certain places to represent the activation of transduces while some of them are represented as contacts of relays in the real-life arm system. According to the petri net rule, the role of places "p19", "p36", "p40" and "p43" are to apply the logical controls and to generate linkage from transitions "R" and "H" to transitions "Move Upward", linkage from transition "Move Backward" to transition "t37", linkage from transitions "t37" and "t42" to transition "Suction_1" and linkage from transition "H" to transition "t42" respectively.

On the other hand, there are also certain transitions can be represented by the contraction-extension mechanism of the actuators which determining the directions of the pick and place arm moved while a few transitions are represented as coils of relays in the real-life arm system. These transitions include "R", "H", "t37" and "t42" which functioned to apply the logical controls and to link the place from "Release" to "p19", place from "Hold" to "p19" and "p43", places from "p36" and "Bottom" to "p40" and place form “p43” to “p40”. Table 4.5 and Table 4.6 show the representative descriptions of places and transitions in model C to the real-life pick and place arm system.

Table 4.5: Representation descriptions of places in petri net model C to the real-life pick and place system.

Name in petri net model	**Representation in real system**
Pallet	Pallet is present
Base	Base is present
Rear	The arm is in rear position
Front	The arm is in front position
Top	The arm is in top position
Bottom	The arm is in bottom position
Hold	The base is held by the arm
Release	The base is released by the arm
p19	Contact of relay
p36	Contact of relay
p40	Contact of relay
p43	Contact of relay

Table 4.6: Representation descriptions of places in petri net model C to the real-life pick and place system.

Name in petri net model	**Representation in real system**
Move Backward	The arm is moving to backward
Move Downward	The arm is moving to downward
Move Forward	The arm is moving to forward
Move Upward	The arm is moving to upward
Suction_1	The vacuum suction is turned on
Suction_0	The vacuum suction is turned off
H	Coil of relay
R	Coil of relay
t37	Coil of relay
t42	Coil of relay

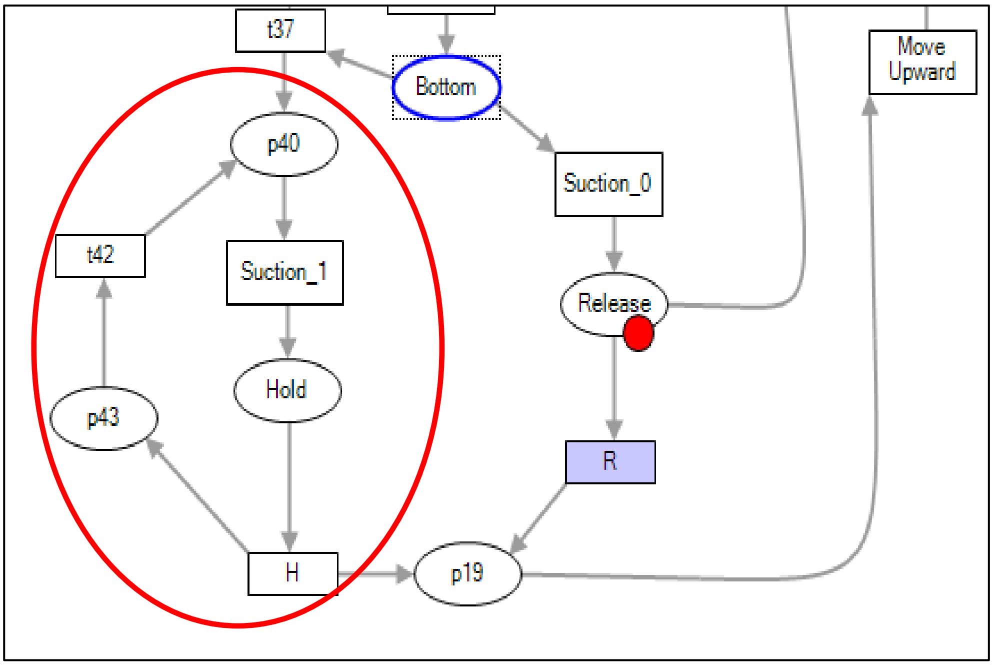

Figure 4.4: Loop in suction process.

Figure 4.4 shows that there is a loop in the suction process in the design of model C. This loop is functioned to keep the place “p40” activate so that the vacuum suction can be kept activate while the pick and place arm is moving upward. This can ensure the base is held simultaneously while the pick and place arm is moving.

From the model C as shown in Figure 4.3, there are 5 places are assigned with initial markings which are “Pallet”, “Base”, “Top”, “Front” and “Suction_0”. These initial markings denote the pick and place arm is initially located in front and top position, with vacuum suction is turned Off and the presence of base and pallet in their desired locations.

4.2 Identify the incidence matrix of the petri net models by using Hierarchical Petri Net Simulator (HiPS).

An incidence matrix is the difference of post condition of inputs to the post-condition of the inputs. It describes the process sequence through accepting and releasing of the tokens to form a new marking from its initial marking. A marking represents the possible state activation of the transducers in real life pick and place arm system.

Incidence Matrix - HiPS

Transition / Place	id0(Pallet)	id1(Base)	id23(Release)	id15(Hold)	id16(Bottom_1)	id18(Rear_1)	id33(Front_1)	id35(Top_1)
id4(Move Backward)	-1	-1	0	0	0	1	-1	-1
id13(Suction_1)	0	0	0	1	-1	0	0	0
id14(Move Downward)	0	0	0	0	1	-1	-1	0
id40(Move Forward)	0	0	0	0	0	0	1	-1
id42(Move Upward)	0	0	-1	-1	0	0	0	1
id20(Suction_0)	0	0	1	0	-1	0	0	0

Figure 4.5: Incidence matrix table of petri net model A.

The incidence matrix of model A is generated by HiPS as shown in Figure 4.5. The rows of the table represent the transitions while the columns represent the place of the petri net model. In this incidence matrix table, the negative values indicate the releasing of tokens (deactivation of transducers) while the positive values indicates the accepting of tokens (activation of transducers). The incidence matrix of model A is generated by HiPS as shown in Figure 4.5. The rows of the table represent the transitions while the columns represent the place of the petri net model. In this incidence matrix table, the negative values indicate the releasing of tokens (deactivation of transducers) while the positive values indicates the accepting of tokens (activation of transducers). Zero in the incidence matrix indicates the certain place is unchanged. From the 1st row of the incidence matrix table obtained, each of the places "Pallet", "Base", "Front_1" and "Top_1" releases 1 token but the place "Rear_1" accepts 1 token when the transition "Move Backward" is activated. From the 2nd row of the incidence matrix table, the place "Bottom_1" releases 1 token but the place "Hold" accepts 1 token when the transition "Suction_1" is activated. From the 3rd row of the incidence matrix table, each of the places "Rear_1" and "Front_1" releases 1 token while the place "Bottom_1" accepts 1 token when the transition "Move Downward" is activated. From the 4th row of the incidence matrix table, the place "Top_1" releases 1 tokens but the place "Front_1" accepts 1 token when the transition "Move Forward" is activated. From the 5th row of the incidence matrix table, each of the places "Release" and "Hold" release 1 token but the place "Top_1" accepts 1 token when the transition "Move Upward" is activated. From the 6th row of the incidence matrix table, the place "Bottom_1" release 1 token but the place "Release" accepts 1 token when the transition "Suction_0" is activated. (4.1) shows the transpose of the incidence matrix of model A. The adjacent of incidence for model C obtained is a 8 X 6 matrix.

$$Adjacent\ of\ Incidence\ Matrix, C^T$$

$$= \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 \\ 0 & 1 & 0 & 0 & -1 & 0 \\ 0 & -1 & 1 & 0 & 0 & -1 \\ 1 & 0 & -1 & 0 & 0 & 0 \\ -1 & 0 & -1 & 1 & 0 & 0 \\ -1 & 0 & 0 & -1 & 1 & 0 \end{bmatrix} \tag{4.1}$$

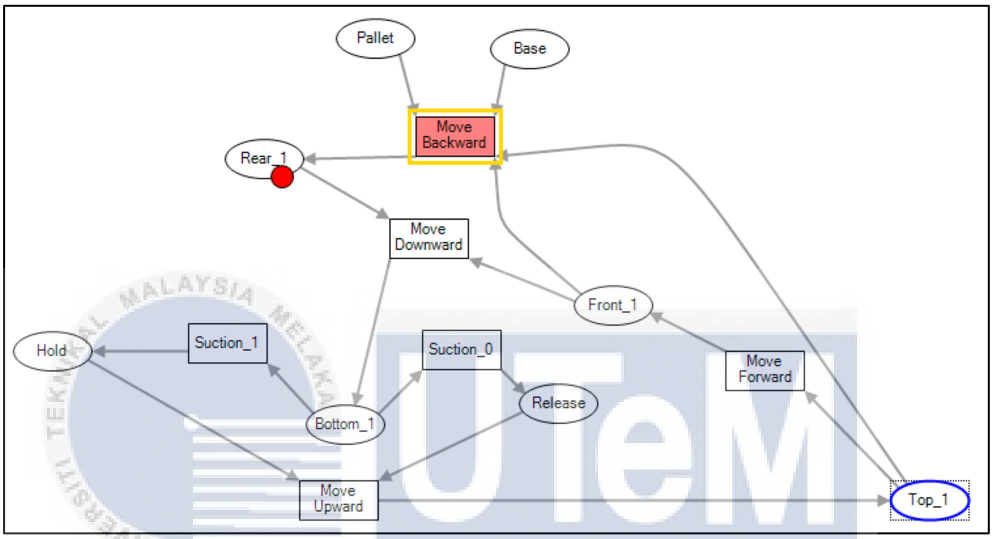

Figure 4.6: 1st firing step of petri net model A

From Figure 4.6, the token in a place is functioned to visualize the flow of the pick and place mechanism. The number of the tokens in a place can be cumulated. By comparing the 1st firing step of model A to its original state, the initial marking of tokens form “Top_1”, “Front_1”, “Pallet” and “Base” are fired by transition “Move Backward” which indicates that the arm moves backward at the 1st step of the possible state activation of transducers. However, the firing sequences of transitions is not unique in petri net which means the sequences may be different for every demonstration.

