

MODELLING AND SIMULATION OF SPINE LAYOUT DESIGN FOR  
FLEXIBLE MANUFACTURING SYSTEM IN DIGITAL FACTORY  
PLATFORM

PHOON SIN YE

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Name of Candidate: **PHOON SIN YE**

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# **MODELING AND SIMULATION OF SPINE LAYOUT DESIGN FOR FLEXIBLE MANUFACTURING SYSTEM IN DIGITAL FACTORY PLATFORM**

## **ABSTRACT**

This research presents the integration of information technology and digital three-dimensional (3D) modelling and simulation technology to build a digital factory in a virtual environment. Within the digital factory platform, a robotic work-cell and multi-stations flexible manufacturing system were developed to serve as an alternative decision-making tool in solving manufacturing system problems intuitively. The general framework for digital factory platform development was designed by utilizing various software such as 3D modelling, computer graphic programming, virtual reality (VR) and programming language. In the first phase of this study, a virtual robotic work-cell is built as a test model to determine the degree of interaction between the user and the digital factory, the capability of work-cell simulation, and the data collection from the digital factory platform to aid in decision-making. The digital platform enables intuitive interaction between the user and the virtual robotic work-cell while being capable of data collection. Through multiple simulation scenario of various process sequence of the same manufacturing part, simulation result shows that the difference in travel distance of part is up to 441.96% for different process sequence. In the second phase, a virtual loop layout model is developed and validated with a difference of 1.0% to 1.2% comparing to numerical results from literature study. A case study of allocation of shortcut conveyor in various positions within the developed virtual loop layout is then conducted to investigate the capability of digital factory platform to solve plant layout design problem. The digital factory platform simulated the impact of shortcut conveyor allocation in different position, and the results show that proper design of layout successfully reduced

the loop congestion by 33.33% and total part travel distance by 10.64%. The developed digital factory platform in a virtual environment shows its capability to model and simulate manufacturing activities in 3D and to control and receive manufacturing data intuitively. The platform also acts as a scenario-based decision-making tool for optimizing process sequences and layout design.

**Keywords:** Digital Factory, Virtual Simulation, Flexible Manufacturing System, Facility Layout Problem, Process Sequencing Problem

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# **MODEL DAN SIMULASI REKAAN SUSUN ATUR JENIS SPINE UNTUK SISTEM PEMBUATAN FLEKSIBEL DALAM PLATFORM KILANG DIGITAL**

## **ABSTRAK**

Kajian ini membentangkan integrasi teknologi maklumat dan digital tiga dimensi (3D) pemodelan dan simulasi teknologi untuk membina sebuah kilang digital dalam persekitaran maya. Dalam platform kilang digital, robotik kerja-sel dan sistem pembuatan fleksibel multi-stesen telah direka dan diguna sebagai alat alternatif dalam membuat keputusan untuk menyelesaikan masalah sistem pembuatan secara intuitif. Rangka kerja umum untuk pembinaan platform kilang digital direka dengan penggunaan pelbagai perisian seperti perisian 3D pemodelan, perisian pengaturcaraan grafik komputer, perisian realiti maya dan bahasa pengaturcaraan. Dalam fasa pertama pengajian, robot kerja-sel maya dibina sebagai model ujian untuk mengkaji tahap interaksi antara pengguna dan kilang digital, keupayaan mensimulasi kerja-sel dan pengumpulan data dari platform kilang digital. Platform digital membolehkan interaksi intuitif antara pengguna dan maya robot kerja-sel dengan keupayaan pengumpulan data. Melalui pelbagai senario simulasi pelbagai urutan proses pembuatan bahagian sama, hasil simulasi menunjukkan bahawa perbezaan dalam jarak perjalanan bahagian mencapai 441.96% dalam urutan proses yang berbeza. Dalam fasa kedua, susun atur gelung model maya telah dibina dan disahkan dengan peratusan perbezaan dari 1.0% ke 1.2% berbanding dengan keputusan berangka daripada kajian sebelumnya. Satu kajian kes peruntukan penghantar jalan pintas di kedudukan pelbagai dalam susun atur gelung maya telah dijalankan untuk mengkaji keupayaan platform kilang digital dalam menyelesaikan masalah susun atur kilang. Platform kilang digital simulasi kesan penghantar jalan pintas dalam kedudukan yang berbeza, keputusan menunjukkan bahawa reka bentuk susun atur

yang sesuai berjaya mengurangkan kesesakan gelung dengan 33.33% dan jumlah jarak perjalanan dengan 10.64%. Platform kilang digital yang dibina dalam persekitaran maya menunjukkan keupayaan untuk pemodelan dan simulasi aktiviti perkilangan dalam 3D dan mampu untuk mengawal dan menerima data pembuatan secara intuitif, platform kilang digital boleh digunakan sebagai alat membuat keputusan berasaskan senario mengoptimumkan urutan proses dan reka bentuk susun atur.

**Kata Kunci:** Kilang Digital, Simulasi Maya, Sistem Pembuatan Fleksibel, Masalah Atur Susun Faciliti, Masalah Atur Susun Proses

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## **CHAPTER 1**

### **INTRODUCTION**

#### **1.0 Introduction**

This chapter begins with a background study on two major elements of this research; the manufacturing sector and the digital factory theory with emphasis on the importance of manufacturing sector in the world's perspective, and the basic digital factory theory with its current development. After that, the major problems faced by current manufacturing industries is discussed in the next section, followed by the objective of this study which is to provide an alternative method based on digital factory theory to solve the aforementioned problems. Lastly, the significance of this study along with the scope and limitation is discussed, finally concluding with the thesis organization structure.

#### **1.1 Manufacturing Industry**

Manufacturing industry is a complex system which greatly affects the economic structure of a country. In some cases, manufacturing industry is the main contributor to the gross value added (GVA) of the country. A review conducted by Maynard (2015) based on the database from National Accounts Statistics: Analysis of Main Aggregates 2013 analysed the importance of manufacturing industry for the economy for different nations. In the review, the importance of manufacturing industry was measured by the percentage of gross added value of the manufacturing industry to their national economic output and summarized in a horizontal bar graph (Figure 1.1). Based on the review, the

manufacturing sector remains as the largest contributor to the GVA in the countries reviewed compared to other fields such as agriculture, mining, construction, trading, logistics, and others,.

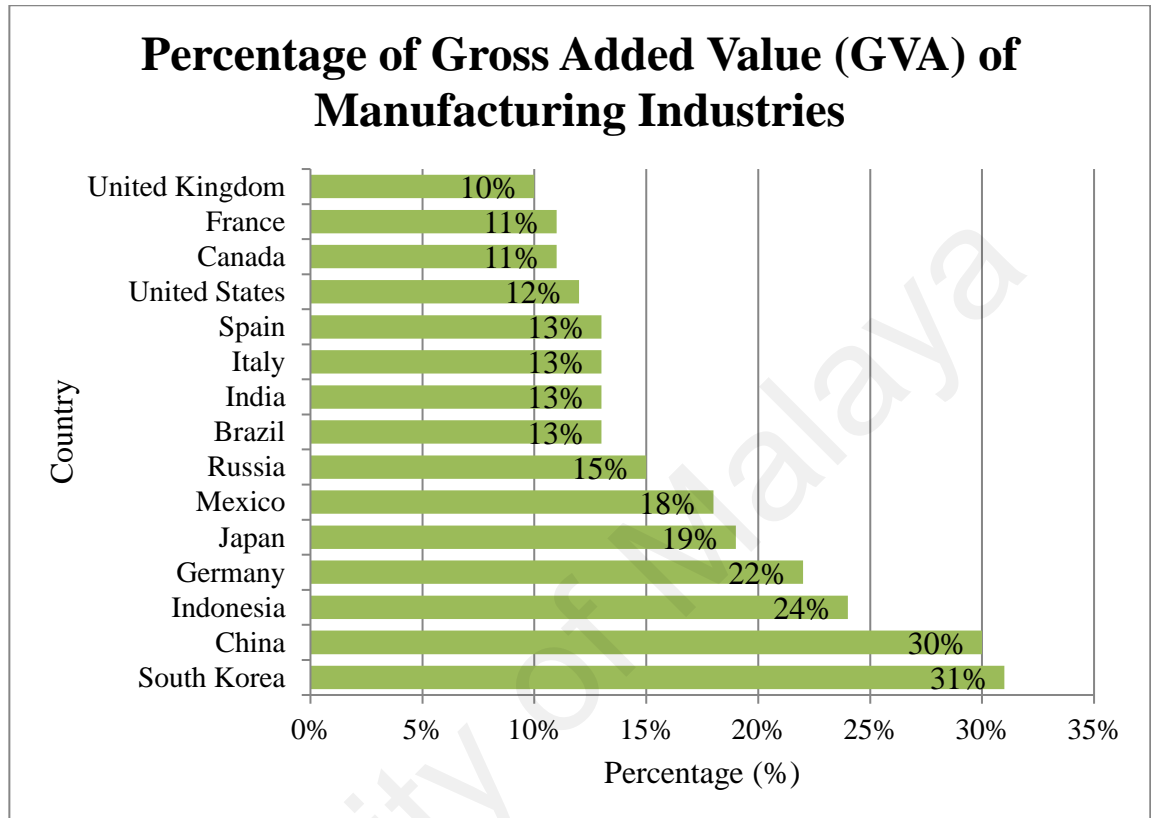


Figure 1. 1 Percentage of Gross Added Value of Manufacturing Industries (Maynard, 2015)

The report entitled “Fact about Manufacturing” (National Association of Manufacturers, 2012), stated that manufacturing’s multiplier effect is stronger than other sectors’. A measure of the breadth of the supply chain is the backward linkage in the input-output structure of the economy. For an industry with a larger backward linkage, growth in its output induces more production (both directly and indirectly) from other sectors. Figure 1.2 shows how much additional output is generated by a dollar’s worth of final demand for each industry. It is obvious that manufacturing sector has the highest backward linkage (multiplier effect) as a dollar in final sales of manufactured products

supports \$1.34 in output from other sectors whereas the retail and wholesale trade sectors generated only 55 cents and 58 cents respectively. Therefore, manufacturing plants have a powerful and positive impact on economic development.



Figure 1. 2 Multiplier Effect of Sectors (Facts about Manufacturing, 2012)

Due to the importance of manufacturing sector in the world's economy, much research had been funded to improve the performance of manufacturing sector to generate economic benefits.

## 1.2 Digital Factory and Virtual Reality

Digital factory is a new concept based on integration of diverse digital methodologies and tools in visualising and managing the manufacturing and production system. The concept is defined as “*comprehensive network of digital models, methods, and tools, including modelling, simulation and three-dimensional or virtual reality visualization, integrated by a continuous data management*” (Stef, Draghici, & Draghici 2013). The main objective of digital factory is to design, model, simulate, evaluate, and optimise the manufacturing process and system before capital investment to build the



physical factory to reduce development cost and time. In other words, digital factory is a complex digital network to simulate the factory in a digital or virtual environment resembling the physical factory with its complete manufacturing processes, activities, layouts, and data for management purposes.

Virtual Reality (VR) has gained worldwide interest, with an increasing trend in investment and funding in related fields encouraging the growth of VR technology and has led to the growth of interest in the application of VR in manufacturing system simulation and visualisation. As VR technology is introduced to manufacturing industries, it has grab the attention of researchers to use it as a major visualization tool in constructing digital factory platform. A statistical report (PitchBook Inc.,2015) has shown that the total investment in augmented reality (AR) and VR from 2010 to 2015 is increasing (Figure 1.3) and the number of new investors in VR technology development have continued to rise over the past five years (Figure 1.4). The report also states the application of VR has expanded to more fields, where the use of VR is not only confined to the video game industry but other industries (construction, manufacturing. etc.) are also beginning to adopt such technology in their future investment.

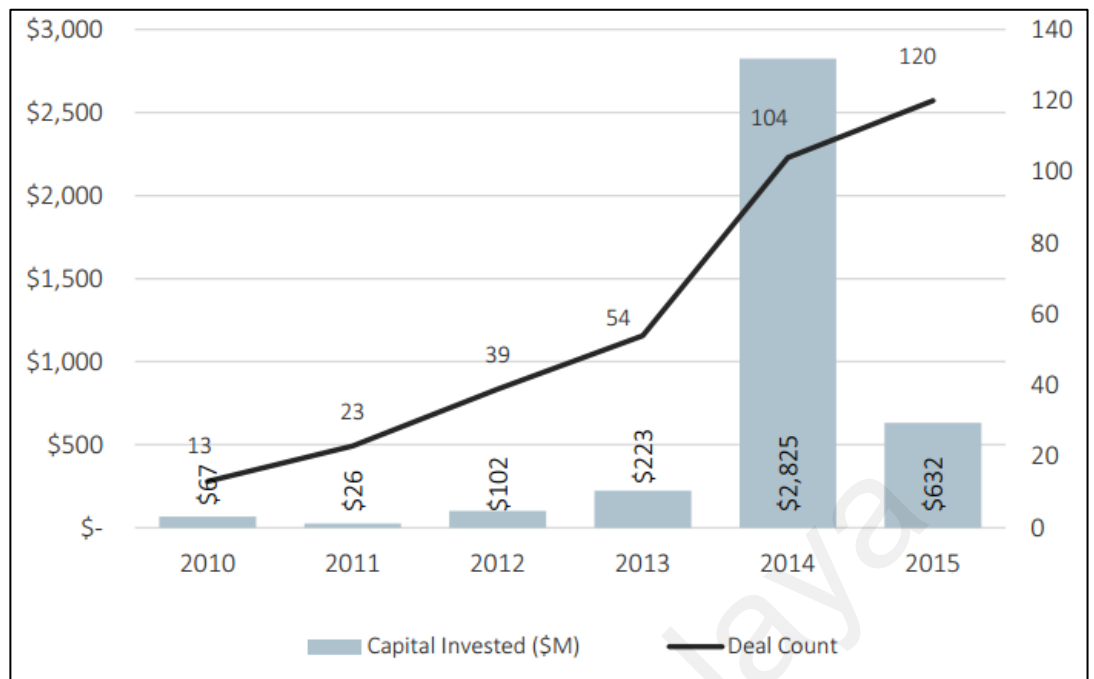


Figure 1. 3 VR/AR Deal Flow and Capital Invested (PitchBook Inc., 2015)