Incidence Matrix - HiPS

Transition / Place	id0(Pallet_1)	id2(Base_1)	id4(Top_1)	id5(Top_0)	id6(Front_1)	id7(Front_0)	id10(Rear_0)	id11(Rear_1)	id14(Bottom_0)	id15(Bottom_1)	id18(Hold)	id19(Release)	id30(M1)	id28(p28)
id8(Move Backward)	-1	-1	0	0	0	1	0	1	0	0	0	0	0	0
id51(t51)	1	1	0	0	0	0	0	0	0	0	0	-1	1	0
id12(Move Downward)	0	0	0	1	0	0	0	0	0	1	0	0	-1	-1
id16(Suction_1)	0	0	0	-1	0	0	0	0	0	-1	1	0	1	0
id17(Suction_0)	0	0	0	0	-1	0	-1	0	0	-1	-1	1	1	0
id20(Move Upward)	0	0	1	0	0	0	0	0	1	0	0	0	-1	0
id22(Move Forward)	0	0	-1	0	1	0	1	0	-1	0	0	0	1	1
id9(t9)	0	0	0	0	0	-1	0	-1	0	0	0	0	0	1

Figure 4.7: Incidence matrix of petri net model B.

Figure 4.7 shows the incidence matrix of model B obtained from HiPS. From the 1st row of the incidence matrix table, each of the places "Pallet_1" and "Base_1" releases 1 token but each of the places "Front_0" and "Rear_1" accepts 1 token when the transition "Move Backward" is activated. From 2nd row of the incidence matrix table, the place "Release" releases 1 token but each of the places "Pallet_1", "Base_1" and "M1" accepts 1 token when the transition "t51" is activated. From the 3rd row of the incidence matrix table, each of the places "M1" and "p28" releases 1 token but the place "Bottom_1" accepts 1 token when the transition "Move Downward" is activated. From the 4th row of the incidence matrix table, each of the places "Top_0" and "Bottom_1" release 1 token but each of the place "Hold" and "M1" accepts 1 token when the transition "Suction_1" is activated. From the 5th row of the incidence matrix table, each of the places "Front_1", "Rear_0", "Bottom_1" and "Hold" releases 1 token but each of the places "Release" and "M1" accepts 1 token when the transition "Suction_0" is activated. From the 6th row of the incidence matrix table, the place "M1" releases 1 token but each of the places "Top_1" and "Bottom_0" accepts 1 token when the transition "Move Upward" is activated. From the 7th row of the incidence matrix table, each of the places "Top_1" and "Bottom_0" releases 1 tokens but each of the places "Front_1", "Rear_0", "M1" and "p28" accepts 1 token when the transition "Move Forward" is activated. From the 8th row of the incidence matrix table, each of the places “Front_0” and “Rear_1” releases 1 token but the place “p28” accepts 1 token when the transition “t9” is activated. (4.2) shows the transpose of the incidence matrix of model B. The adjacent of incidence for model B obtained is a 14 X 8 matrix.

$$Adjacent\ of\ Incidence\ Matrix, C^T = \begin{bmatrix} -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 1 & 1 & -1 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{4.2}$$

Incidence Matrix - HiPS

Transition / Place	id0(Pallet)	id1(Base)	id2(Top)	id3(Front)	id5(Rear)	id7(Bottom)	id10(Hold)	id26(Release)	id19(p19)	id36(p36)	id40(p40)	id43(p43)
id4(Move Backward)	-1	-1	-1	-1	1	0	0	-1	0	1	0	0
id6(Move Downward)	0	0	0	0	-1	1	0	0	0	0	0	0
id8(Suction_1)	0	0	0	0	0	0	1	0	0	0	-1	0
id9(Move Upward)	0	0	1	0	0	0	0	0	-1	0	0	0
id22(Move Forward)	0	0	-1	1	0	0	0	0	0	0	0	0
id25(Suction_0)	0	0	0	0	0	-1	0	1	0	0	0	0
id30(H)	0	0	0	0	0	0	-1	0	1	0	0	1
id31(R)	0	0	0	0	0	0	0	-1	1	0	0	0
id42(t42)	0	0	0	0	0	0	0	0	0	0	1	-1
id37(t37)	0	0	0	0	0	-1	0	0	0	-1	1	0

Figure 4.8: Incidence matrix of petri net model C.

Figure 4.8 shows the incidence matrix of model C which obtained by using HiPS. From the 1st row of the incidence matrix table, each of the places “Pallet”, “Base”, “Top”, “Front” and “Release” releases 1 token but each of the places “Rear” and “p36” accepts 1 token when the transition “Move Backward” is activated. From the 2nd row of the incidence matrix table, the place “Rear” releases 1 token but the place “Bottom” accepts 1 token when the transition “Move Downward” is activated. From the 3rd row of the incidence matrix table, the place “p40” releases 1 token but the place “Hold” accepts 1 token when the transition “Suction_1” is activated. From the 4th row of the incidence matrix table, the place “p19” releases 1 token but the place “Top” accepts 1 token when the transition “Move Upward” is activated. From the 5th row of the incidence matrix table, the place “Top” releases 1 token but the place “Front” when the transition “Move Forward” is activated. From the 6th row of the incidence matrix table, the place “Bottom” release 1 token but the place “Release” accepts 1 token when the transition “Suction_0” is activated. From the 7th row of the incidence matrix table, the place “Hold” releases 1 token but each of the places “p19” and “p43” accepts 1 token when the transition “H” is activated. From the 8th row of the incidence matrix table, the place “Release” releases 1 token but the place “p19” accepts 1 token when the transition “R” is activated. From the 9th row of the incidence matrix table, the place “p43” releases 1 token but the place “p40” accepts 1 token when the transition “t42” is activated. From the 10th row of the incidence matrix table, each of the places “Bottom” and “t36” releases 1 token but the place “p40” accepts 1 token when the transition “t37” is activated. (4.3) shows the transpose of the incidence matrix of model C. The adjacent of incidence for model C obtained is a 12 X 10 matrix.

$$Adjacent\ of\ Incidence\ Matrix, C^T = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 \end{bmatrix} \quad (4.3)$$

4.3 Identify the structural and behavior properties of the petri net models by using Hierarchical Petri Net Simulator (HiPS).

4.3.1 Structural Properties

The structural properties analysis were carried out on model A, model B and model C are T-Invariants analysis and S-Invariants analysis. T-Invariant and S-invariant are the firing vectors that exist when there is a possible loop in the petri net where T-invariant respects to transition and S-invariant respects to place. The invariants for transition and place exist when the value of *CU*, dot-product of incidence matrix, *C* and the firing vector, *U* is equal to zero in (4.3). Hence, every marking will remain unchanged if there is an invariant in the petri net. This means that the next possible state activation of the transducers in the pick and place arm system is same as the initial one after a contraction-extension mechanism of actuator.

Table 4.7: Analysis on structural properties of model A, model B and model C.

	Model A	**Model B**	**Model C**
T-Invariant Analysis	No	No	No
S-Invariants Analysis	No	No	2 invariants

From the T-invariant analysis, all 3 models are verified that there is no looping process which respects to transitions can be happened throughout all the possible activations of transition. On the other hand, model A and model B are verified that there is no looping process which respects to can be happened throughout all the possible activations of transition. However, model C is verified that there are 2 set of places appear as S-invariants in model C with arrays [1 0 0 0 0 0 1 0 0 1 1 1] and [0 1 0 0 0 0 1 0 0 1 1 1] which respect to the arrangement of places "Pallet", "Base", "Top", "Front", "Rear", "Bottom", "Hold", "Release", "p19", "p36", "p40" and "p43". The values in the S-invariant indicate the number of tokens held by respective places for a looping process to happen. In case of S-invariant [1 0 0 0 0 0 1 0 0 1 1 1], the value of vector CU is equal to zero and therefore the marking for reaching exactly same set of places to the S-invariant is same to its initial marking. This told that the pick and place process will be stopped when the transducers include “Pallet”, “Hold”, “p36”, “p40” and “p43” are activated. Meanwhile, in case of S-invariant [0 1 0 0 0 0 1 0 0 1 1 1], the value of vector CU is equal to zero and therefore the marking for reaching exactly same set of places to the S-invariant is same to its initial marking. This told that the pick and place process will be stopped when the transducers include “Base”, “Hold”, “p36”, “p40” and “p43” are activated. From the analysis, model C is verified that there is 2 possible looping processes can be happened throughout all the possible activations of transition.

4.3.2 Behavior Properties

The behavior properties analysis were carried out on model A, model B and model C are analysis for reachability, deadlock, boundedness and reversibility.

Table 4.8: Analysis on behavior properties of model A, model B and model C.

	Model A	**Model B**	**Model C**
Reachability Analysis	2 reachable markings	359 reachable markings	35 reachable markings
Deadlock Analysis	Yes	No	Yes
Boundedness Analysis	2-bounded	51-bounded	32-bounded
Reversibility Analysis	None	10 reversible markings	9 reversible markings

From the reachability analysis, there are only 2 reachable marking in the model A which represents there are only 2 possible state activations of the transducers in the pick and place arm system. These markings are [0 0 0 0 0 1 0 0] and [1 1 0 0 0 0 2 0] which arranged orderly in places “Pallet”, “Base”, “Release”, “Hold”, “Bottom_1”, “Rear_1”, “Front_1” and “Top_1”. The initial marking of model A is expressed as [1 1 0 0 0 0 1 1]. The values in the marking represent the cumulative number of tokens in the respective places.

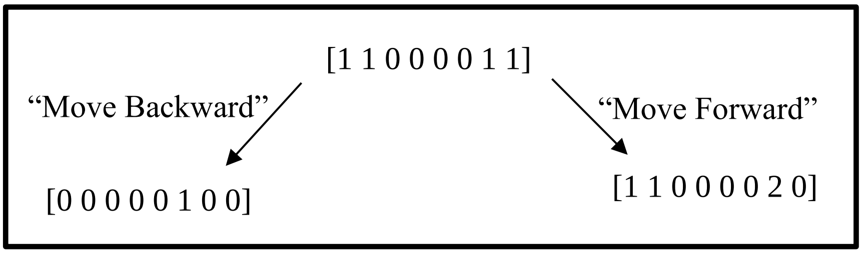

Figure 4.9: Reachability Graph of petri net model A.

Figure 4.9 shows the reachability graph of the model A. The marking [0 0 0 0 0 1 0 0] is generated from the initial marking through the activation of transition “Move Backward”. Besides, the marking [1 1 0 0 0 0 2 0] is generated from the initial marking through the activation of transition “Move Forward”. There are 359 reachable markings in the model B which represents there are 359 possible state activations of the transducers in the pick and place arm system. These reachable markings are arranged orderly in places “Pallet_1”, “Base_1”, “Top_1”, “Top_0”, “Front_1”, “Front_0”, “Rear_0”, “Rear_1”, “Bottom_0”, “Bottom_1”, “Hold”, “Release”, “M1” and “p28”. The initial marking of model B is expressed as [1 1 0 0 0 0 1 1]. There are 35 reachable markings in the model C which represents there are 35 possible state activations of the transducers in the pick and place arm system. These reachable markings are arranged orderly in places “Pallet”, “Base”, “Top”, “Front”, “Rear”, “Bottom”, “Hold”, “Release”, “p19”, “p36”, “p40” and “p43”. The initial marking of model C is expressed as [1 1 1 1 0 0 0 1 0 0 0 0].

From the deadlock analysis, there is 1 deadlock found after the activation of transition “Move Backward” where marking [0 0 0 0 0 1 0 0] is generated respected to arrangement of places “Pallet”, “Base”, “Release”, “Hold”, “Bottom_1”, “Rear_1”, “Front_1” and “Top_1”. From the result obtained, the cause of occurrence of deadlock in the model A is preemption where the place “Front_1” releases voluntarily its token to place “Rear_1” via transition “Move Backward” as shown in Figure 4.10. Thus, there is no more token left in the place “Front_1” to activate the transition “Move Downward”. As the result, the pick and place arm will be stopped after it moved backward.

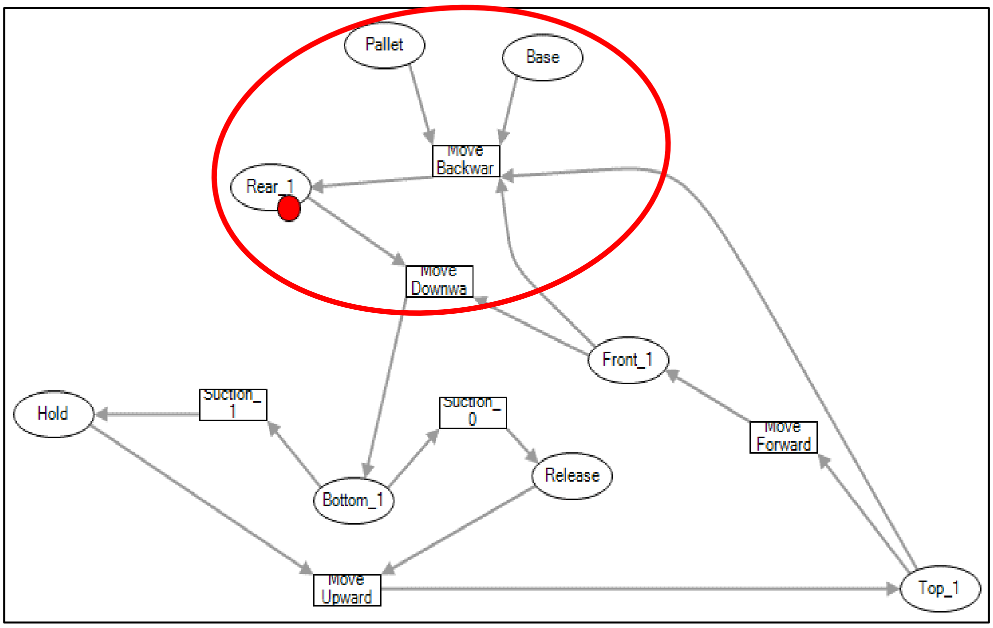

Figure 4.10: Firing step where deadlock occurs in model A.

However, there is no deadlock found in model B. For model C, there is 1 deadlock found after the activation of transition "Move Forward" where the marking [0 0 0 1 0 0 0 0 0 1 0 0] is generated respected to arrangement of places "Pallet", "Base", "Top", "Front", "Rear", "Bottom", "Hold", "Release", "p19", "p36", "p40"and "p43". From the result obtained, the cause of occurrence of deadlock in the model C is hold and wait where the place "Front" is waiting for the places "Pallet", "Base", "Release" and "Top" to be refilled with token to activate the transition "Move Backward" as shown in Figure 4.11. As the occurrence of deadlock, the process of pick and place mechanism will be stopped after the pick and place arm is moved backward.

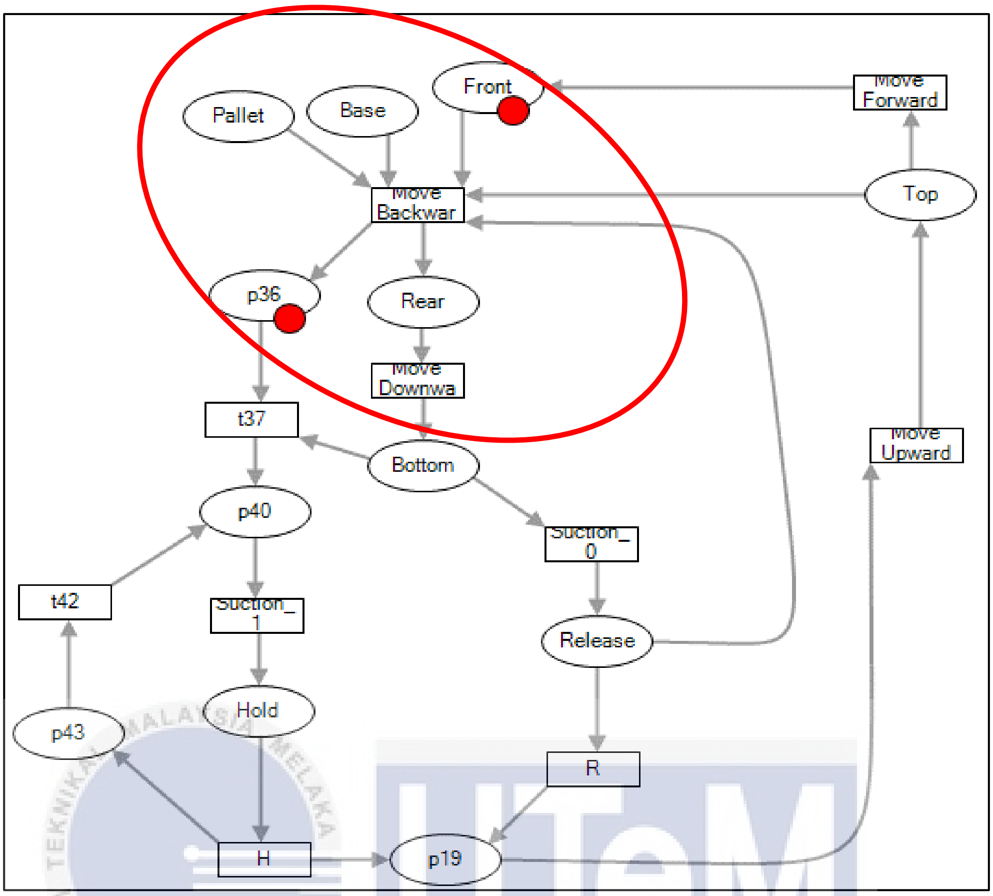

Figure 4.11: Firing step where deadlock occurs in model C.

From the boundedness analysis, the bounded value for the model A is 2 which mean the maximum tokens held by the place “Front_1” against other places is 2 tokens where occurs in marking [1 1 0 0 0 0 2 0] which respect to arrangement of place “Pallet”, “Base”, “Release”, “Hold”, “Bottom_1”, “Rear_1”, “Front_1” and “Top_1”. Besides, the bounded value for the model B is 51 which means the maximum tokens that can be held by each of the places “Front_1” and “Rear_0” against other places is 51 tokens where occurs in marking [1 1 0 0 51 0 51 0 0 0 0 0 1 50] which respect to arrangement of places “Pallet_1”, “Base_1”, “Top_1”, “Top_0”, “Front_1”, “Front_0”, “Rear_0”, “Rear_1”, “Bottom_0”, “Bottom_1”, “Hold”, “Release”, “M1” and “p28”. Since the tokens in the marking is added cumulatively, the tokens amount is reached to 51 tokens throughout all 359 times activations of transitions. This indicates that the certain states of the system will be kept at status activated to 51 steps although there are other state changes to be occurred throughout the whole process. For model C, the bounded value reached 32 which means the maximum tokens that can be held by the place “p19” against other places is 32 tokens where occurs in markings [0 0 0 0 0 0 0 0 32 0 0 1] and [0 0 0 0 0 0 0 0 32 0 1 0] which respect to arrangement of places “Pallet”, “Base”, “Release”, “Hold”, “Bottom_1”, “Rear_1”, “Front_1” and “Top_1”. Since the tokens in the marking is added cumulatively, the tokens amount is reached to 32 tokens throughout all 35 times activations of transitions. This indicates that the certain states of the system will be kept at status activated to 35 steps although there are other state changes to be occurred throughout the whole process.

From the reversibility analysis, there is no reversible marking in the model A which mean the initial marking cannot be reached from any reachable marking. This means that the initial positions of the pick and place arm cannot be reached for every possible activations of transducers. For model B, there are 10 reversible markings include [0 0 1 0 1 1 1 1 1 0 0 0 0 0], [0 0 0 0 2 1 2 1 0 0 0 0 1 1], [0 0 0 1 2 1 2 1 0 1 0 0 0 0], [0 0 1 0 2 1 2 1 1 0 0 0 0 1], [0 0 0 0 2 0 2 0 0 0 0 0 1 2], [0 0 1 0 1 0 1 0 1 0 0 0 0 1], [1 1 0 0 2 0 2 0 0 0 0 0 1 1], [1 1 0 1 2 0 2 0 0 1 0 0 0 0], [1 1 0 0 2 0 2 0 0 0 1 0 1 0] and [1 1 1 0 2 0 2 0 1 0 0 0 0 1] which means the initial marking can be reached from any of these reversible markings. The arrangement of tokens in these reversible markings respect to “Pallet_1”, “Base_1”, “Top_1”, “Top_0”, “Front_1”, “Front_0”, “Rear_0”, “Rear_1”, “Bottom_0”, “Bottom_1”, “Hold”, “Release”, “M1” and “p28”. Therefore, the process of pick and place mechanism is able to be reversed in these sets of state changes which indicates the flexibility of the system. For model C, there are 9 reversible markings include [0 0 0 0 1 0 0 0 0 1 0 0], [0 0 0 0 0 1 0 0 0 1 0 0], [0 0 0 0 0 0 0 1 0 1 0 0], [0 0 0 0 0 0 0 0 0 0 1 0], [1 1 0 2 0 0 0 1 0 0 0 0], [1 1 0 2 0 0 0 0 1 0 0 0], [1 1 1 2 0 0 0 0 0 0 0 0], [1 1 1 1 0 0 0 0 1 0 0 0] and [1 1 2 1 0 0 0 0 0 0 0 0] in the model C which means the initial marking can be reached from any of these reversible markings. The arrangement of tokens in these reversible markings respect to “Pallet”, “Base”, “Release”, “Hold”, “Bottom_1”, “Rear_1”, “Front_1” and “Top_1”. Thus, the process of pick and place mechanism is able to be reversed in these sets of state changes which indicate the flexibility of the system.