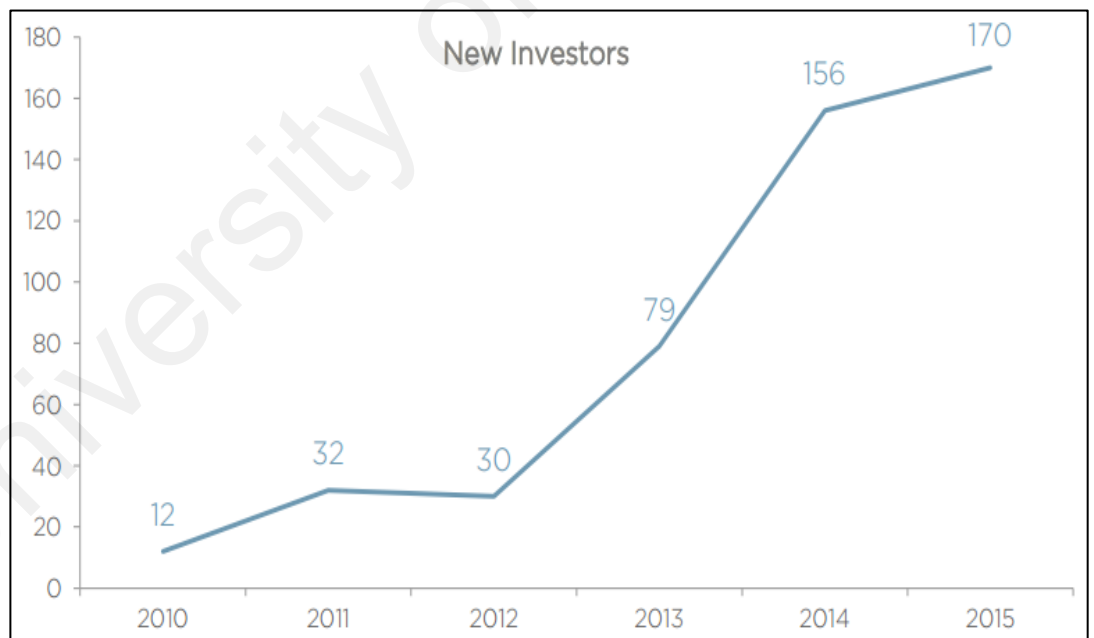


Figure 1. 4 New Investor in VR (PitchBook Inc., 2015)

### 1.3 Problem Statement

Plant layout is a major factor in the total operation of a company which includes the production process, equipment, storage, dispatch, and administration (Mobley, 2001). It even directly affects production efficiency, economics of the operation, morale of employees, and physical health of operatives. Recent research (Abhinav, Jyoti, & Vedansh, 2013, Arya & Chauhan, 2013, Hossain, Rasel, & Talapatra, 2014, Patil & Kuber, 2014) has proven that good plant layout improves the productivity of a manufacturing plant in the aspect of minimized facility distance, improved workflow, decreased work accident, time, and cost saving in material handling. Jain (2014) even showed an increment of production by 20% to 30% by improving the plant layout without a noticeable investment in a case study. Various approaches such as exact procedure, heuristics and metaheuristics was proposed and applied to assist the plant layout design, yet the results are not satisfying as might be too idealistic and not be applicable in real situations.

Digital factory platforms with virtual simulation has attracted the attention of manufacturers as it claims it is able to provide intuitive methods to solve manufacturing problems through scenarios and virtual data management. Manufacturing and engineering businesses are realizing the potential of digital factory and VR technology to assist in manufacturing sectors. These include structure facility location, optimized production flow, operation of virtual tools, evaluation of ergonomic factors, and maintenance assessment (Advice Manufacturing, 2015). An effort to make the resolution approaches (3D representations related) more generic should be considered as the graphical tools may be more efficient in layout problem solving (Drira, Pierreval, & Hajri-Gabouj, 2007).

In current research trend, 3D modelling software and VR had been mostly used as simulation tool for the physical factory, which the solution of manufacturing system is

still depends on external numerical simulation or algorithms. The potential of virtual simulation as an alternate solving tools for manufacturing system through multiple scenarios simulation technique without numerical simulation need to be further explore to make virtual manufacturing system more versatile.

#### 1.4 Objective of Study

This study proposes the integration of digital 3D modeling and virtual simulation to construct digital factory platform as an alternative decision making tool in solving flexible manufacturing system problem. As the current method for plant layout problem might not be realistic, this research will build a digital factory platform to create virtual manufacturing system that highly resembles the physical manufacturing system as an alternative method to obtain a realistic solution for the problem. The objectives of this research are as follows:

- I. To develop a digital factory model of a robotic work cell and a loop layout based flexible manufacturing system
- II. To validate the model with existing data in literature
- III. To apply the model in a case study of short-cut conveyor allocation in loop layout

#### 1.5 Significance of Study

This study researches on the possibility of a virtual manufacturing system within a digital platform as an alternative tool to solve loop layout problem through scenario technique. The contributions of this study listed as follows:

- I. Development of a realistic platform to evaluate the performance of current method (exact procedure, heuristic, metaheuristics, and intelligence technique) for manufacturing system layout problem

- II. Reduction of development cost, time, and risk for a physical factory as the design of the factory been assessed and tested in the digital factory platform

## 1.6 Thesis Organization

This thesis is divided into five chapters as follows:

### Chapter 1: Introduction

This chapter provides the background of the manufacturing industry and the digital factory with VR as simulation tool. The current problem of the manufacturing industry is stated within this chapter followed by a proposed solution with its objectives and significant value.

### Chapter 2: Literature Review

This chapter reviews the past studies conducted by other researchers in related fields including manufacturing system, digital factory, virtual manufacturing, and design for manufacture and assembly (DFMA). The method of applying VR as a simulation tool for a digital factory platform is the major focus of the literature review and serves as the main reference for the design of methodology of this research.

### Chapter 3: Methodology: Virtual Robotic Work Cell

This chapter explains how all digital methodologies connect each other to form a digital network in constructing a digital factory platform. The work flow of constructing a complete virtual manufacturing system by utilizing all the digital tools is explained in detail. A complete construction of virtual robotic work cell is explained within this chapter.

#### Chapter 4: Methodology: Virtual Loop Layout

This chapter describe the second stage of this study which is construction of loop layout based flexible manufacturing system. The step to construct digital model loop layout explain in detail, this model would be used to validate with existing data in literature in chapter 5.

#### Chapter 5: Result and Analysis

This chapter is the collection of data from the virtual manufacturing system within digital factory platform which utilises VR as a visualisation tool. The collected simulation data is compared with the numerical data obtained from the literature review for validation. Based on multiple simulation scenarios, the data can be used as a reference for manufacturing problem solving and optimization. The collected data could affect the design of the product by considering the production sequence, in which the data shall be considered in the design phase of the product by applying the guidelines from DFMA.

#### Chapter 6: Conclusion

This chapter concludes all work done in the study and propose future work to improve and enhance this study.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.0 Introduction**

This chapter reviews on the flexible manufacturing system, digital factory, VR and DFMA. The concept of flexible manufacturing would be explained followed by the detail studies on the loop layout in flexible manufacturing system and current approaches used for the loop layout problem. Then the concept of digital factory would be explained and follow by the VR technology. Application of VR in manufacturing system to achieve various objectives would be presented as VR is the newest technology to be use as the visualization tool in digital factory platform. The data from digital factory and virtual manufacturing could be greatly affecting the design of the product for the ease of manufacture and assembly. Thus, the concept and guideline of DFMA would be included for reference.

#### **2.1 Flexible Manufacturing System**

In general, flexible manufacturing is defined as a manufacturing system that consists of a group of workstations interconnected by automated material handling and storage system controlled by integrated computer control system with certain amount of flexibility to adapt predicted or unpredicted changes (Shivanand, Benal, & Koti, 2006). From the definition, flexible manufacturing system formed by three major components which are workstations, automated material handling and storage system and computer control system. In present day, workstations can be standalone computer numerical control machine tools to perform various machining process or a group of identical

machines based on the functional purpose. Different automated material handling systems are used in the system such as conveyor belt, automated guided vehicle to transfer material from station to station. An integrated computer control system adopts in the system to control activities of workstations and automated material handling and storage system to ensure the flow of the part and performance of the system. Figure 2.1 shows the conceptual layout of a flexible manufacturing system which all three components are included.

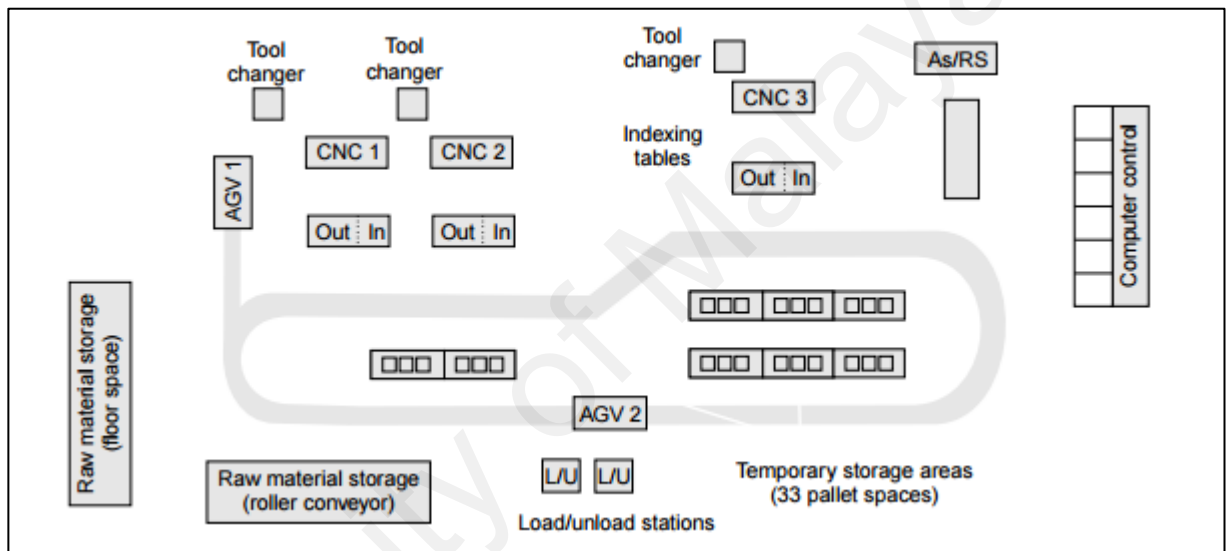


Figure 2. 1 Flexible Manufacturing System (Shivanand et al., 2006)

There are five major layouts in flexible manufacturing system which are progressive or line type, loop type, ladder type, open field type and robot centered type (Shivanand et al., 2006). Progressive also known as line layout that machines and handling system are arranged in a line (Figure 2.2(a)) that a part travelled from station to station in a straight-line pattern. Loop layout which machines are arranged in cellular configuration and parts move in one direction around the loop (Figure 2.2(b)). Ladder type layout having the ladder configuration which the sequence to the next operation is in the form of ladder steps (Figure 2.2(c)). Open field type layout (Figure 2.3) which the parts will go through all the workstations with automated guided vehicle as there is



usually no solid-linked material handling system in the layout. Robot centred type layout is a robot centred work cell which one or more robots are used as the material handling systems to transfer part from station to station (Figure 2.4).

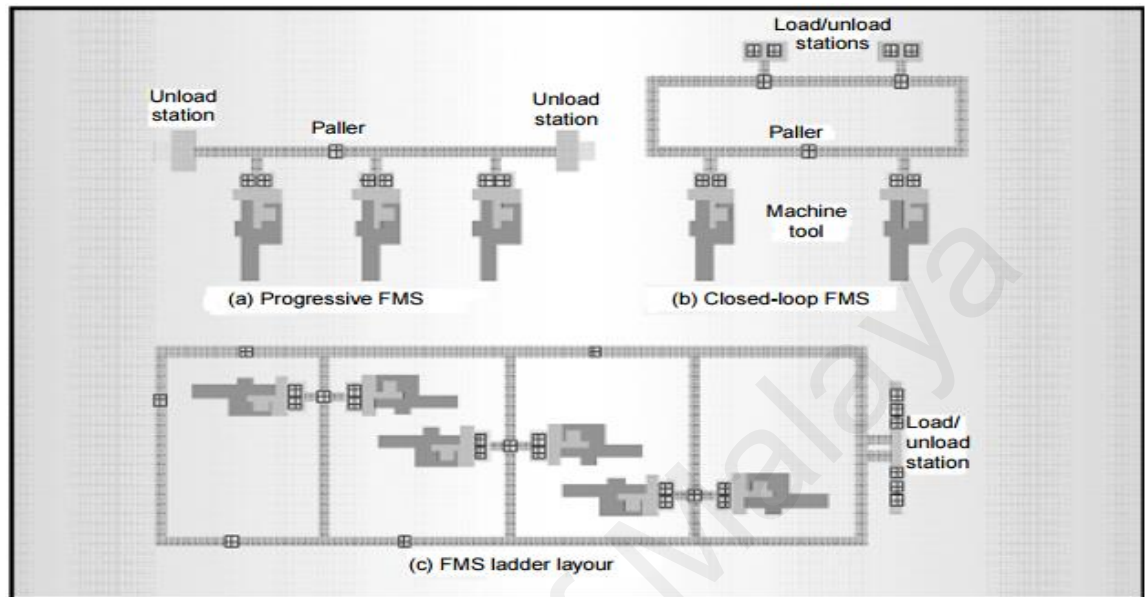


Figure 2. 2 System Layouts (a) Progressive Layout, (b) Loop Layout, (c) Ladder Layout  
(Shivanand et al., 2006)

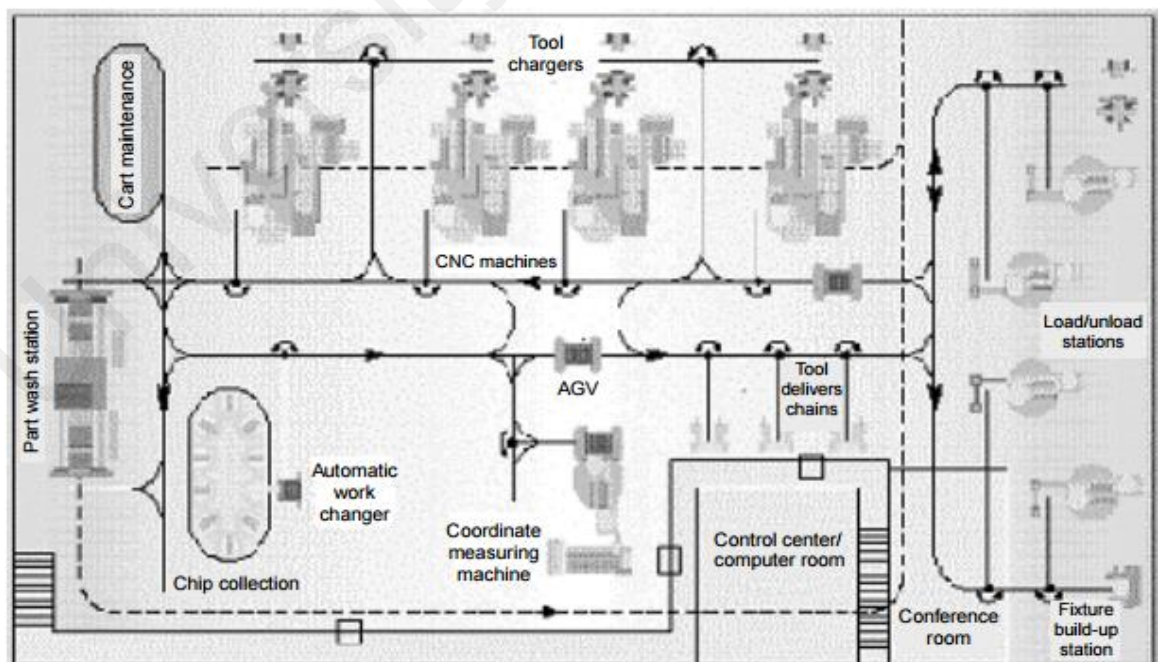


Figure 2. 3 Open Field Layout (Shivanand et al., 2006)

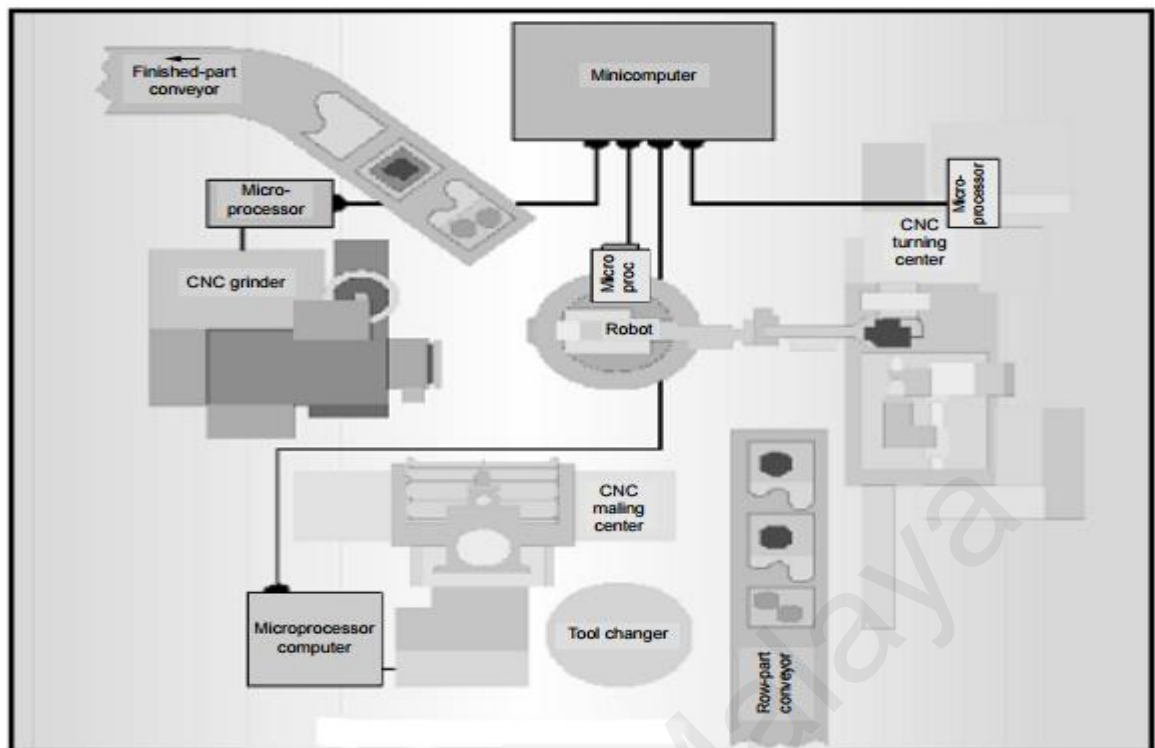


Figure 2. 4 Robot Centred Layout (Shivanand et al., 2006)

#### 2.1.1 Loop Layout

Loop layout also known as cellular layout had attracted most of the research interest as it has relatively low initial cost and high flexibility in material handling compare to other form of layouts (Sambathkumar et al., 2013). Thus, more literature review on loop layout would be included as it is the focus of current research trend in solving FMS problem. The main issue faced by current manufacturing industries is to locate the machine facilities with the optimum sequence around the loop (Saravana and Ganesh Kumar ,2013) which also refer as loop layout problem or loop based station sequencing problem to maximize the loop layout efficiency in terms of manufacturing time and cost.

Based on the review done by Saravana and Ganesh Kumar (2013) and Patel and Patel (2014) which focus on current approaches to solve loop layout problem, the mainstream approaches been used fall into four main categories which are exact procedure method, heuristics methods, metaheuristics method and hybrid method which

combining two methods to solve the problem. Both papers had agreed that all four methods had shown the ability to solve the loop layout issue by providing a final machine sequence around the loop but having the drawback that the solution may be far from the desire optimum solution and time consuming. In another review paper by Kulkarni, Talib and Jahagirda (2013) also notice the similar drawbacks of the aforementioned approach that the effort to obtain the best layout is not very efficient and the multi-objective nature are not considered in the problem. Then they observed that there is a trend of combining intelligence techniques into traditional optimization method been mentioned and this appeal to be able to obtain a better result. Other than the mentioned methods, Drira et al. (2007) also pointed that commercial software tools available on the market to assist manufacturing design are limited. Authors suggest that the resolution approaches be more generic and combine with graphical tools to made a more efficient solution for facility layout problem and consider the possibility to interface with VR as part of solution in future.

#### 2.1.2 Loop Layout Benchmark Test Bed

Nearchou (2006) had addressed the loop layout design problem using differential evolution algorithm (DEA) which is a modern metahueristics from the field of evolutionary computation. As there is no public benchmarks for the loop layout design problem at that time, authors had experiment their method with randomly generated test problems. The same test problems would be used to compare the previous existing metahueristics method for providing a fair platform for algorithm efficiency comparison. Throughout their experiment, the loop layout performance was evaluated in traffic congestion measurement which would be explained in next section and the efficiency of algorithm would be evaluated in percentage solution effort and computational time. The performance of differential evolution algorithm was compared to the genetic algorithm (GA) proposed by Cheng and Gen (1998) and simulated annealing method (SA) proposed

by Tian, Ma, and Zhang (1999). From the result, the proposed differential evolutionary equation is superior to previous existing metaheuristics method and the direction of future work would be integrating the algorithm with existing 3D modelling software for it to be applied in layout design and scheduling applications of real world facility floor.

Satheesh Kumar, Asokan, and Kumanan (2007) had proposed particle swarm optimization (PSO) in solving loop layout design problem with the objective to minimize the total traffic congestion and overall travelling distance of parts. The randomly generated test problem by Nearchou et al. (2006) had been used by Satheesh Kumar et al. (2007) as the test bed for algorithm comparison. From the result, particle swarm optimization is efficient in obtaining optimal machine layout sequence with lesser percentage solution effort compare with all three previous algorithms. Satheesh Kumar, Asokan, and Kumanan, (2008) proposed another algorithm which prove to be more efficient to solve loop layout design problem which is artificial immune system. This algorithm tested on the same test bed as their previous work and the result showed that artificial immune system had shown significant improvement in solving large size problem by applying shortcuts within the loop layout that had greatly reduce material handling cost.

Zeng and Teng (2010) had proposed an improved differential evolutionary equation which is relative position-coded differential equation and made comparison with previous algorithm based on the same test bed. The result indicates that this algorithm performs better in the search for optimal solution compared with all previous algorithm that was tested in the same test bed as it has the capability of avoiding illegal chromosomes and the non-correspondence between coding space and solution space.

Zuhdi (2013) had integrated genetic algorithm with rectilinear steiner minimum tree (RSMT) and the algorithm was tested in the same test bed by Nearchou (2006). From

the research, he proposed that the rectilinear distance should be included to obtain the real travel distance of a part with the provided machine sequence and the use of 3D modeling simulation software to investigate and validate the optimal machine sequence. He found out that there is a difference between the computational results with the 3D model simulation result. Table 2.1 concluded the previous study accordingly.

Table 2. 1 Loop Layout Benchmark Test Bed Review

Author (year)	Method for solving Loop Layout Problem	Description
Cheng and Gen (1998)	Genetic Algorithm (GA)	The author proposed GA as tool for loop layout problem.
Tian et al. (1999)	Simulated Annealing (SA)	This paper used SA as an alternative algorithm for loop layout problem solving.
Nearchou (2006)	Differential Evolution Equation (DEA)	The author proposed DEA as a better algorithm to solve loop layout problem, this method been compared to the previous method (GA and SA) based on the test bed generated by author. The key evaluation criteria to compare the effectiveness of each algorithm are number of congestion, solution effort and computational time.
Satheesh Kumar et al. (2007)	Particle Swarm Optimization (PSO)	Author proposed PSO to solve loop layout problem and compare his result with previous study by using the same test bed developed by Nearchou (2006).
Satheesh Kumar et al. (2008)	Artificial Immune System (AIS)	The author proposed another method AIS as an alternative algorithm to solve loop layout problem. The result showed that AIS having better performance in solving loop layout problem compared to the PSO after comparing both algorithm in same test bed.
Zeng and Teng (2010)	Improved DEA	Authors did some improvements in DEA and compare the algorithm with previous work under the same test bed.
Zuhd (2013)	GA-Rectilinear Steiner Minimum Tree 9GA-RSMT)	This author applies RSMT rule into GA and developed a new algorithm GA-RSMT for loop layout problem. The criteria for the system evaluation have further improved which the total travel distance of part as the main evaluation criteria. Author also noticed that the computational result varied from the 3D model simulation results.

### 2.1.3 Traffic Congestion

The mainstream criteria to evaluate loop layout performance is traffic congestion proposed by Afentakis (1989). This measure is defined as the number of times a specific part traverses the loop before its processing is complete denoted as  $Cost_{Min\_Sum}$  (1.1) with the objective to minimize the total congestion of all part.

$$Cost_{Min\_Sum}(s) = \sum_{i=1}^M reload_i \quad (2.1)$$

where,  $s$  is a loop layout solution (sequence of machines), and  $reload_i$  ( $i=1, \dots, M$ ) is the summation of the reloads for the  $i$ th part in the  $S$  layout.

### 2.1.4 Rectilinear Distance

The distance between two workstations can be determined by rectilinear measurement which is the total length of the straight lines connecting two points while travelling in only one axial direction at a time (Malakooti, 2013). The rectilinear distance is expressed in absolute value of x-distance and y-distance and expressed as in (1.2) (Pang, 2004):

$$Rectilinear\ distance = |x - a_i| + |y - b_i| \quad (2.2)$$

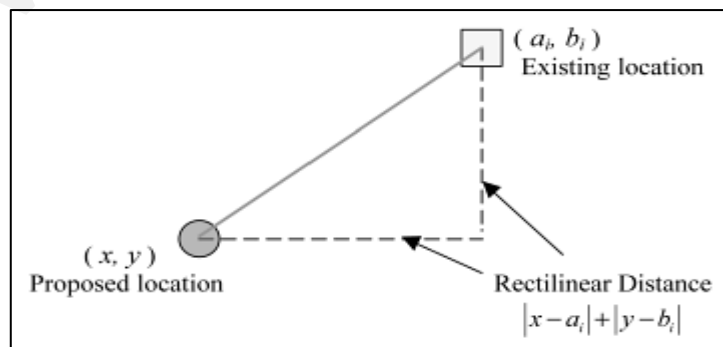


Figure 2. 5 Rectilinear Distances (Pang, 2004)

In Zuhdi (2013), the rectilinear distance is used to obtain the total travel distance of a part in specific loop based station sequence. The related equation as follows:

$$d_{ij} = d_{ij}^v + d_{ij}^l + d_{ij}^u \quad (2.3)$$

$d_{ij}$  : total travel distance

$d_{ij}^v$  : travel distance of part from station  $i$  to station  $j$  where

$$d_{ij}^v = |b_j - b_i| + |o_j - o_i| \quad (2.4)$$

$d_{ij}^l$  : travel distance of part loading to facility where

$$d_{ij}^l = d_{li} = |b_i - b_l| + |o_i - o_l| \quad (2.5)$$

This equation is only applicable if the loading station is next to the facility.

$d_{ij}^u$  : travel distance of part unloading from facility where

$$d_{ij}^u = d_{uj} = |b_j - b_u| + |o_j - o_u| \quad (2.6)$$

This equation is only applicable if the unloading station is next to the facility.

## 2.2 Digital Factory

Digital factory is a new concept based on the extensive use of information technology in manufacturing system from factory layout simulation to factory data management. Through the work of Westkämper, Gottwald, and Fisser (2005), digital factory is a concept of “*network of digital models, methods, and tools such as simulation and 3D visualization that integrated through a comprehensive data and flexible modules management*”. This digital factory concept assist manufacturing system to face the dynamic challenge based on digital tools and techniques for engineering, control, supervision, and management (Westkämper, 2007).