4.4 Summary

From the results obtained, I notice that the petri net modeling is easy to carry out and visualize in graphically. The activation of transducers are interpreted as places while the contraction-extension mechanism of actuators are interpreted as transition in petri net. The markings of a petri net model are based on the probability of the outputs (transitions) which controlled by the manipulated inputs (places).

From the incidence matrix obtained, I can conclude that petri net can prevent the state explosion problem as this approach can be applied on the system with incidence matrix size up to 14 X 8. The steps to generate the incidence matrix become easier with the use of petri net approach.

The results show that the structural properties have close associations with the behavior properties. This can be seen from the invariants which indicate that the next possible state activation of the transducers in the pick and place arm system is same as the initial one after a contraction-extension mechanism of the actuator.

To relate the invariants to deadlock properties, I notice that there is a possible for a deadlock to occur in the system model with invariants which may causes the pick and place mechanism to stop. To relate the invariants to reachability properties, I notice that there are lesser reachable markings in the system with invariants. This is because the pick and place mechanism is stopped when there is a deadlock and no other possible state activation of transducers can be generated to conduct the contraction-extension mechanism of the actuators.

The invariants cannot be interconnected with the reversibility properties because the unchanged states are totally differed to the reversible states. Besides, the boundedness is related to the reachability properties because the bounded states can be formed when only all the reachable markings are executed. The symbol "ω" in the reachable markings indicates the cumulative addable tokens number throughout all the reachable markings. After passing all the reachable marking, "ω" is replaced with the cumulated tokens number which also called as the bounded value in boundedness analysis.

Model B is the best design among these 3 petri net models because it is verified as deadlock-free. Besides, model B is verified with the highest amount of reachable markings which indicates there is higher possibility for every contraction-extension mechanisms of the actuators to be performed. Moreover, model B is verified to have the highest amount of reversible markings which the pick and place mechanism can be retraced in reverse order. This eases the problem-troubleshooting process when the pick and place arm system is down. However, model B is unsafe since the bounded value is high which is 51-bounded.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the objectives of this project which includes modeling, incidence matrix identification and properties verifications with petri net approach were accomplished in 3 tasks assigned. Hierarchical Petri Net Simulator (HiPS) was used in modeling and verifications of the structural and behavior properties of the pick and place arm model. With the petri net approach, the state explosion problem can be prevented since graphical modeling method was used. The steps for petri net verification is simple with the use of HiPS. From the results, the invariants should be eliminated in the petri net model to prevent deadlock occurs and produce more reachable and reversible markings. However, HiPS software is not completely designed on the Linear Time Logic temporal modal checking technique yet. This may cause poor conviction on the verified results of the petri net model. Besides, there are spaces for improvement for the petri net model B designed in this project by reducing its size and bounded value to increase the safeness of the model.

To increase the efficiency and durability of the pick and place arm system, petri net approach should be taken for the system modeling during the system development and system verification during the product design process. This can reduce the high cost in human labor during machine operations and maintenance fees for system breakdown. At the same time, it can increase the productivity of a company.

5.2 Future Works

More researches and developments on the HiPS software should be done to idealize the model checking techniques via petri net approach. The performance of the pick and place system can be enhanced by designing better petri net model by using states reduction technique. This can reduce the number of inputs and outputs of the system which can save cost during developing the pick and place system.

With the petri net approach, the verifications on safeness and liveness properties can be carried out in the future. This can increase the parameters of system properties which can increase the accuracy of the verification results.

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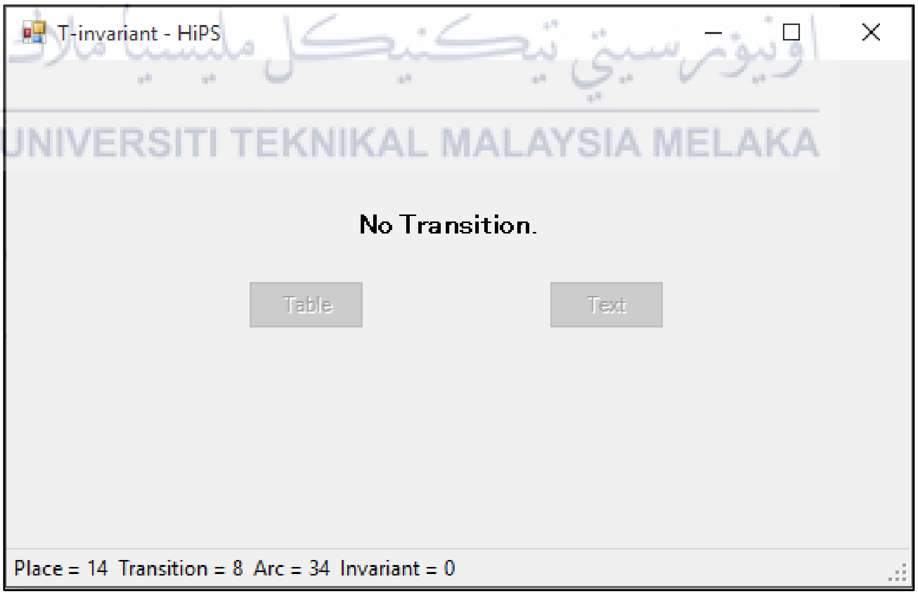
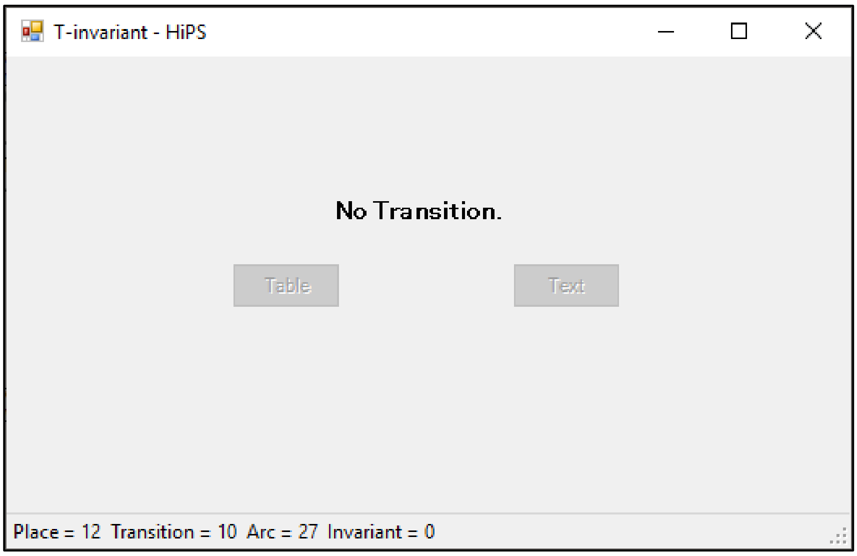
APPENDICES

APPENDIX A: T-INVARIANT ANALYSIS OF MODEL A.

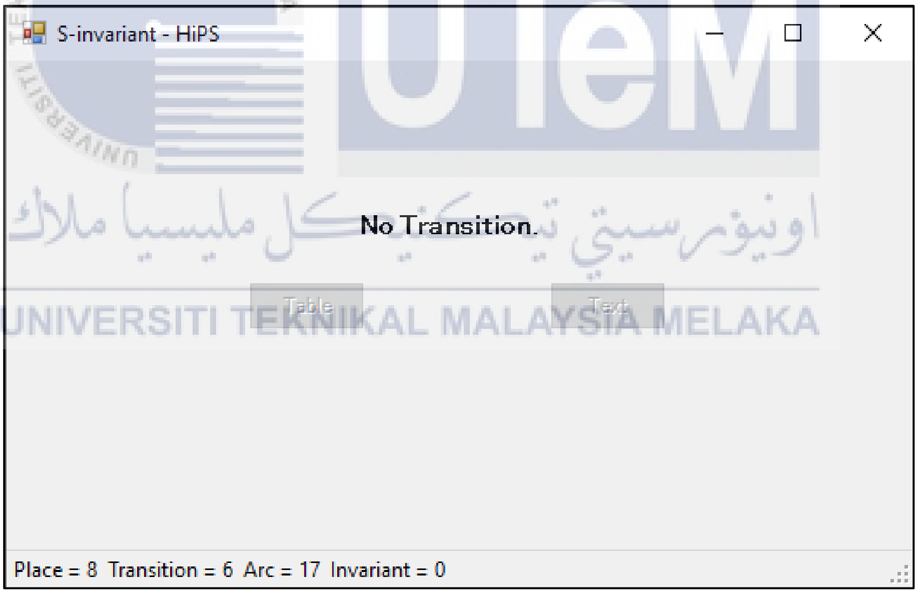
APPENDIX B: T-INVARIANT ANALYSIS OF MODEL B.



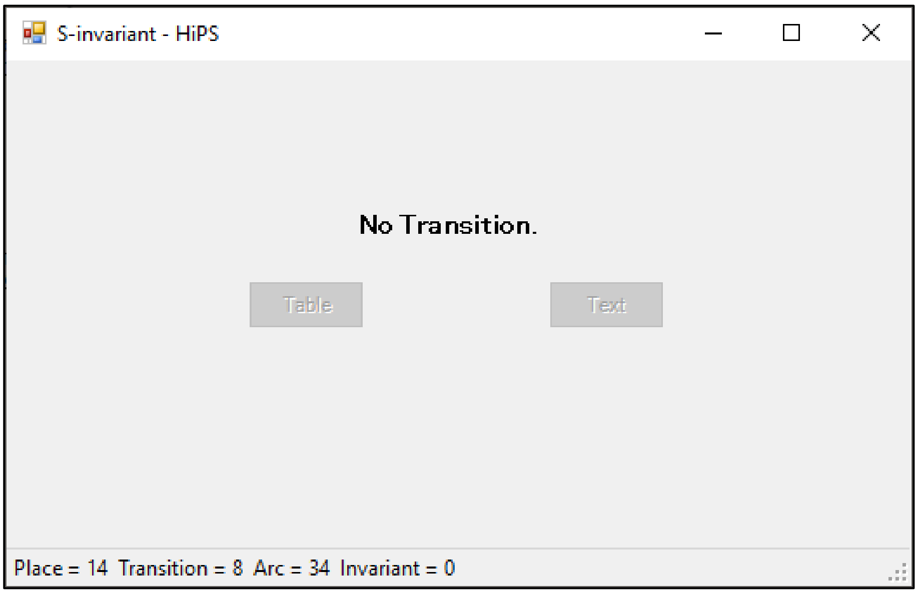
APPENDIX C: T-INVARIANT ANALYSIS OF MODEL C.