The University of Žilina in co-operation with the Central European Institute of Technology built their own digital factory concept (Fig. 2.6) that explains how digital factory is created in each stage from the design of conceptual model to the training of

factory operator through multiple digital methodologies and software tools. The digital factory concept entitles a virtual picture of a real production environment with the virtual environment integrated by computer and information technologies that replaced physical factory model with 3D model. The utilization of VR technology in the visualization system is often entitled as digital factory (Gregor, 2006) or also known as virtual manufacturing system based on digital factory platform. The integration of discrete event simulation, supported by 3D animation and virtual simulation serves as a powerful tool for estimation and evaluation of future manufacturing system behaviour and performance (Gregor, Hromada, & Matuszek, 2008). The digital factory concept is based on three main parts (Gregor & Medvecký, 2010):

- I. Digital products – product within digital factory with its static and dynamic properties
- II. Digital production planning
- III. Digital production – with the possibility of utilization of planning data for enterprise processes effectiveness growth



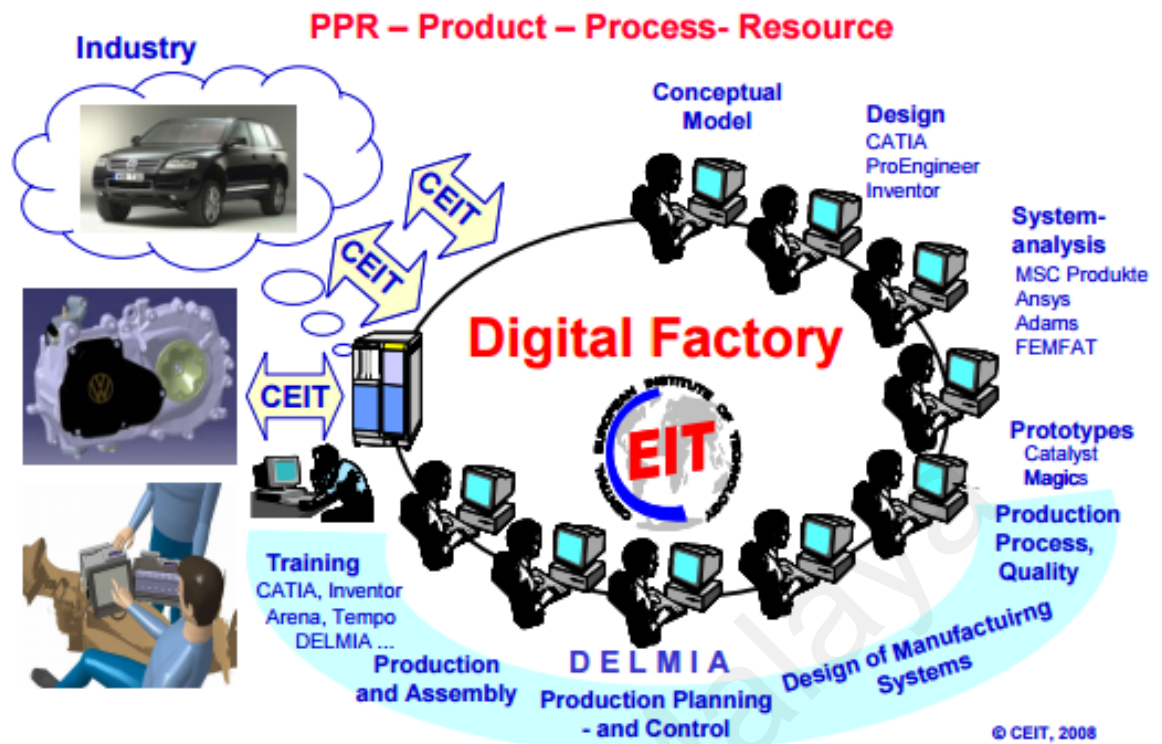


Figure 2. 6. Digital Factory Concept Built at the University of Žilina (Gregor, 2006)

The digital factory concept is an integrated approach to enhance the product and production engineering processes while simulation is a key technology and can be applied in virtual models on various planning levels and stages for this purpose (Kuehn, 2007). This concept involves two phases, first phase is the integrated product engineering, second phase is plant design and optimization in collaborative environment.

The main characteristics of a digital factory can be identified as follows (Caggiano, 2010):

- I. Digitalization - the conversion of the physical factory into a digital factory to realize simulation, all the entities within a factory model would be digitalized and replace by virtual model

- II. Design and optimization based on simulation - through the science visualization and simulation, the design and optimization could be done within the digital factory
- III. Distributed and hierarchic integration - The complex factory planning can be decomposed into many hierarchies such as factory, workshops, production lines, cells and equipment's which are harmonized and dynamic linked one to the other. By simulating each hierarchy, some aspects of manufacturing system can be optimized and validated including planning design, system capability, production line balance, planning process etc.

Digital factory is a concept that integrates design, engineering, planning, simulation, communication, and control tool on all factory level through complex digital tools network used to create virtual models. The virtual models enable the immersion of 3D factory model which allowed certain level of collaborative activities to view, analyses and inspect the factory performance. In general, the typical simulation applications of the digital factory are (Kuehn, 2006):

- I. Layout planning and simulation for layout validation and optimization
- II. Static analysis and dynamic simulation of logistic and production flows
- III. Line balancing of assembly processes
- IV. Simulation of complex material handling
- V. Robotics and complex motion
- VI. Simulation of part manufacturing
- VII. Simulation of human resources
- VIII. Ergonomic simulation
- IX. Simulation of production logistics
- X. Simulation for control software testing

## XI. Simulation for operative production control

### 2.3 Virtual Reality

Definition of simulation in manufacturing context was generalized (Mourtzis, Doukas, & Bernidaki, 2014) into two different categories which are:

- I. Simulation modelling and analysis is the purpose of creating and experimenting with computerized mathematical model of a physical system (Chung, 2004)
- II. Simulation is the imitation of the operation of a real-world process or system over time. It generates an artificial history of the system and observes it to draw inferences about the operating characteristics of real system that is presented (Banks, 1998).

Based on the historical evolution of simulation as reviewed by Mourtzis et al. (2014) a significant leap from the computerized mathematical model to artificial environment generation started around 1950s to 1960s. As Morton Heilig (1956), created the first simulator known as “Sensorama” with the use of light, sound, motion and even smell to immerse the participant in motorcycle ride through Brooklyn which was the first approach to create immersive artificial environment but it was not interactive (Lu, Shpitalni, & Gadh, 1999). Sutherland (1965) introduced the “Ultimate Display” concept stated that *“computer could be a window to virtual world and the virtual world should be undistinguished from real world”* and successfully built head mounted display known as “Sword of Damocles” (Figure 2.7) in 1968 that enhanced the immersion sensation by continuously tracking head position of user’s head and stereo view was updated correctly according to the head position.

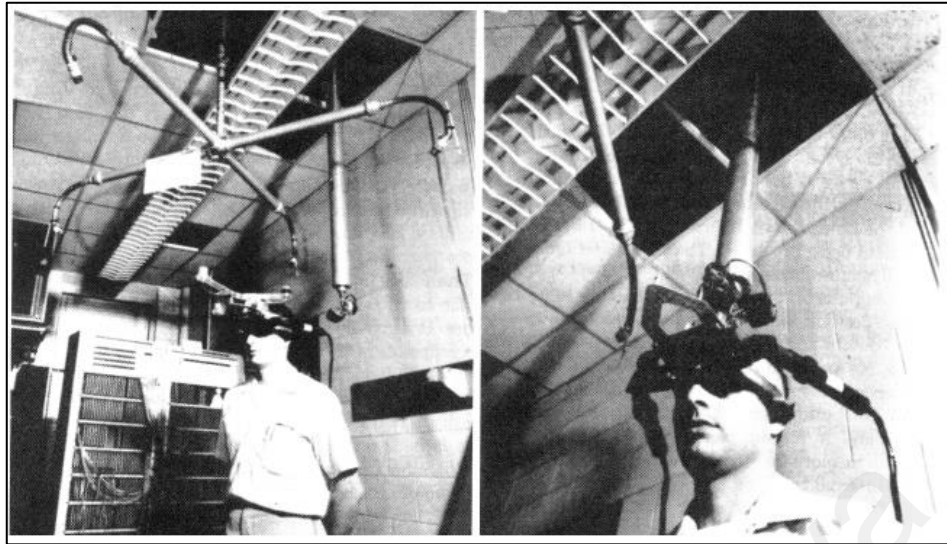


Figure 2. 7 Head Mounted Display (Sutherland, 1968)

The term VR was coined in 1989 by computer expert Jaron Lanier (Qvortrup, 2002). This VR concept presents the world with new technology possibility and implicitly guided the concern on 3D modelling which leading to the ideals that 3D computer graphic should aim at creating as “realistic” presentation as possible. Jaron Lanier and Jean Jacques Grimaud (1985) founded VPL Research Inc. and become famous for making the first consumer grade virtual environment hardware: the DataGlove and the EyePhone head mounted display (Figure 2.8). Together with Body Electric software they provide the first complete commercial VR system.



Figure 2. 8 Data Glove and EyePhone Head Mounted Display in 7th June 1989

Due to the development of computer technology and hardware improvement, the vision of VR had been realized. Today, the term VR is redefined as high end user computer interface that involve real time simulation and interaction through multiple sensory channels such as visual, auditory, tactile smell and taste (Burdea and Coiffet, 2013). According to their definition, VR should have the three major feature called as three “P”s which refers to immersion, interaction and imagination. The immersion refers to capability of VR device in providing the realistic sense of existence of the world or personal presence in the virtual world that made people feel standing on a real world from screen. The interactive is the capability of the VR system providing realistic connection between human and virtual environment realistically which the same they had with physical world. While the imagination refers to the mind’s capability to perceive non-existent things as real.

### 2.3.1 Types of Virtual Reality System

VR aims to generate sensory impressions that are delivered to user, thus the type and the quantity of these impressions determine the level of immersion and the feeling of presence in VR (Mandal, 2013). According to the degree of immersion, the VR can be categorized into three main levels as in Table 2.2 (Sahol Hamid, Abdul Aziz, & Azizi, 2014, Pakhira, 2010, Moses Okechukwu Onyesolu & Felista Udoka Eze, 2011):

- I. Non-immersive or Desktop VR systems: The lowest level of immersion in VR system that can be easily construct without special devices. This system also known as Window on World (WoW) systems which a computer user use computer screens to view virtual world and having certain level of interaction with that environment, but is not immersed in it. Desktop VR is preferred in modern

education because of its ability to provide real time visualization and interaction within a virtual world that closely resembles a real world.

- II. Semi-Immersive systems: These systems provided higher degree of immersion as it supports head tracking. This system still use a conventional monitor (very often with LCD shutter glasses for stereoscopic viewing but generally do not support sensory output.
- III. Immersive systems: The highest immersion level of VR systems which let the user totally immerse in computer generated world which usually presented by CAVE system (Cave Automatic Virtual Environment).

Table 2. 2 Types of Virtual Reality System

VR System	Non-Immersive	Semi Immersive	Full Immersive
Input devices	<ul style="list-style-type: none"> <li>• Mouse</li> <li>• Keyboard</li> <li>• Track balls</li> </ul>	<ul style="list-style-type: none"> <li>• Joystick</li> <li>• Data Gloves</li> </ul>	<ul style="list-style-type: none"> <li>• Gloves</li> <li>• Voice Demand</li> <li>• Navigation controller</li> </ul>
Display devices	<ul style="list-style-type: none"> <li>• Standard high resolution monitor</li> </ul>	<ul style="list-style-type: none"> <li>• Large screen monitor</li> <li>• Large screen projector system</li> <li>• Multiple television projection</li> </ul>	<ul style="list-style-type: none"> <li>• Head mounted display</li> <li>• (CAVE)</li> </ul>
Immersion level	No	Medium	High
Interaction	Low	Medium	High

### 2.3.2 Basic Component in Virtual Reality

A complete VR system (Figure 2.9) consists of three major components which are input devices, output devices and software (Mazuryk and Gervautz, 1996). The input device would receive signal from user so the signal would be send to computer as input data stream, then the computer would process the input data stream and react accordingly.

An output data stream generated from computer to the output device to give feedback to user (Bamodu and Ye, 2013).

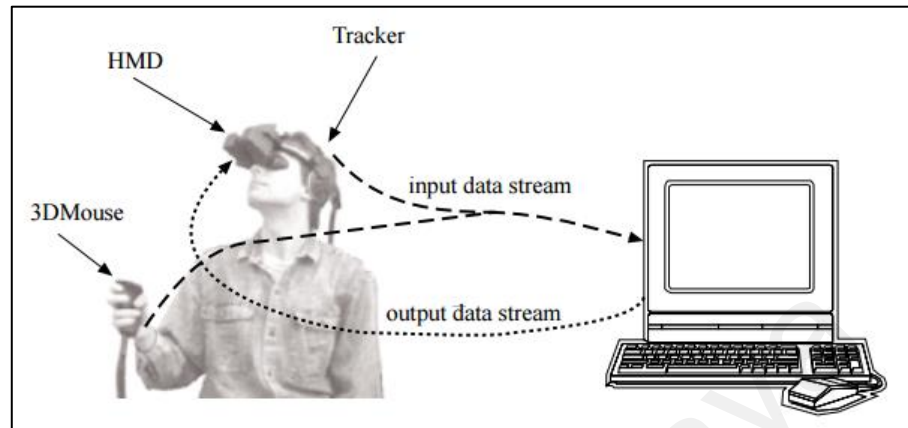


Figure 2. 9 Basic Components in Virtual Reality System (Mazuryk and Gervautz, 1996)

#### 2.3.2.1 Input Devices

The input device is for user able to be interacted with the simulated scene or virtual world. The input device plays important role as sensing the action of user and send the information to the computer for information processing in real time. In general input devices can be classified as:

- I. Tracking devices: Refers to position sensor that senses the position and reaction of user continuously and send the collected reaction to VR engine as input data stream. Examples of device are data glove, head tracking system which consists of gyroscopic sensor or muscular controllers.
- II. Point input device: This required user to send information through specific devices at the specific point of scene for the interaction. Example: mouse, keyboard, navigation controller, and space ball.
- III. Voice device: This required the use voice recognition system to identify the verbal command from user.

### 2.3.2.2 Display Devices

The output devices get feedback from the VR engine and pass it to the user through corresponding device. The classification is based on the sensory immersion provided by the device as follows:

- I. Visual interfaces: In general, there are two classes which are head-mounted and off head display. Head-mounted display is physically attached to the head of user by mounting display hardware on a helmet or headband. The off-head display is usually referring to desktop monitors and projection technology such as panoramic displays, cave automatic virtual environment (CAVE) and workbenches virtual world surround the user. The main advantages of off head displays are enable to give a shared VR environment to a small group of people that allow the group of people to have communication and discussion on the share virtual world in real time (Akay, 2006).
- II. Aural interfaces: This audio feedback device aims to convey the complex environment such as realistic workplace environment with different noise to user and enhance the immersion experience of the user. Generally, loudspeaker and headphone been used to convey the audio sensory to user. The professional headphone is preferable in precision source localization and better control in sound quality.
- III. Haptic Interface: It has two main functions which are measure the positions and contact force and display it to the user providing higher degree of immersion to the virtual environment. The simple haptic interfaces that provide haptic feedback are joystick, mice and trackballs. The advanced haptic interfaces usually have two components which are tactile sensing (limb position and movement) and kinetic sensing (awareness of stimulation to the outer surface of body). This haptic device



usually used in task required hand performance in real world such as manual exploration, surgical training, and work training.

#### 2.3.2.3 Software or Virtual Reality Engine

The most important component for a success VR system construction is the computer software or VR engine. The choice of VR engine highly depends on the application of VR, degree of immersion required and graphic output required.

Typical VR engine includes four main components that act in consort and act in real time to create a virtual world (Akay, 2006):

- I. World modelling: It defines the shape, behaviour, and appearance of objects included in the virtual environment. The detail such as geometric, surface, and physical properties must be included for simulation and rendering purposes.
- II. Visual scene navigation software: this allowed user to navigate the virtual world for the purpose of exploration
- III. Interaction software: this interaction software must be in package in VR engine as it serves as a communication platform for input and output devices. Through the interaction software, the simulation created by VR engine able to change according the user requirement.
- IV. Hypermedia integration software: This is to allow hyper-navigation that involves the use of nodes that can be travelled within.

#### 2.4 Virtual Manufacturing

The term virtual manufacturing was first introduced in early 1990s by United State Department of Defense Virtual Manufacturing Initiative (Barnejee and Zetu, 2001). This concept had gained wide international acceptance and broaden in scope. Iwata, Onosato, Teramoto, & Osaki (1995) had given a specific definition to virtual

manufacturing as “*integrated computer models that represent the precise and whole structure of manufacturing system and simulate their physical and logical behaviour in operation*”. Now the term virtual manufacturing refers broadly to the modelling of manufacturing systems and components with effective use of audio-visual devices to simulate or design alternatives for a physical manufacturing environment (Novack-Marcincin, 2011). Implementation of virtual manufacturing contribute several benefits such as extended tool life, reduced cycle time, optimize manufacturing design to enhance production quality and improved flexibility manufacturing system (Bharath and Patil, 2015).

In 1994, Lawrence Associates had proposed that the scope of virtual manufacturing as to define product, processes and resources within cost, weight, investment, timing and quality constraint in the context of plant. Thus, three paradigms of virtual manufacturing introduced to define the main functions of VR applied in manufacturing related to product, processes and resources as follows:

- I. Design centred virtual manufacturing: In this paradigm, virtual manufacturing designed to provide manufacturing information to the designer during product design phase. In this case, virtual manufacturing aims to optimize the design of the product and the processes for specific manufacturing goal. In this paradigm, it utilized the VR to simulated production process to evaluate production scenario at different levels of fidelity and scope to assist the product design and decision.
- II. Production centred virtual manufacturing: In this paradigm, VR uses the simulation capability to perform manufacturing process and allow the evaluation of other processing alternative in the virtual environment with shorter time and lower cost. Virtual manufacturing aims to optimizes manufacturing processes and adds analytical production simulation to other integration and analysis technologies to allow high confidence validation of new processes and paradigms.

III. Control-centred virtual manufacturing: This paradigm is the addition of simulations to control models and actual processes allowing for seamless simulation for optimization during the actual production cycle.

#### 2.4.1 Application of Virtual Manufacturing

The application of virtual manufacturing can be group in three main areas which are design, operational management, and manufacturing process (Mujber, Szecsi, & Hashmi, 2004). In design, VR is used in product design and prototyping. In the operation management area, VR shows the ability to be in part of planning, simulation, and training. In the manufacturing process, VR is applied in machining simulation and assembly.

##### 2.4.1.1 Design

VR proved to be an effective tool in assisting product design through providing a virtual environment for product performance evaluation. Kan, Duffy, & Su (2001) and Tideman, Van Der Voort, & Van Houten (2008) had used VR in product design process. Kan et al. (2001) had developed VR based collaborative environment by using Vnet (freeware), Java and VR Modeling Language (VRML) to provide a platform of product design and testing for small and medium company. While Tideman et al. (2008) create virtual environment for product testing to obtain the feedback of product user of the sense of applicability of the design in real life. Both researches found out that the VR had a positive impact in shortening the product design life cycle. VR technology is able to close up the gap from designer to manufacturer on the product design, empowering a positive communication on the product design. The application of VR in validating product design is lesser while most of the research direction of virtual manufacturing is focus on operational management and manufacturing process.

Table 2. 3Virtual Reality in Design

Author (year)	Application area	Immersion level	Function of VR
Kan et al. (2001)	Product design	Non-immersive	Provide interaction for user in virtual environment to enhance the product design
Tideman et al. (2008)	Product design	Non-immersive	Provide virtual environment for product design evaluation

#### 2.4.2.2 Operation Management

Application in operation falls into three main purposes which are planning, simulation and training. In most of the time, VR had been seen as a visualization tool in operational management instead of an interactive tool to made operation management decision. Zhong and Shirinzadeh (2008) suggested a framework that integrates discrete event simulation directly to 3D animations with its novel methods that analyse and convert discrete simulation results into animation events to trigger 3D animations. This framework successfully transform all manufacturing data and activities into virtual world but only allowed the visualization of the factory layout which has no direct input from user to the virtual world. Noak-Marcincin (2011) had use the VR in simulating the automated workplace to view the factory operations. With the use of virtual factory (factory simulation in virtual world), the best solution for performance improvement of the factory design and operation can be obtained. Nevertheless, Jiang and Tai (2012) and Terkaj and Urgo (2015) also use the VR as the simulation tool for the design of manufacturing layout. VR was proven by both paper to be an effective tool to simulate the manufacturing system which enable the visualization feature for the layout design to spot the hidden problem of current layout.

Iqbal and Iqbal (2001) had reviewed the possibility of applying VR as a tool for plant planning in which the VR is not only limited to visualization purpose but also an interactive tool for layout planning. VR have the possibility to be the solution to overcome the issue of the lack of realistic sensation and evaluation of the plant layout in conventional analytical system. Iqbal and Hashmi (2001) applied VR in the redesigning and evaluation of a existing factory layout. In the study, the current factory layout was evaluated in the virtual environment and the bottleneck of the production system is identified, The factory layout was redesigned by relocating the machine sequence virtually to obtain the best layout. In the study, VR produced significant results in assisting the plant layout evaluation and improvement. The idea of using VR technology as an interactive tool was continued by Ding, Wang, & Chen (2010). The developed virtual factory layout in 3D virtual environment allowed user input to the virtual world in which the user is able to select virtual objects and place it in the virtual world to form an interactive work layout. The re-location of machine can be done by the user directly in the virtual world; the interactive virtual factory layout helps in evaluating plant layout before building them and assisting in avoiding the financial problems involved in doing a physical re-layout.

Menck, Weidig, & Aurich (2013) proposed VR as a collaboration tool for factory planning based on scenario technique while Colledani, Pedrielli, Terkaj, & Urgo (2013) used VR as the integration tool for manufacturing system design. According to Menck et al. (2013) VR tool should be extended to the early stage of manufacturing system which refers to the system layout design. In the work of Colledan et al. (2013) a framework named Integrated Virtual Platform was constructed that integrates VR in a manufacturing system to enable user to design and analyse manufacturing system. Figure 2.10 showed the Integrated Virtual Platform that was applied in a milling process simulation.



Figure 2. 10 Integrated Virtual Platform (Colledan et al., 2013)

In their latest research, Tyagi and Vadrevu (2015) had used VR to vindicate the application of value stream mapping in a United State based small medium enterprise while Terkaj, Tolio, & Urgo (2015) use the virtual factory as an approach to in situ simulation to support production planning. A VR software (EON Reality) was used by Tyagi and Vadrevu to design a 3D which had improved layout from the current layout. The cost and time for the plant layout evaluation was reduced and, using the immersive feature of the software, the space between facilities in the plant layout can be estimated and be used in future plant set up. In Terkaj et al. (2015), the virtual factory approach was implemented to support the integrated design of a roll shop defining the layout in a VR environment and evaluating its performance through a customizable discrete event simulation model. The proper set up of the machine and facility can be defined in the simulated factory as shown in Figure 2.11.



Figure 2. 11 Virtual Factory Approach (Terkaj et al., 2015)

Other than serving as a visualization and evaluation tool, VR technology also been applied as a training tool to train workers in manufacturing process. A novel training system of lathe works in VR platform (Chang, 2010) and assembly operation evaluation system in EON reality (Zhao, 2012) demonstrated that VR is effective in giving tutorial and training to worker, while the investigation on the effect of virtual training conducted by Tsai, Kao, & Lee (2012) had even support the effectiveness of VR for training purpose. Chang (2010) had developed a virtual lathe machine which resembles the real lathe machine with the application of 3D solid model and VR software (EON Reality). Users were able to learn in the simulated environment without much trouble, increasing the impact of training. The accumulation of learning experience can improve workers' skill and be applied in actual environment to accomplish the mission of operation. Zhao & Tai (2012) developed an assembly operation evaluation system through the same software (EON Reality) to provide virtual training in die assembly process. In the developed virtual die assembly system, the sequence of assembly would be provided and the time taken by

a complete assembly training would be record for the performance evaluation In the case study, the efficiency of the system for training purpose was proven. In the investigation conducted on the effect of VR application on teaching assistance for machine tools operation education by Tsai et al. (2012), 175 subjects were recruited to operate the VR machine and feedback response had confirmed interaction feature of VR plays an importance role for training and skill improvement. The application of VR in operational management including simulation, planning and training is summarized in Table 2.4.

Table 2. 4 Virtual Reality in Operation Management

Author (year)	Application area	Immersion level	Function of VR
Zhong and Shirinzadeh (2008)	Simulation	Non-immersive	VR is only to visualize the factory layout and activities
Noak-Marcincin et al. (2011)	Simulation	Non-immersive	VR use to visualize the factory design and operation to seek for room of improvement
Jiang and Tai (2012)	Simulation	Non-immersive	VR as visualization tool for factory layout design
Terkaj and Uργο (2015)	Simulation	Non-immersive	VR as visualization tool to evaluate the performance of production system.
Iqbal and Hashmi (2001)	Planning Layout Design	Non-immersive	VR as visualization and evaluation tool in factory layout design. Layout is changeable within the virtual world.
Ding et al. (2010)	Planning Layout Design	Non-immersive	The VR enable direct user input to build and re-locate the facility in manufacturing system. The interaction feature being fully utilizes and has great feedback in best layout selection.
Colledani et al. (2013)	Planning Layout Design	Non-immersive	VR technology use to build integrated virtual platform for manufacturing system design and evaluation.
Chang (2010)	Training	Non-immersive	VR as training tool to train workers' skill in lath operation.
Zhao rt al. (2012)	Training	Non-immersive	Virtual die assembly system built, in which die assembly training was provided in virtual environment to worker and its efficiency proved.



#### *2.4.2.3 Manufacturing Process*

The application of VR in manufacturing process covers the machining process and assembly process. VR is widely applied in machining process (Wang, Orban, Cunningham, & Lang, 2004, Li, Zhao, Yao, & Liu, 2007, Zhu, Wang, Chen, Yang, & Wang 2008 and Soori, Arezoo, & Habibi, 2014) to improve the machining performance. Wise-ShopFloor (Web-based-integrated sensor-driven e-ShopFloor) designed by Wang et al. (2004) with the objectives of real-time monitoring and remote control of networked computerized numerical control (CNC) machines. A case study on a milling machine shows the possibility of virtual control of CNC machine as an approach to the emerging distributed manufacturing paradigm and anticipated the possible application to more process other than milling. Li et al. (2007) developed a virtual machining system the aim of evaluating and verifying the effectiveness of the GA for finding optimum cutting condition for milling machine. In virtual machining system, the accuracy and error distribution can be predicted by comparing the virtual work piece to the desired work piece model. The result shows that the off-line optimization on NC machining based on virtual machining is effective and the improvement is remarkable. Zhu et al. (2008) used 3D computer graphics, interactive devices and stereo glasses, to realize a turn-milling center machining in a virtual world. Results show that VR offers the engineer's new ways to not only visualize their problems effectively and efficiently but also provided certain degree of user-machine interaction which could improve the decision-making capabilities of engineers thereby improving quality and reducing the development time for new products. Soori et al. (2014) identified the geometric errors of a 3 axes CNC milling machine tool and the tool deflection errors are embedded in G-Codes of parts to produce actual 3D parts with free form surfaces in virtual environment built from visual basic programming language. The result shows that the virtual environment is an effective tool to enhance the quality of produced parts as well as efficiency of parts production by

improving the milling machine performance. VR seems to effectively reduce the possible error through simulation and virtual inspection which had enhance the part quality, extended tool life and improving machining performance.

VR was also used in assembly process for assembly planning and evaluation (Chen, Wu, & Li, 2010, Gonzalez-Badillo, Medella-N-Castillo, & Lim, 2013 and Gao, Shao, & Liu, 2014). A virtual assembly system with force feedback was developed by Chen et al. (2010) through transforming secondary development of commercial CAD system into a virtual assembly model. Through the system, operator or the user of the system would be guided through the assembly process and operation. The assembly constraint would be predefined in the virtual system and activated gradually according to the assembly progress of user, the force feedback would give alert to operator whether they assembly the part at the right position through haptic device (Phantom device). Figure 2.12a showed the constraint between part A and part B. If the part A (Figure 2.12b) is misplaced, the haptic device would give force feedback (blocking forward movement) to the user until part A is correctly placed (Figure 2.12c) and completing the assembly task (Figure 2.12d). This system had assisted the evaluation of assembly design through haptic feedback. Gonzalez-Badillo et al. (2013) also using a similar method developed a haptic VR system for assembly planning and evaluation. In his research, the same haptic device (Phantom device) was applied in the virtual environment (Figure 2.13). The system allowed the user to modify simulation parameters and components in real time which enables the evaluation of the effect of different parameters on the virtual assembly performance. Gao et al. (2014) proposed a novel approach to solve the problem of VR being incapable of generating realistic assembly process due to inaccurate positioning. The new approach uses motion navigation method based on force guidance where the assembling part is positioned under the combined action of external forces and moment while the dynamic equations are calculated at each assembly step to obtain the position,

attitude, and motion parameters of the assembling part. This method accurately simulates real-world interactions with virtual parts, along with their physical behaviour and properties. VR that has been applied in assembly process had shown the ability to assist in assembly process planning and evaluation with the feature of human-machine interaction. The application of VR in manufacturing process including machining and assembly is summarized in Table 2.5.