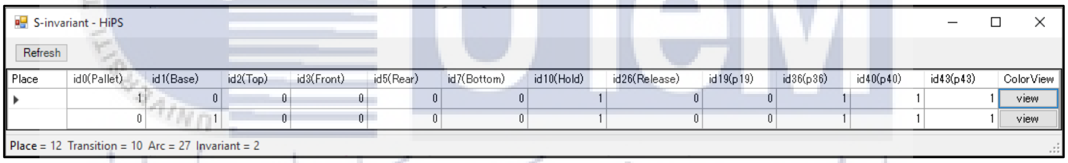
APPENDIX D: S-INVARIANT ANALYSIS OF MODEL A.



APPENDIX E: S-INVARIANT ANALYSIS OF MODEL B.



APPENDIX F: S-INVARIANT ANALYSIS OF MODEL C.

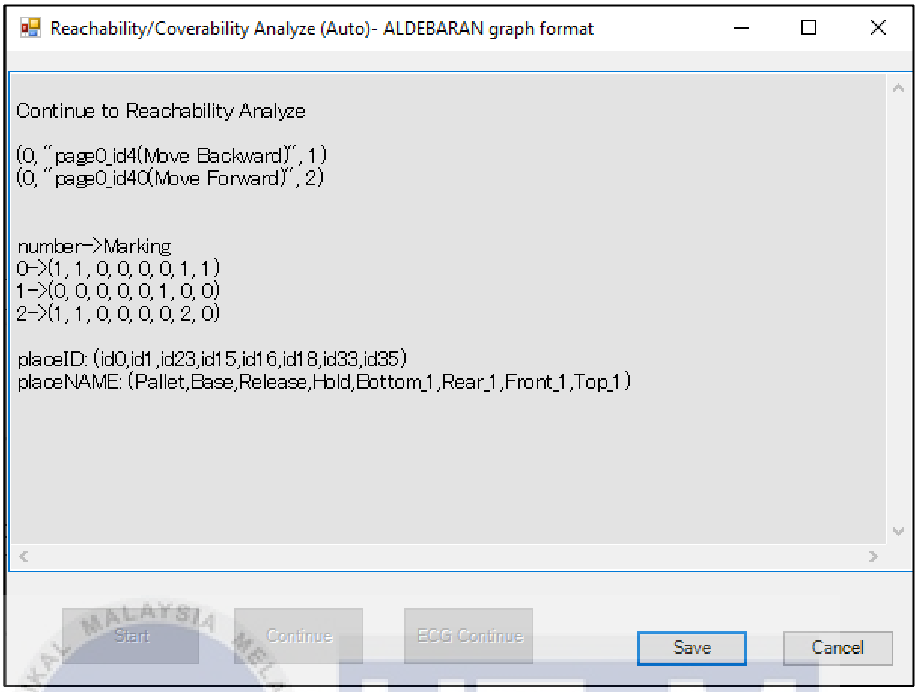

S-invariant - HiPS

Refresh

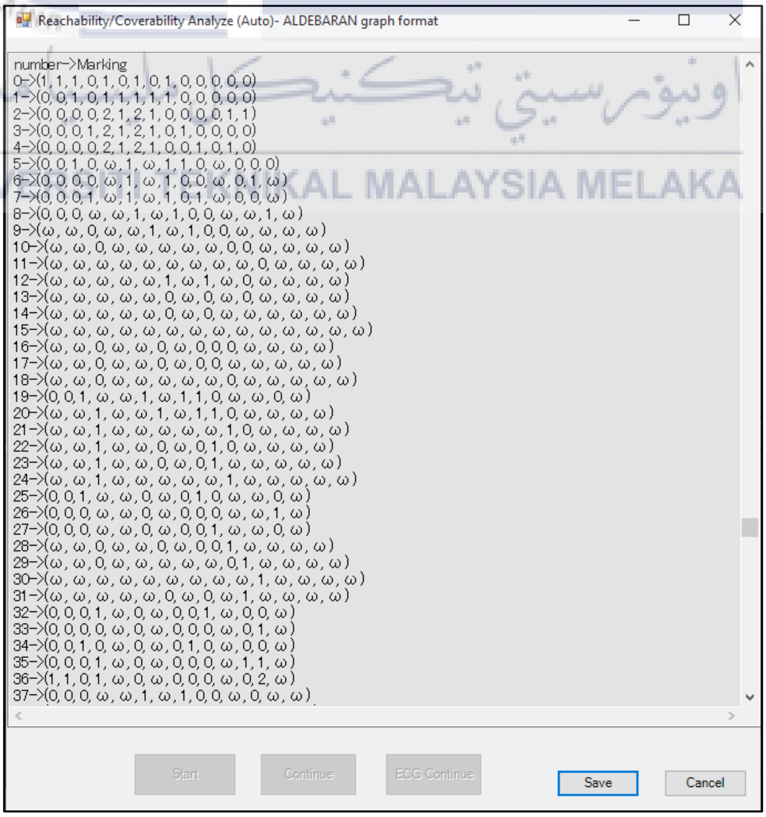
Place	id0(Pallet)	id1(Base)	id2(Top)	id3(Front)	id5(Rear)	id7(Bottom)	id10(Hold)	id26(Release)	id19(p19)	id36(p36)	id40(p40)	id43(p43)	ColorView
▸	1	0	0	0	0	0	1	0	0	1	1	1	view
	0	1	0	0	0	0	1	0	0	1	1	1	view

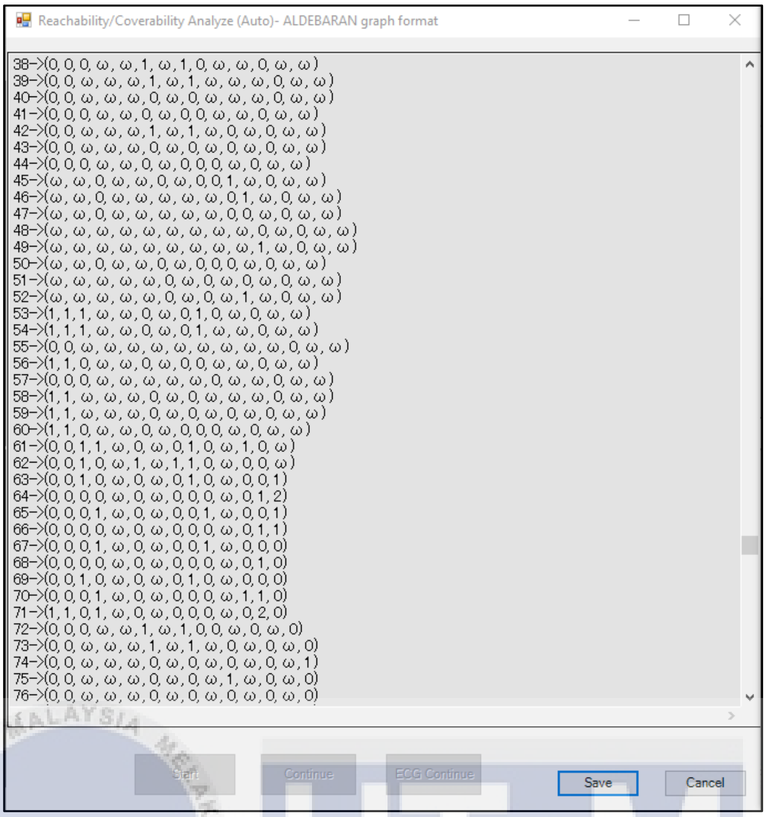
Place = 12 Transition = 10 Arc = 27 Invariant = 2

APPENDIX G: REACHABILITY ANALYSIS OF MODEL A.



APPENDIX H: REACHABILITY ANALYSIS OF MODEL B.