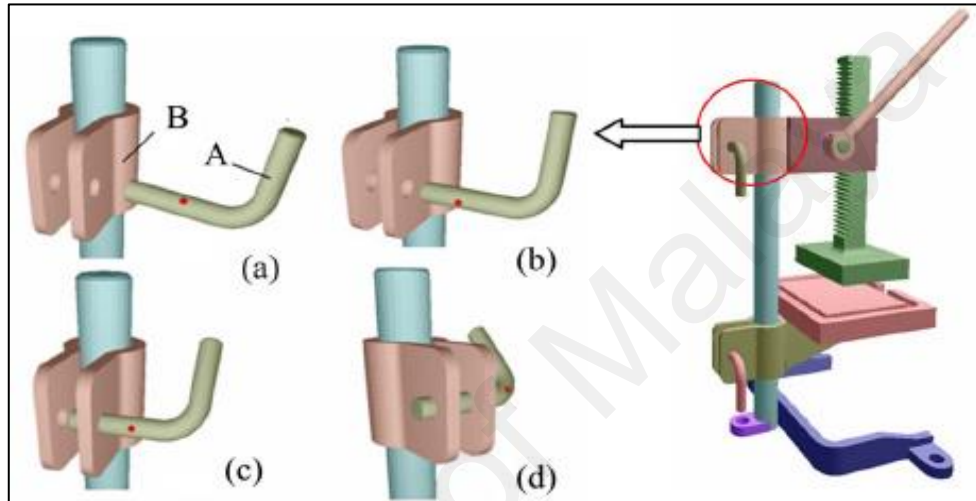


Figure 2. 12 Assembly constraints (Chen et al., 2010)



Figure 2. 13 Haptic Virtual System (Gonzalez-Badillo et al., 2013)

Table 2. 5 VR in Manufacturing Process

Author (year)	Application area	Immersion level	Function of VR
Wang et al. (2004)	Machining	Non-immersive	Use as VR as visualization platform to control activities of CNC machine (milling)
Li et al. (2008)	Machining	Non-immersive	Built virtual environment for the evaluation of optimization algorithm (GA) used in numerical control (NC) milling process.
Zhu et al. (2008)	Machining	Semi-immersive	VR provides human-machine interaction which improve machining performance and prove to be an effective tool in decision making
Soori et al. (2014)	Machining	Non-immersive	Construct a virtual system to evaluate milling performance thus reducing the possible error in real machining process.
Chen et al. (2010)	Assembly	Semi-immersive	Application of haptic device in virtual environment for part assembly process that provide higher degree of human-machine interaction for assembly design evaluation.
Gonzalez-Badillo et al. (2013)	Assembly	Semi-immersive	Developed haptic VR system for assembly process planning g and evaluation
Gao et al. (2014)	Assembly	Non-immersive	Apply motion navigation method in VR system to overcome the problem of inaccurate position and perform a more realistic assembly process simulation to enhance part assemability and assembly process evaluation.

## 2.5 Design for Manufacture and Assembly

The term design for manufacture and assembly (DFMA) is a combination of design for manufacture (DFM) which is the design for the ease of manufacture of the parts which would be assemble to form product and design for assembly (DFA) means the design of product for the ease of assembly (Boothroyd, 2011) which is used as the guide for product design in order to reduce manufacturing and assembly cost.

### 2.5.1 History

Traditionally, engineering graduates are expected to attend “shop” course which give exposure of manufacturing process to avoid unnecessary manufacturing cost during product design. Unfortunately, the course disappeared from the university curricula in United States in 1960s.

In early 1970s, Geoff Boothroyd and his colleagues (Corrado Poli and Laurence Murch) with his graduate student (Alan Redford) published handbook that catalogs feeding and orienting techniques for small parts. Then Boothroyd’s student, C. Ho, developed a part coding system based on group technology devised for the handbook, with the combination of coding system and research data form a systematic method for product designers in quantifying the ease of product manufacturing. Through the continuous efforts of numerous undergraduate and graduate students that had built and tested 140 feeding and orienting system led to the development of Design for Automatic Assembly methodology.

Later, Boothroyd and his colleague Bill Wilson present a proposal and received funding for research program in Design for Manufacturability. The purpose of this research was to help develop analytical methods to guide product designers for the ease of part manufacture and the ease of product assembly. Boothroyd and his student

developed the analysis method for Design for Manual Assembly, while Wilson had constructed a study on initial Selection of Material and Processes for manufacturing part. The third research area of this research was DFM for part which is completed with the collaboration of Winston Knight, especially in Design for Forging. From here, the DFA and DFM was born and later become DFMA.

It been agreed that over 70% of the final product costs are determined during the design phase (Yang, et al., 2000). However, the “over-the-wall” approach (Figure 2.14) where product designers sits on one side of the wall and just throw the design of product over the wall to the manufacturing engineer resulted in unnecessary manufacturing costs. Thus the concept of concurrent engineering teams was introduced which break the wall between design and manufacture, involving both product designer and manufacturing engineering in the early stage of product design.

#### 2.5.2 General Application Flow

DFMA appear to be one of the effective analytical method to be considered during the product design phase where DFMA could analysis the ease of parts manufacture and ease of assembly of a product form the collections of parts that been manufacture. Figure 2.15 is the general flow of how DFMA work during product design phase. The DFA analysis is first conducted to simplified product structure. Then, using DFM and early estimates for the parts obtained from both original and new design to made trade-off decision. During this phase, the best material and process for various parts is considered. Then the prototype would be produced and the design would be send for production (Boothroyd et al., 2011).

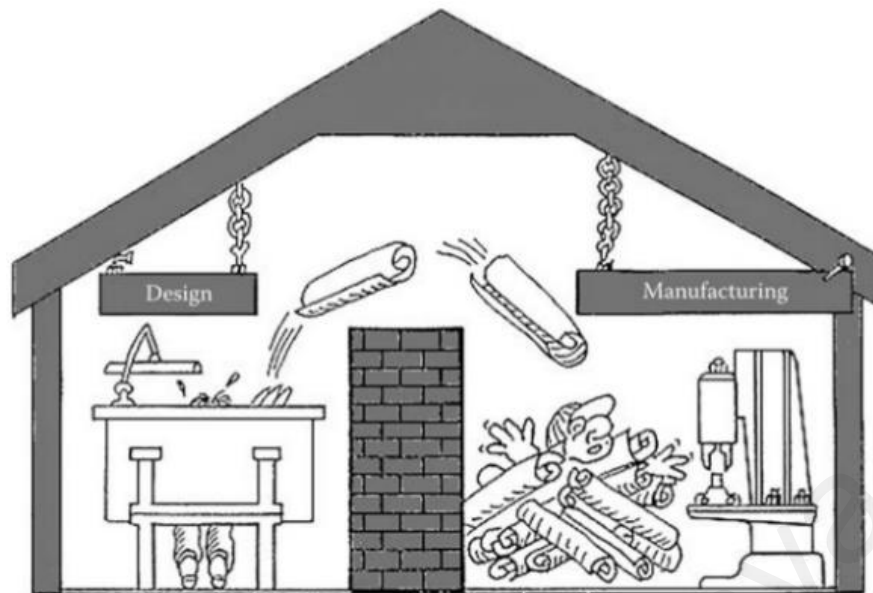


Figure 2. 14 Over the Wall Approach

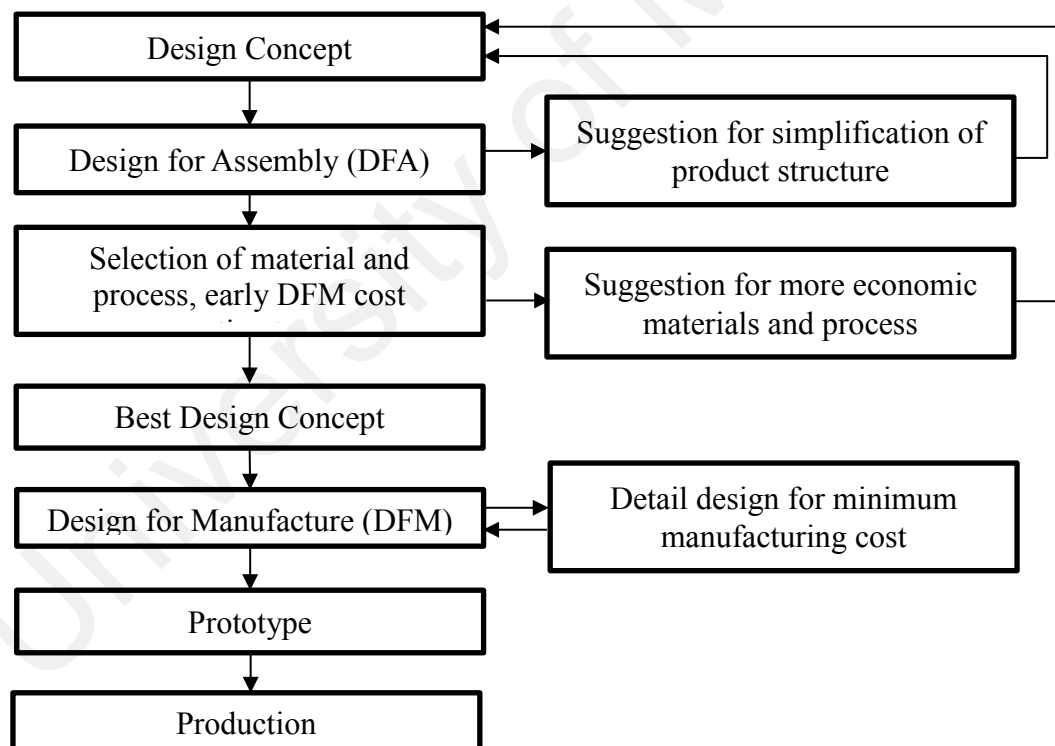


Figure 2. 15 DFMA steps (Boothroyd et al., 2011)

In DFMA, Boothroyd et al., (2011) had classified the guideline of design into DFA based and DFM based. DFA includes design for manual assembly, design for electrical connections and wire harness assembly, design for high speed automatic assembly, design for robot assembly, printed circuit board design for assembly. In DFM, it includes design for machining, printed circuit board design for manufacture, design for injection molding, design for sheet metalworking, design for die casting, design for sand casting, design for powder metal processing, design for investment casting and design for hot forging. Design for robot assembly is reviewed in detail in this

Three representative types of robotic assembly systems are considered in DFMA namely single-station with one robot arm, single station with two robot arms and multi-station with robots. To determine the assembly cost of the product four main aspects are necessary to be considered which are total cost of all general-purpose equipment (robot, versatile gripper), total cost of all special purpose equipment and tooling, average assembly cycle time, cost per assembly of manual labour involved.

Figure 2.16 show the example cost estimation for each type of robot assembly system based on a case study of the 4 degree of freedom Selective Assembly Robot Arm (SCARA) robot which only performs insertion along vertical axis. While the relative affective basic operation time (TP) of this data is based on the average time taken by the robot to move approximately 0.5m which involves grasping the part, return, and insert the part, assume the motion is easy and no insertion problem exists. By using this robot, if the part is inserted vertically, the robot cost remains the same while if the part is inserted horizontally, the robot cost would be 1.5 time of the basic robot cost. Based on the data been collected, the cost can be estimated based on the design of the product. For example, a part is design to be inserted along the horizontal axis that does not required special gripper but requires temporary clamping which is easily align for single station single arm system. Then referring to Figure 2.6, the product code is 12 and the AR (relative



robot cost) is 1.5. Thus, if the basic capital cost of installation is \$60,000, a cost of \$90,000 is assumed, which means \$30,000 is the penalty.

There are few general rules suggested for the ease of robotic assembly for the product design phase as follows:

- I. Reduce part count – reduce assembly cost and enhance quality of product by reducing part connections
- II. Use standard commercially available components – reduce design time as part is available
- III. Use common parts across product line – apply group technology for ease of manufacture
- IV. Design part for ease of fabrication – simplified geometry of part
- V. Design product to be foolproof – design part feature such as chamfer for the ease of assembly to avoid unnecessary steps for assembly such as self-locating features or self-fastening features
- VI. Develop modular design – for the ease of manufacturing activities such as testing, inspection, design, maintenance
- VII. Minimize assembly direction – part should design to be assembly form one direction, minimize the reorientation during assembly



### 2.5.3 Impact of DFMA in Industry

The DFA methodology for both automatic and manual assembly with the key criteria of product design simplification were published in University of Massachusetts Amherst (UMass) and gained 2000 subscription and used to supplement the DFA work within 4 years. After the official publication of DFA handbook, studies were conducted at Diablo Printer Division (Xerox Corporation) with the redesign of assemblies led to significant reduction in manufacturing by reducing part count for assembly. Soon, major company join in the alley such as General Electric, Westinghouse Electric, IBM and Digital Equipment (Boothroyd et al.,2011)

In 1980s, Peter Dewhurst joined Boothroyd in developing a computer version of DFA handbook and successfully release a software package “Design for Automation and Manual Assembly” that led to the incorporation of Boothroyd Dewhurst Inc. in 1981. The breakthrough of DFA implementation happened during 1988 when Ford Motor Company reported that this software had save billion dollars in Taurus line. Other than large volume production company, DFA also showed its capability in helping small volume production company such as QSTAR team in MDS Sciex, which produce mass spectrometer, a large and sophisticated instrument produced in low volume. The team reported that with the redesign on product for the ease of assembly, the total part count had reduced led to reduction of material costs by \$35,000 per unit and lowered the design and production error. Later, Dell Corporation had implemented DFMA to redesign Optiframe® chassis for PCs saving \$11.6 million in 1998, reduced assembly time by 32%, reduced part count by 50%, reduced Screw type count by 67% and average service count by 44%.

According to the record from Boothroyd Dewhurst Inc., over 800 different U.S. companies have implemented DFMA software in 1990s. Table 2.6 showed the feedback report from 123 published case studies after the implementation DFMA software showed

the impact of DFMA on their company through the concept of design for manufacture and assembly.

Table 2. 6 Published Cases Showing Improvement After DFMA Software (Boothroyd et al., 2011)

	<b>Average Reduction (%)</b>	<b>Number of Cases</b>
Labour Cost	42	8
Part Count	53	103
Separate Fasteners	57	21
Weight	22	21
Assembly Time	59	68
Assembly Costs	45	20
Assembly Operations	54	25
Product Development Time	45	2
Total Costs	50	32

## 2.6 Industry 4.0

The idea of Industry 4.0 was first proposed in Hanover Fair 2011 with the initiative term “Indutrie 4.0” by association of representative from business, politics, and academia as an approach for securing the future of German manufacturing industry by employing the information and communication technology (Kagermann, Lukas and Wahlster, 2011). German federal government supported this idea and announce this concept as an integral part of “Hi-Tech strategy 2020 for Germany”. Industrie 4.0 Working Group were formed and developed first recommendations for implementation published in April 2013 with the following vision (Kagermann et al., 2013):

“In the future, businesses will establish global networks that incorporate their machinery, warehousing systems and production facilities in the shape of CyberPhysical Systems (CPS). In

the manufacturing environment, these Cyber-Physical Systems comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently. This facilitates fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage and supply chain and life cycle management. The Smart Factories that are already beginning to appear employ a completely new approach to production. Smart products are uniquely identifiable, may be located at all times and know their own history, current status and alternative routes to achieving their target state. The embedded manufacturing systems are vertically networked with business processes within factories and enterprises and horizontally connected to dispersed value networks that can be managed in real time – from the moment an order is placed right through to outbound logistics. In addition, they both enable and require end-to-end engineering across the entire value chain”

Over the decade, scholars have defined Industry 4.0 from diverse perspective. According to the Consortium II, Fact Sheet, Industry 4.0 defined as “the integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes.”. Hermann et al. define this concept as “a collective term for technologies and concept of value chain organization”. After the collective study been conducted by Hofmann, 2017, the research group define the Industry 4.0 as “products and services are flexibly connected via internet or other network application that enables an automated and self-optimized production of goods and services which the value networks are controlled decentralized while system elements are making autonomous decision”. All definition showed the common. Further similar ideas can be found under the term “Integrated Industry”, “Smart Industry” of “Smart Manufacturing”.

### 2.6.1 Industry 4.0 Components

The literature review identified four key components of Industry 4.0: CyberPhysical System (CPS), Internet of Things (IoT), Internet of Services (IoS) and Smart Factory (Hermann et al., 2015).

- I. Cyber-Physical System (CPS) – Main important component of Industry 4.0 was the fusion of physical and virtual world which now is made possible by CPS. CPS is a system that using computers and networks to monitor and control the physical process, usually with feedback loops where the physical process affect computations and vice versa. First generation of CPS includes identification technologies such as RFID. The second generation of CPS are equipped with sensors and actuators. While the third generation of CPS able to store and analyzed data the equipped with multiple sensors and actuators that are network compatible.
- II. Internet of Things (IoS) – This is the major component the initiated idea of Industry 4.0. IoT allows “things” and “objects” interact with each other and cooperate with their neighboring component to reach common goal through unique addressing schemas.
- III. Internet of Services (IoS) – This components enables service vendors to offer their service via internet. Services are offered and combined into value-added services by various suppliers and communicated to users via various channels. This concept will be transferred from single factories to entire value added networks in the future.
- IV. Smart Factory – define as “factory that context-aware assists people and machines in execution of their tasks”. As CPS, IoT and IoS been introduced as core components of Industry 4.0, smart factory refers to a system that links CPS, IoT and IoS so that the machine, human and resources within the factory communicate

each other as naturally as in a social network. Under this context, Products and process are easily identified and locatable at any time and made the increasing complexity of manufacturing processes manageable for people and ensure the production is sustainable and profitable.

### 2.6.2 Applications

The components of Industry 4.0 been applied to assist the connection of manufacturing system components such as human, machines, resources and process. Helu and Hedberg, 2015 proposed a concept for a product lifecycle test bed built on a cyber-physical infrastructure that enables smart manufacturing research and development. This testbed integrates existing technologies for design, fabrication and inspection that enable digital thread of information across the product lifecycle. Wang et al. design a hybrid flow shop scheduling under IoT-enabled nonequal-parallel-machine manufacturing environment. The manufacturing petri net (MPN) where the transition of part are scheduled and reflecting the real time interactions of IoT-enable smart manufacturing resources. Through reflection and feedback of real time behaviors of manufacturing components, the optimal scheduling of part flow could be achieve. Lu and Xu had design and proposed a two stage approaches to configuring a knowledge based decision making process that automatically select best service provider and the time schedule for material planning for operation and production planning that practically solve the company issue in identifying real-time production workload and capability of each manufacturing site. By Iot, all manufacturing data such as production workload, resources availability been collected in real time and integrated with the expert system that contain multiple rules execution such as company specific rules, domain rules and domain ontology to seek for the best resources planning and workload scheduling. This model been applied in their industry partner and showed positive feedback in production control. Zhong et al. proposed the

utilization of CPS tool which is radio frequency identification (RFID) twin with cloud manufacturing to achieve final intelligent manufacturing. The research team developed an innovative RFID-Cuboid Model to reconstructing the RFID raw data given the production logic and tie series and implemented it into real life case. Based on the data collected, the FRID-Cuboid Model that track the shop floor logistic and convert the complex raw data into a readable and interpretable data by user and had efficiently ease the daily operations. The work is summarized in Table 2.7.

Table 2. 7 Applications of Industry 4.0

Research (Year)	Industry 4.0 Component	Findings
Helu and Hedberg, 2015	IoT, Smart Manufacturing	Product lifecycle testbed built in cyber physical infrastructure that enable the sharing of information
Wang et al., 2016	Iot, Ant colony	Manufacturing process connected through IoT, manufacturing data connected to MPN by ant colony algorithm, thus optimal scheduling achieved in real-time.
Lu and Xu, 2017	Cloud Manufacturing, IoT, Expert system	Two stage approaches by IoT and Expert System for cloud manufacturing to solve material and production planning issue faced by industry, and gain positive feedback from industrial partner
Zhong et al., 2015	Iot, RFID, Cloud Manufacturing	The logistic data were track through thr RFID, the flow of product been update throughout the whole system.

## 2.7 Summary

This chapter had reviewed the loop layout, digital factory, VR in manufacturing system, design for manufacture and assembly (DFMA) and Industry 4.0 which are all important elements in the research design which would be applying the digital factory concept with the utilization of VR as simulation tool to construct robotic work-cell and loop layout while the concept of DFMA would be used to design the dummy manufacture part for the simulation and evaluation. Based on the review in flexible manufacturing



system, loop layout problem is the most popular layout among other layouts in flexible manufacturing system and had been studied for a long period. As can be seen that the trend of methods for solving loop layout problem had shifted heuristic to metahueristics to intelligence algorithm. As the concern of the latest study, the algorithm simulated result might not be realistic as all the numerical simulation is not based on factory model. Thus, researchers are trying to search for a breakthrough to parallelizing the simulation result with the real manufacturing system condition which lead to digital factory concept. Digital factory - a concept of simulating the real factory in virtual model which highly resemble real factory model, processes, activities, and information flow through a network of digital methodologies and software tools had brought the interest of manufacturing sector to invest, develop and expanding this platform into all level of factory simulation. The key of realization for digital factory concept is the simulation method, while VR technology appears to be an effective tool for layout simulation and supporting the integration for factory planning and evaluation. After reviewing all the related work on applying VR technology based on digital factory concept, a framework for digital factory building been designed and will be discussed in next chapter.

## CHAPTER 3

### METHODOLOGY: VIRTUAL ROBOTIC WORKCELL

#### 3.0 Introduction

This chapter including description on the equipment used in this study, followed by the general framework to develop a complete digital factory platform in a virtual environment. Next, a detailed description of the development for the virtual robotic work-cell in digital factory platform is provided, including the application of virtual simulation in real time.

#### 3.1 Equipment Description

The main equipment involves both hardware and software which are described in the following section.

##### 3.1.1 Hardware

In this study, the most important hardware for the VR development is a computer workstation, 3D monitor and a dedicated graphic card to run heavy graphical simulation

##### *3.1.1.1 Computer Work Station*

A powerful workstation is used to deliver the performance, speed and scalability that is necessary to compute and render graphically intensive environments, at the same time able to manage massive data sets for the real time virtual simulation. Thus, the Dell Precision T7500 was selected for its capability to handle heavy graphical simulation with high speed and good graphical quality.

Table 3. 1 Specification of Dell Precision T7500 (Dell.com, n.d.)

Features	Technical Specification
Model	Dell Precision T7500
Form Factor	Tower Workstation
Processor	Intel ® Xeon ®
Operating System	Window 7 Professional 64-bit
Memory	12288MB RAM
Hard Disc	500GB SATA
Graphic Card	NVIDIA Quadro FX 4800

### 3.1.1.2 Monitor

A visual display is one of the most important elements for a good quality virtual simulation and provides a better visualization effect for the user. In this study, the Viewsonic 3D monitor was used to bring the best visual display quality.

Table 3. 2 Specification of ViewSonic® VX2268wm (ViewSonic®, n.d.)

Features	Technical Specification
Model	ViewSonic® VX2268wm
LCD	22" wide, TFT (Thin Film Transistor), Active Matrix WSXGA+ LCD, 0.282 mm pixel pitch
Resolution Supported	Maximum: 1680 x 1050 @ 100, 110, 120 Hz Minimum: 720 x 400 @ 70 Hz
Display area	473.76 mm / 18.65" (Horizontal) x 296.1 mm / 11.66" (Vertical)

### 3.1.1.3 Graphic Card

This research requires a fast memory bandwidth to delivers throughput for interactive visualization of large models and high performance for real time processing of large textures and frames. The Nvidia Quadro Fx4800(Figure 3.1) was chosen for this research according to its performance and the technical specification (Table 3.3):

- I. 1.5GB frame buffer and memory bandwidth up to 76.8 GB/sec: supports resolution full-scene antialiasing (FSAA).
- II. Quad Buffered Stereo: Suitable for applications that require stereo viewing capability.

Table 3. 3 Nvidia Quadro Fx4800 (Nvidia.com, n.d.)

Feature	Technical Specification
Form Factor	4.36" (H) x 10.5" (L), Dual slot card
Bus Type	PCI Express x16, Generation 2.0
Memory	1.5 GB GDDR3 SDRAM unified graphics memory
Connectors	2 DisplayPort, 1 Dual-Link DVI-I, 1 3-pin Mini DIN stereo output, Two DisplayPort to DVI-D adapters included
Maximum Resolution	DisplayPort connectors support ultra-high-resolution panels (2560 x 1600) Dual-link DVI-I output drives one digital display (2560 x 1600 @ 60Hz) Internal 400 MHz DACs-One analog display (2048 x 1536 @ 85Hz)
Supported Graphics APIs	OpenGL 3.0 DirectX 10
Available Graphics Drivers	Microsoft Windows XP Professional (64-bit and 32-bit) Genuine Windows Vista Business (64-bit and 32-bit)
High-Resolution Antialiasing	Rotated Grid Full-Scene Antialiasing (RG FSAA) 32xFSAA dramatically reduces visual aliasing artifacts or "jaggies" at resolution up to 1920 x 1200 64x FSAA SLI Mode



Figure 3. 1 Nvidia Quadro Fx4800 (Nvidia.com, n.d.)

### 3.1.2 Software

Three major softwares were utilized in this study; SolidWork 2010, Autodesk 3ds Max 2014 and Eon Reality Professional version (8.4.0 64-bit version). The description and functions of each software is listed in Table 3.4.

Table 3. 4 Software Description

Software	Functions
SolidWork (ver 2010)	A solid modelling computer aided design and computer aided engineering software that utilizes a parametric feature based approach to create models and assemblies Function in this study - generate the 3D model at the same scale of real model for better simulation accuracy
3ds Max (ver 2014)	A professional 3D computer graphic program for making 3D models with good quality of visual details (texture) and having capability in animation creation with its own language. Function in this study – give details on the model and define the geometry properties more accurately
Eon Reality Professional (ver 8.4)	A VR software with the immersion and interaction features for displaying the virtual environment and 3D model. This software consists of a physics engine that provides life-like animation using the correct laws of Newtonian physics. Function in this study – to build a virtual manufacturing system that highly resembles the real manufacturing system.

## 3.2 General Framework of Digital Factory Platform based Virtual Environment Construction

There are six main phases to build a virtual environment (Figure 3.2).

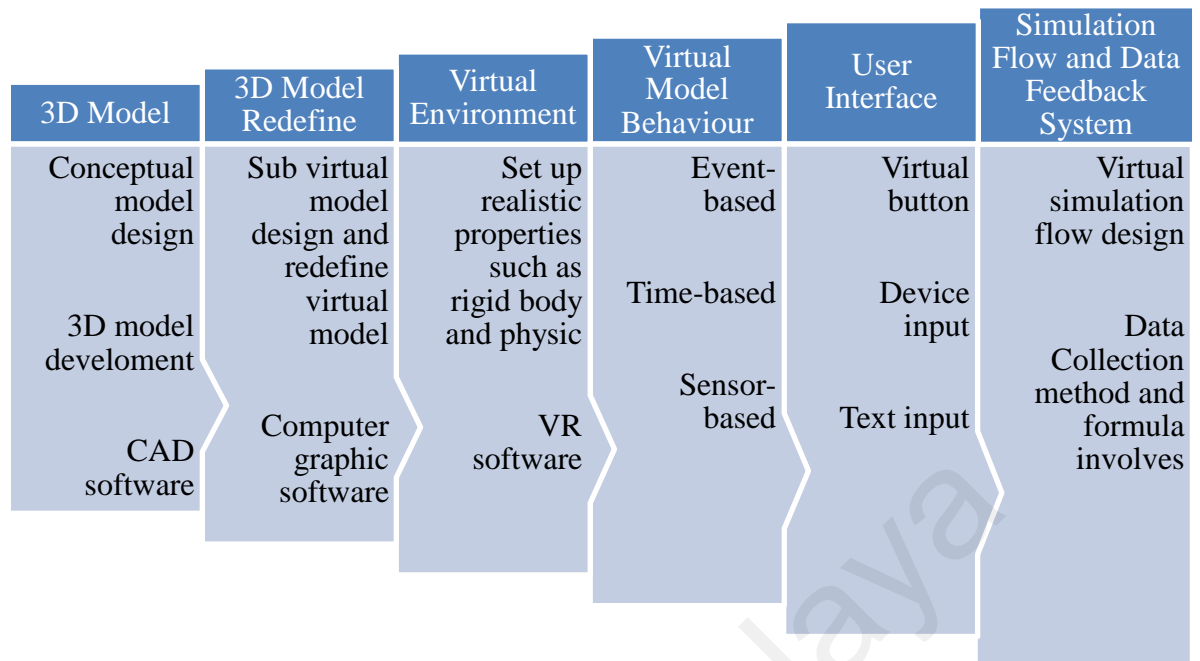


Figure 3. 2 Virtual Environment Development Workflow

Phase 1: 3D model designs (3D modelling software)

In this phase, a 3D model from a real object is modelled through commercial 3D software. SolidWork is used for modelling with a precise scale.

Phase 2: 3D model redefines (3D computer graphic programs)

In this phase, the model is then exported to the computer graphic program for redefining the detail and geometry. 3ds Max is used in this study to do the detail design of each model and to place all the models in a proper geometry layout.