Reachability/Coverability Analyze (Auto)- ALDEBARAN graph format
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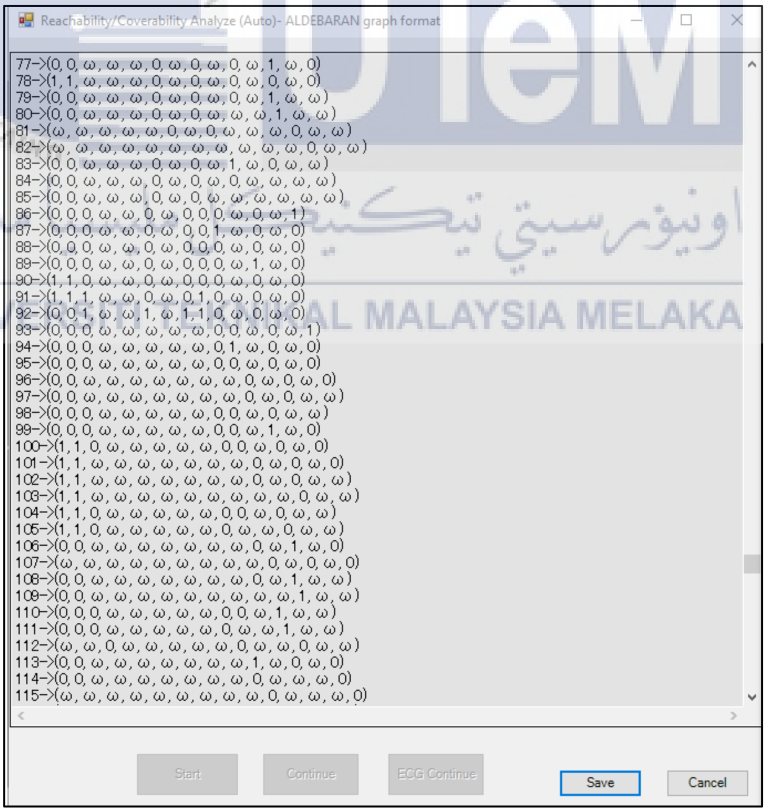
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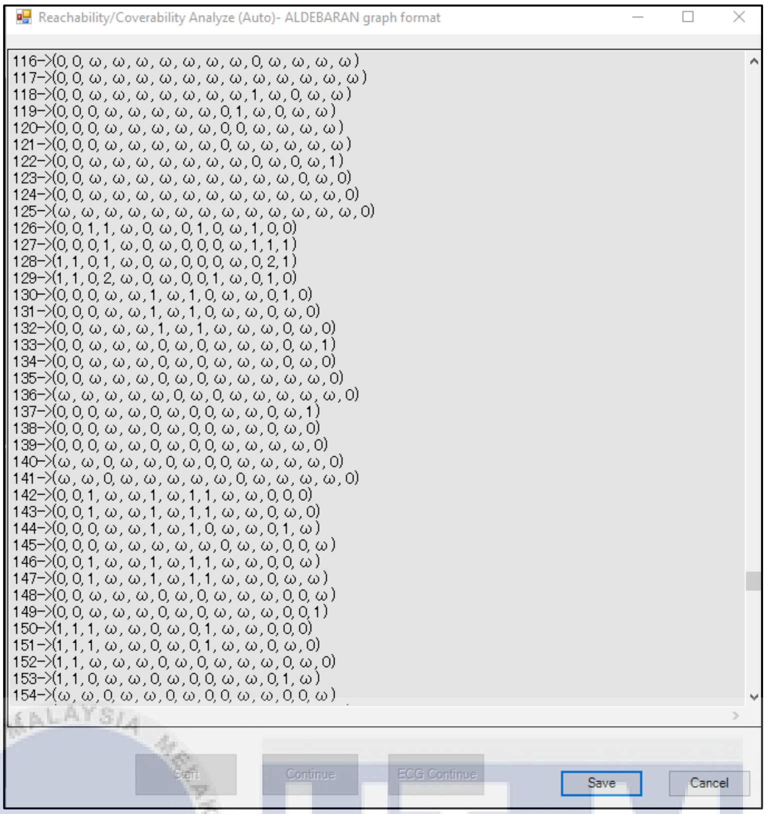
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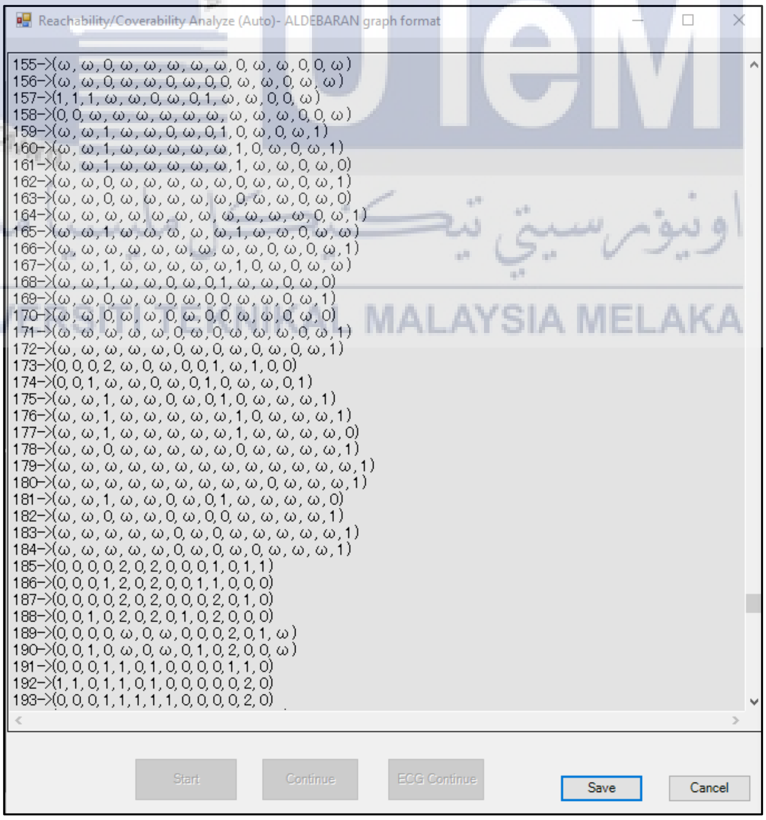
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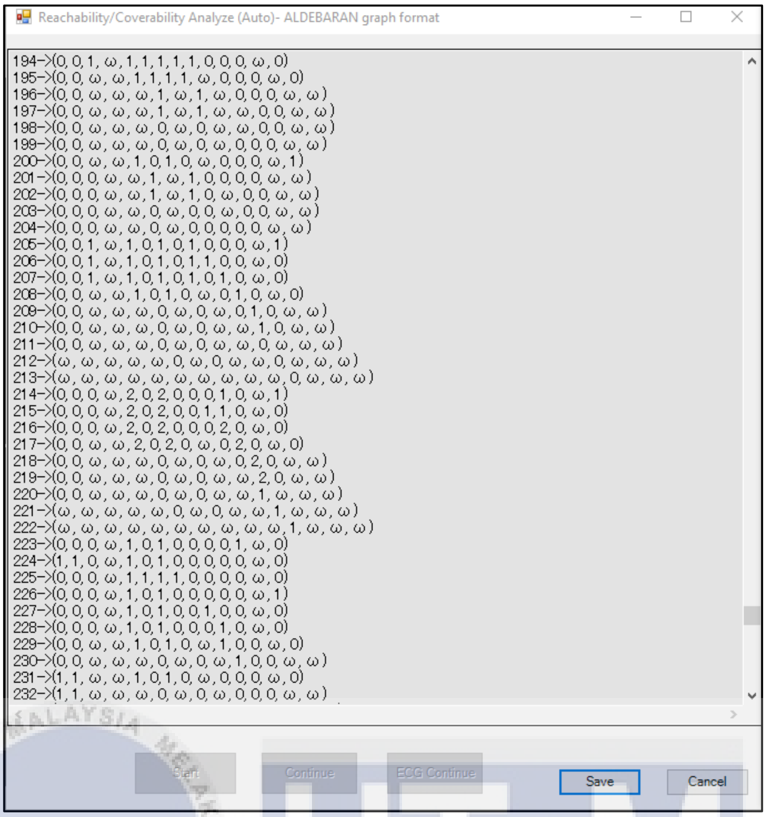
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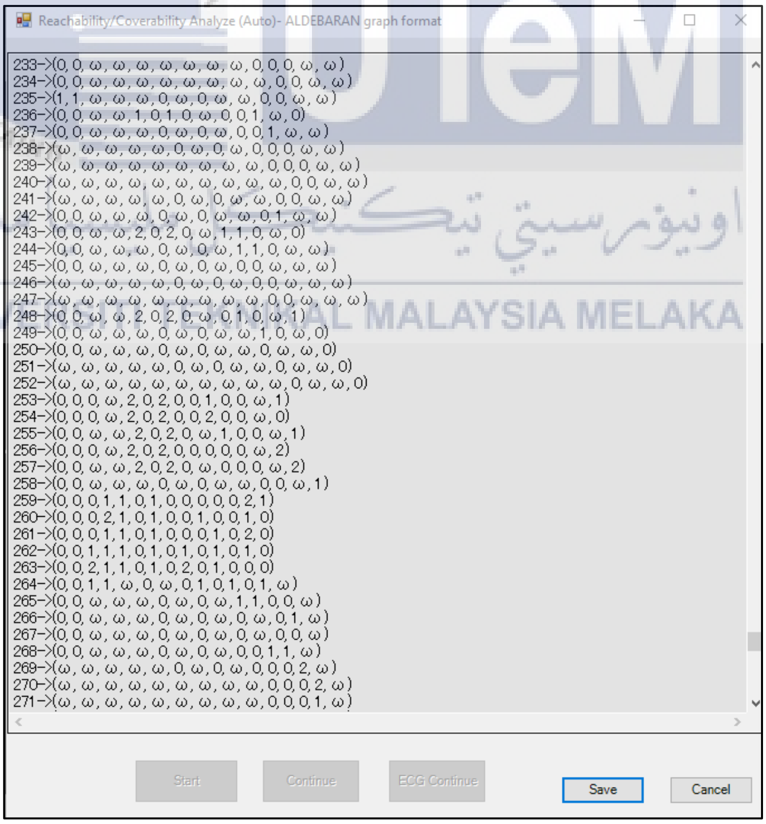
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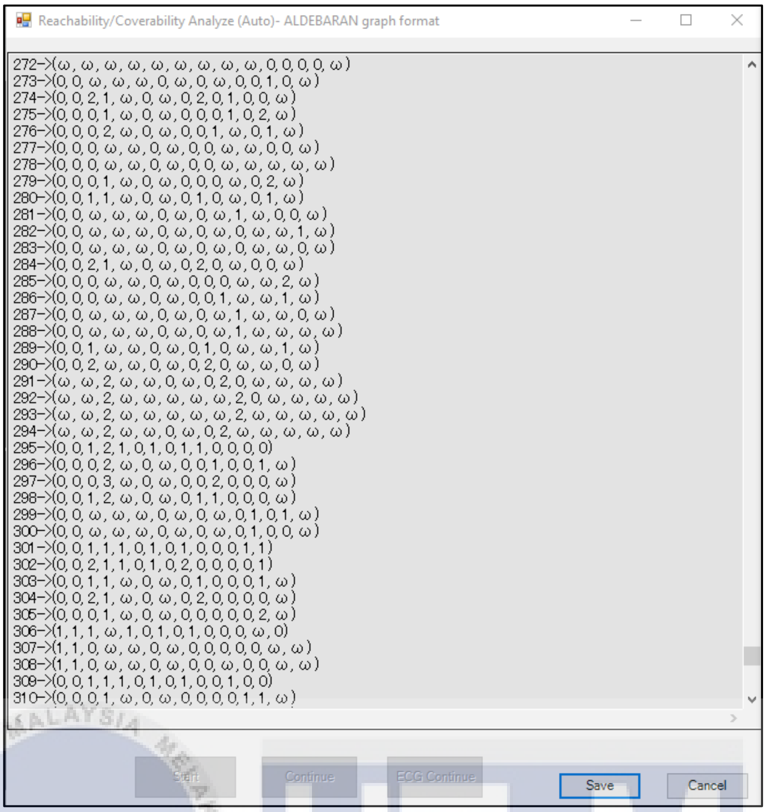
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310->(0, 0, 0, 1, ω, 0, ω, 0, 0, 0, 0, 1, 1, ω)
Start
Continue
ECG Continue
Save
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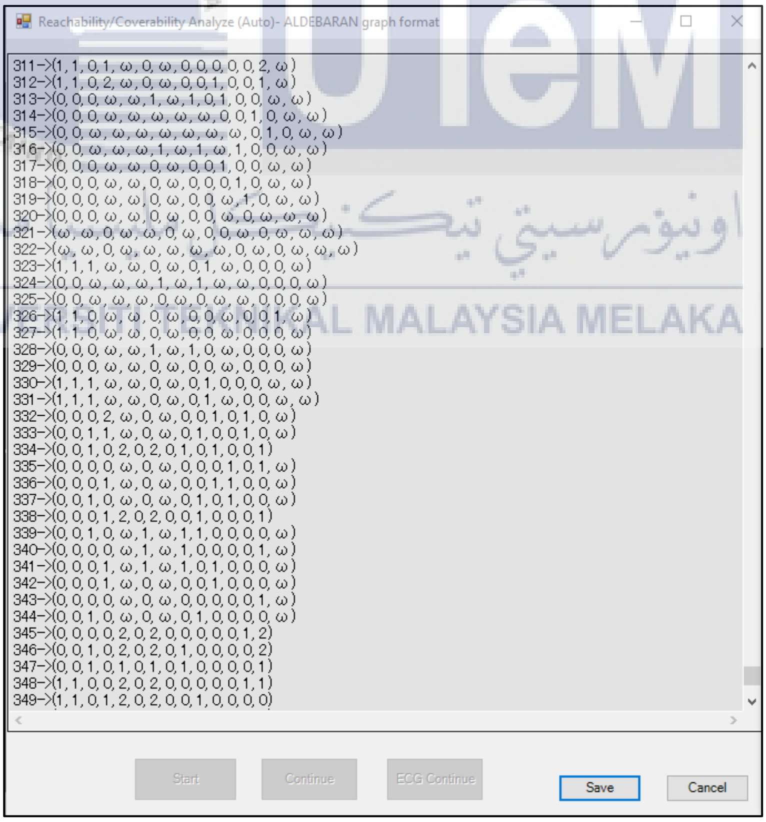
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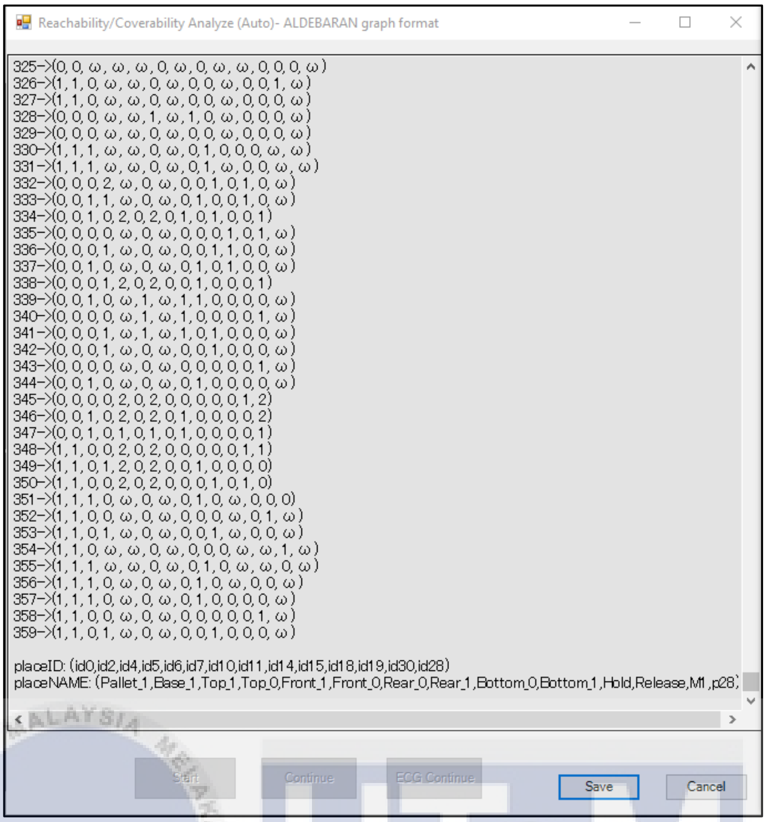
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346->(0, 0, 1 , 0, 2, 0, 2, 0, 1 , 0, 0, 0, 0, 2)
347->(0, 0, 1 , 0, 1 , 0, 1 , 0, 1 , 0, 0, 0, 0, 1)
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350->(1 , 1 , 0, 0, 2, 0, 2, 0, 0, 0, 1 , 0, 1 , 0)
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353->(1 , 1 , 0, 1 , ω , 0, ω , 0, 0, 1 , ω , 0, 0, ω)
354->(1 , 1 , 0, ω , ω , 0, ω , 0, 0, 0, ω , ω , 1 , ω)
355->(1 , 1 , 1 , ω , ω , 0, ω , 0, 1 , 0, ω , ω , 0, ω)
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ECG Continue
Save
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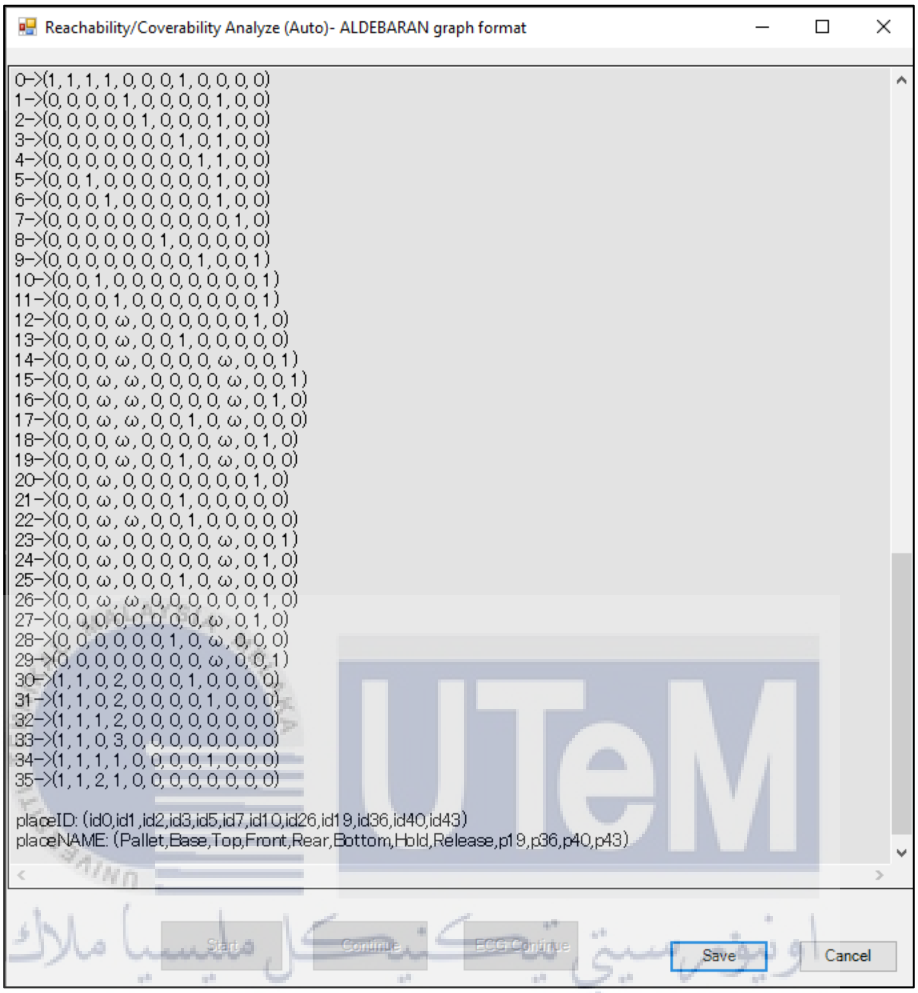
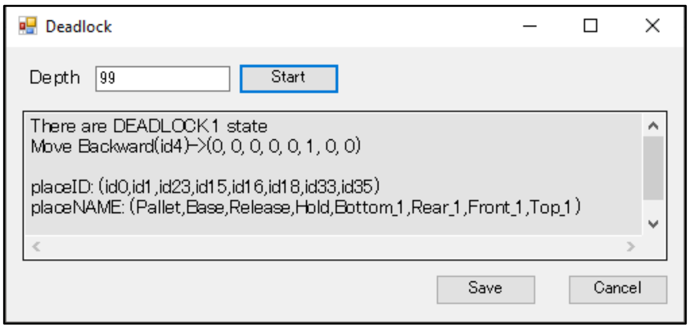
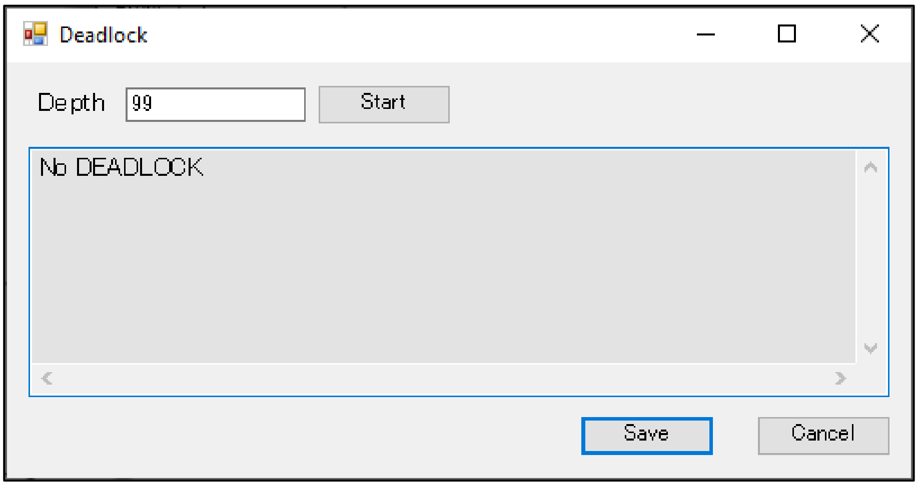
APPENDIX I: REACHABILITY ANALYSIS OF MODEL C.



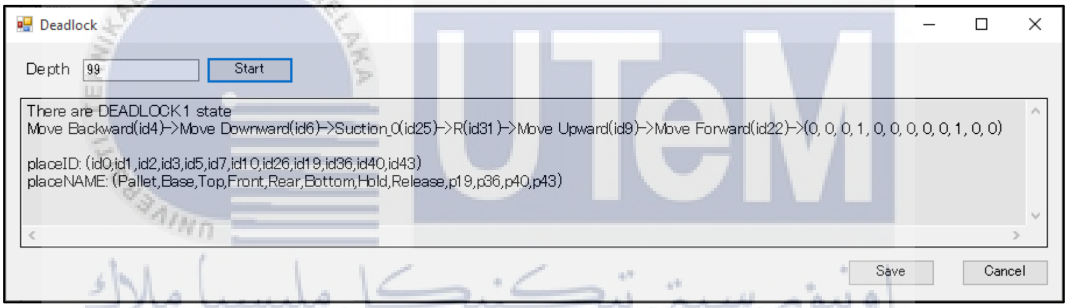
APPENDIX J: DEADLOCK ANALYSIS OF MODEL A.



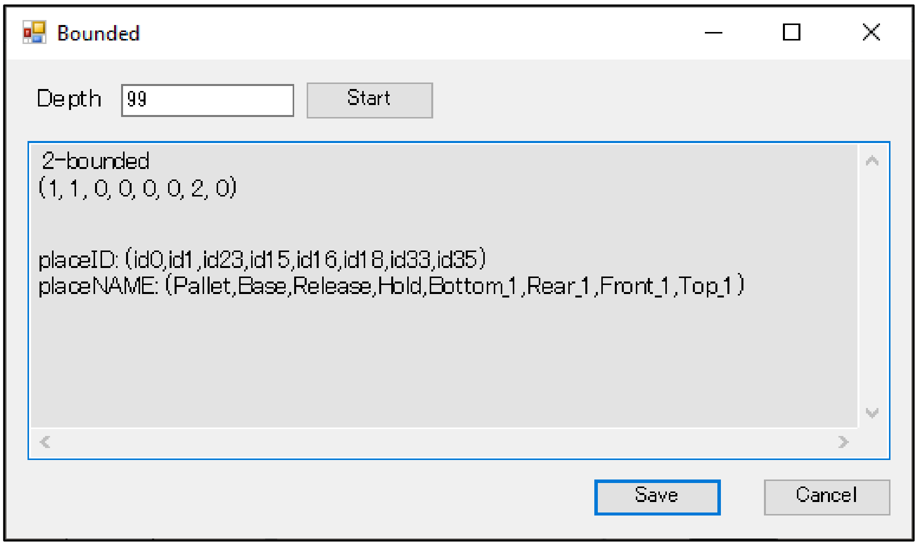
APPENDIX K: DEADLOCK ANALYSIS OF MODEL B.



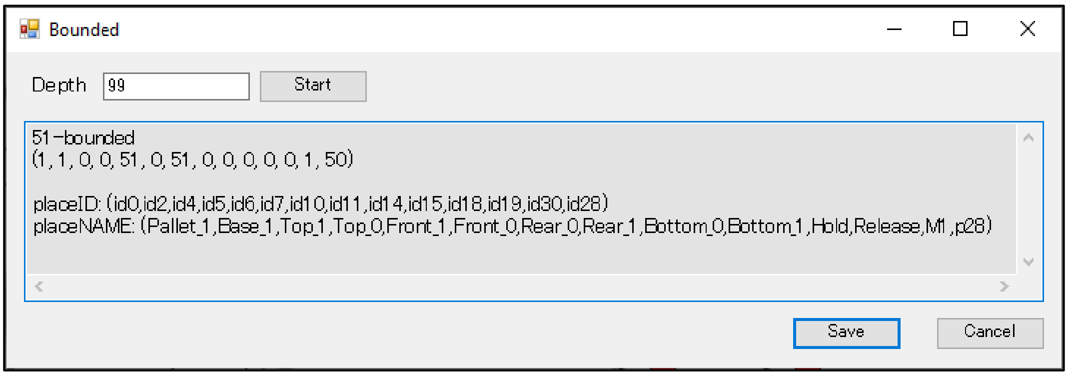
APPENDIX L: DEADLOCK ANALYSIS OF MODEL C.



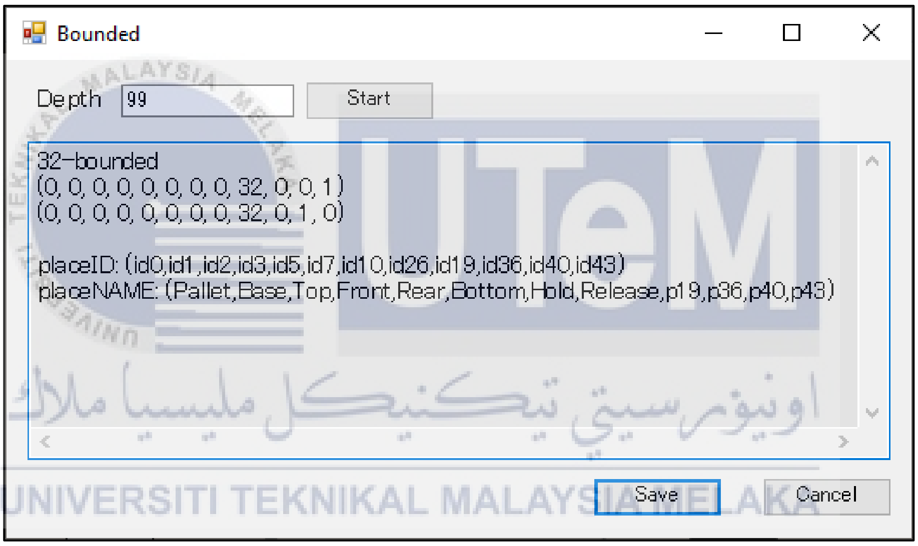
APPENDIX M: BOUNDEDNESS ANALYSIS OF MODEL A.



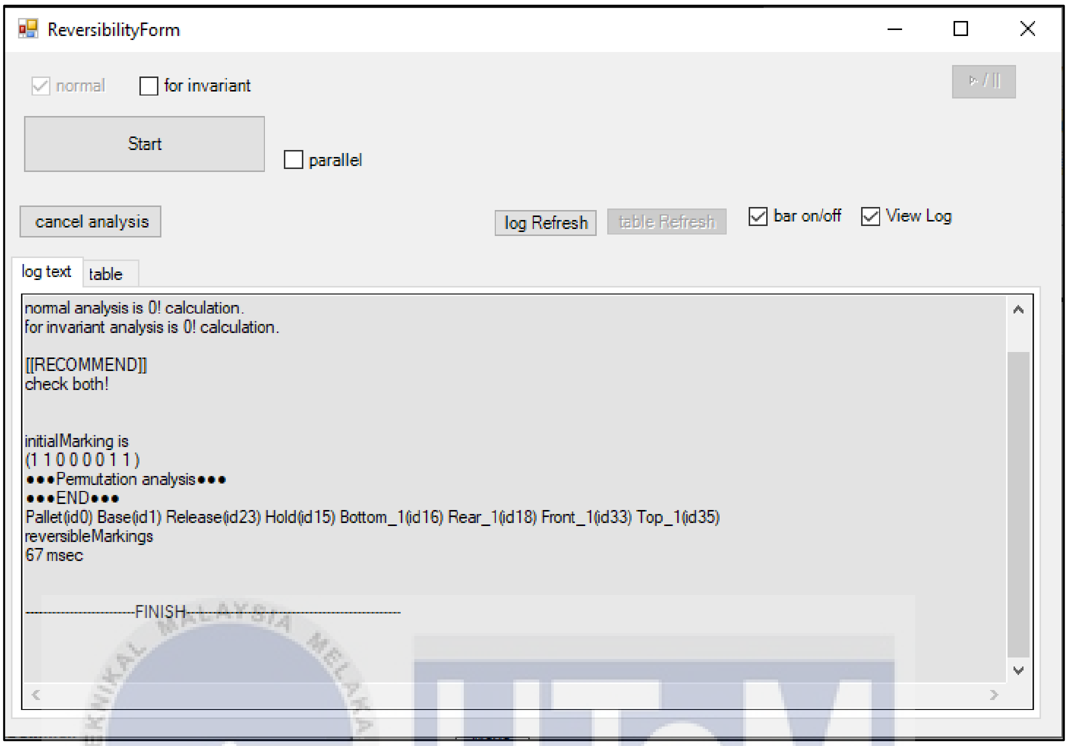
APPENDIX N: BOUNDEDNESS ANALYSIS OF MODEL B.



APPENDIX O: BOUNDEDNESS ANALYSIS OF MODEL C.

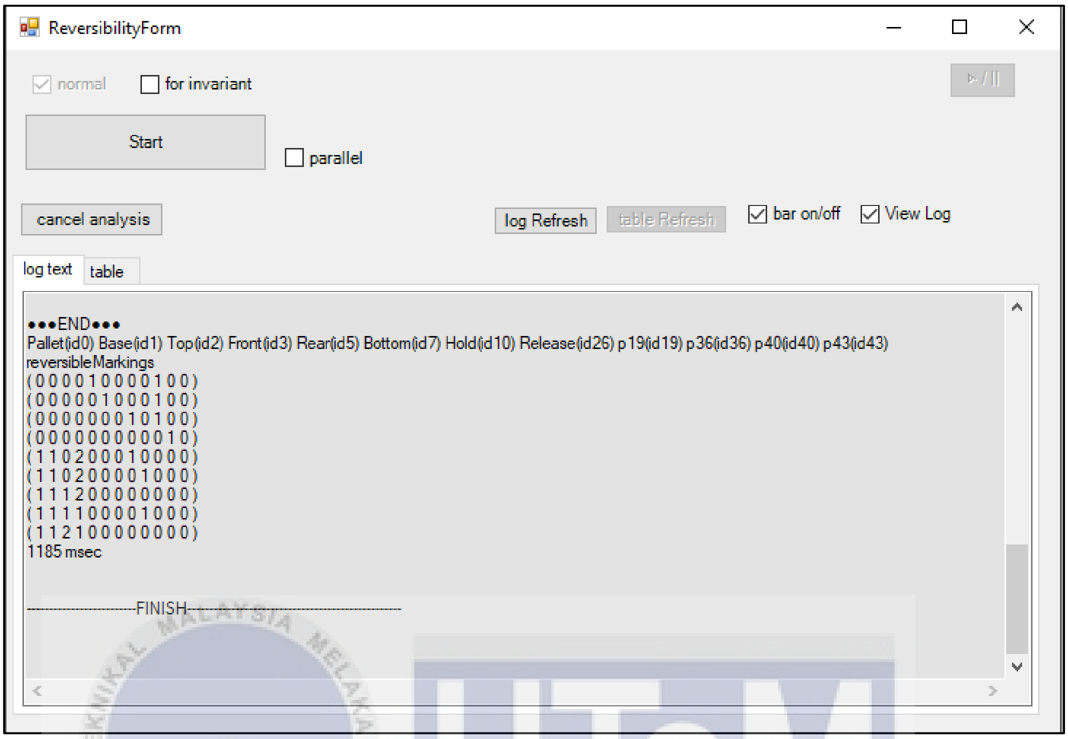


APPENDIX P: REVERSIBILITY ANALYSIS OF MODEL A.



APPENDIX Q: REVERSIBILITY ANALYSIS OF MODEL B.

APPENDIX R: REVERSIBILITY ANALYSIS OF MODEL C.



APPENDIX S: PROJECT GANNT CHART