Phase 3: Virtual environment design (VR software)

All the models with defined properties are then exported to the VR software (hereby refers to Eon Reality) to set up the geometry and physics properties. All the 3D models from the previous stage are arranged in the virtual environment according to a reference scale (1mm = 1 virtual unit)

#### Phase 4: Virtual model behaviour

All the virtual model or graphical representations are scripted to perform their natural behaviour. In this stage, the physic engine is used to impart the physical properties such as friction, gravity and force to the model, achieved through script programming. The interaction between the virtual object used in this study is classified into three forms as in Figure 3.3.

#### Phase 5: User interface design

The user interface need to be designed for users to interact with the virtual environment intuitively. There are there forms of human interfaces for user to interact with the virtual world, explained in Figure 3.4.

#### Phase 6: Simulation Flow and Data Feedback System Design

The simulation flow was design using a selected programming language to connect all the model behaviour and user. The data feedback system is necessary in a digital factory platform to manage the virtual manufacturing system.

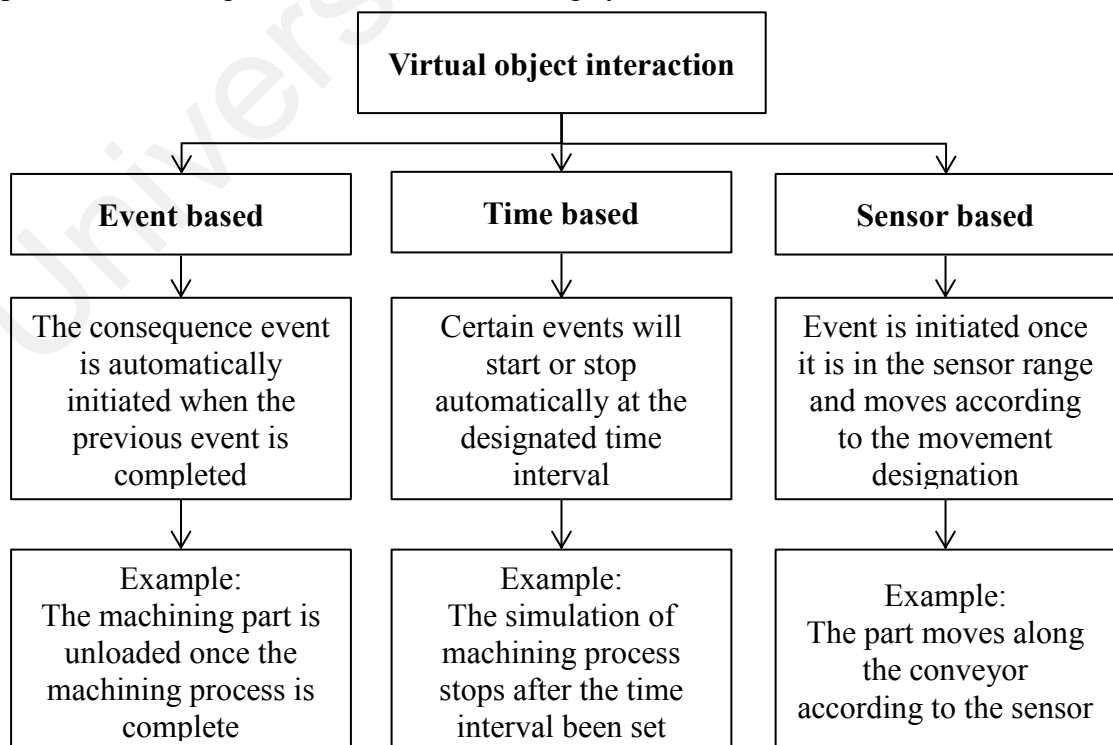


Figure 3. 3 Interaction between Virtual Object

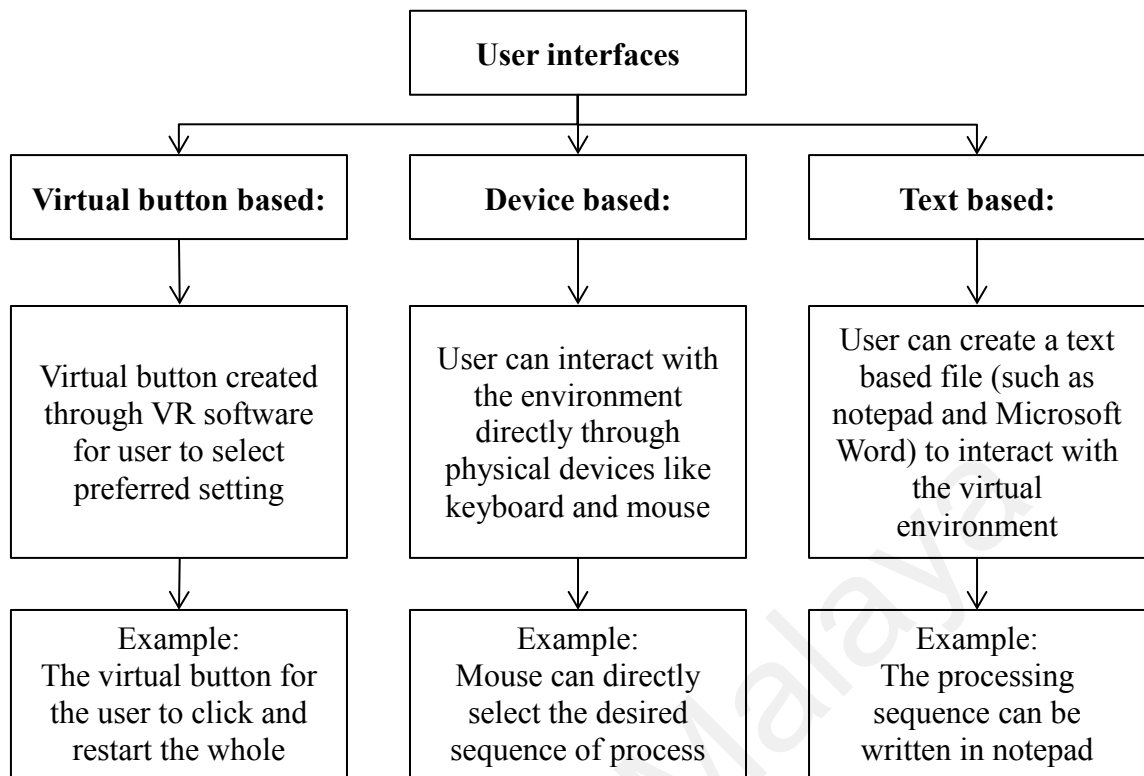


Figure 3. 4 Forms of User Interfaces

### 3.3 Virtual Robotic Work Cell

A virtual robotic work cell is designed and developed to verify the applicability of a digital factory in simulating manufacturing activities with a certain degree of interaction between human and machine.

#### 3.3.1 Phase 1: Conceptual and 3D Model Design (SolidWorks)

The initial design of the robotic work cell is based on a physical conveyor system set up in VR lab University of Malaya which was modelled using SolidWork according to a realistic scale (Figure 3.5). The purpose of adopting a physical set up is to validate the application of virtual manufacturing within the digital factory platform. Three dummy machines (denoted as  $M_3$ ,  $M_4$  and  $M_5$ ) were designed to be located around a closed loop of conveyor belt while two machines with an assigned function (denoted as  $M_1$  – lathe machine and  $M_2$  – milling machine) is located in the centre of the loop at each side of the robotic arm. The robotic work cell (Figure 3.6) been design based on the spine layout design as the machines is located at both sides of the conveyor belt to increase the



flexibility of the entire system. A few assumptions were made for this conceptual design of robotic work cell with the main purpose being to integrate VR technology in a manufacturing system simulation:

- I. Robotic arm only holds one part per time (single gripper robotic arm)
- II. One machine processes only a single part per time
- III. No buffer for intermediate storage between the stages within the cell

Assumptions of part flow for the virtual simulation:

- I. Single part flow per simulation
- II. The part process sequences involve three machines only
- III. The second processing sequence of a part is limited to either  $M_1$  (lathe machine) or  $M_2$  (milling machine)

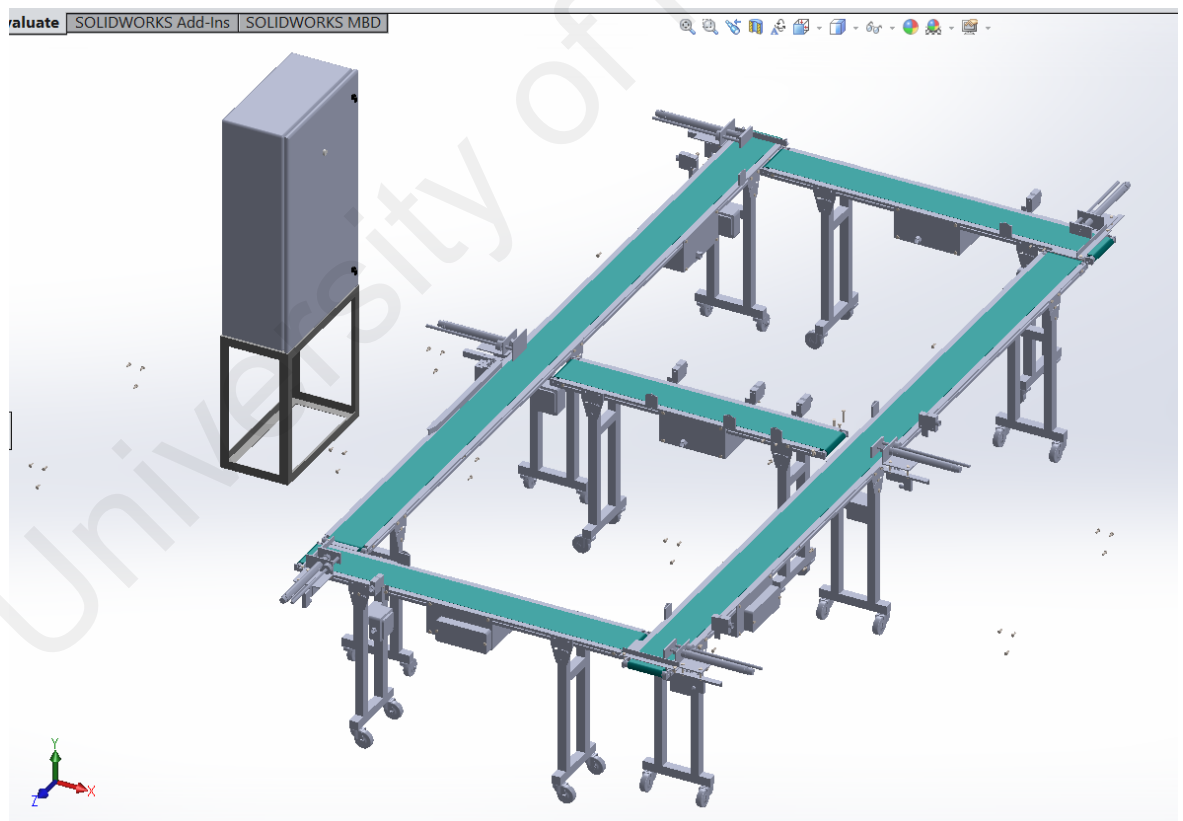


Figure 3. 5 3D Conveyor System in SolidWork

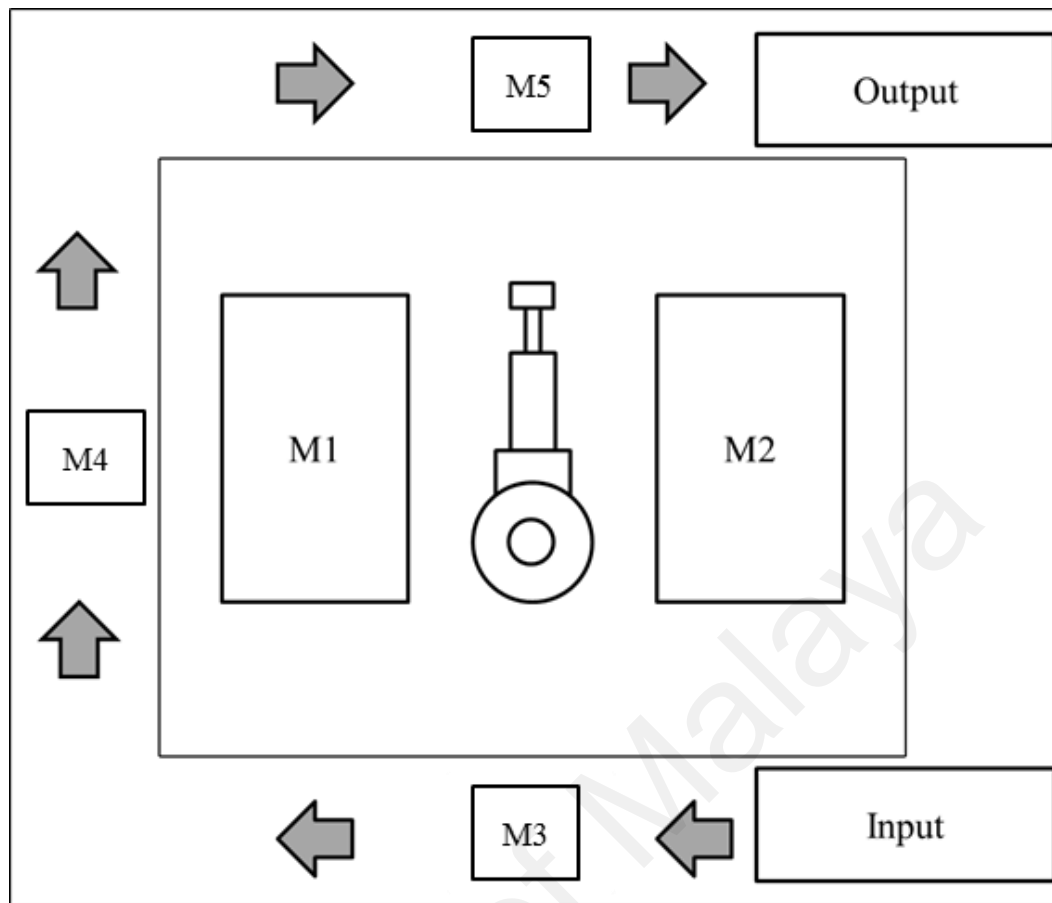


Figure 3. 6 Robotic Work-cell Conceptual Design

### 3.3.2 Phase 2: 3D Model Redefine (3ds Max)

The lathe, milling machine, robotic arm and worktable (Figure 3.7) model is exported to this software to scale and adjust the geometry according to the conveyor scale.

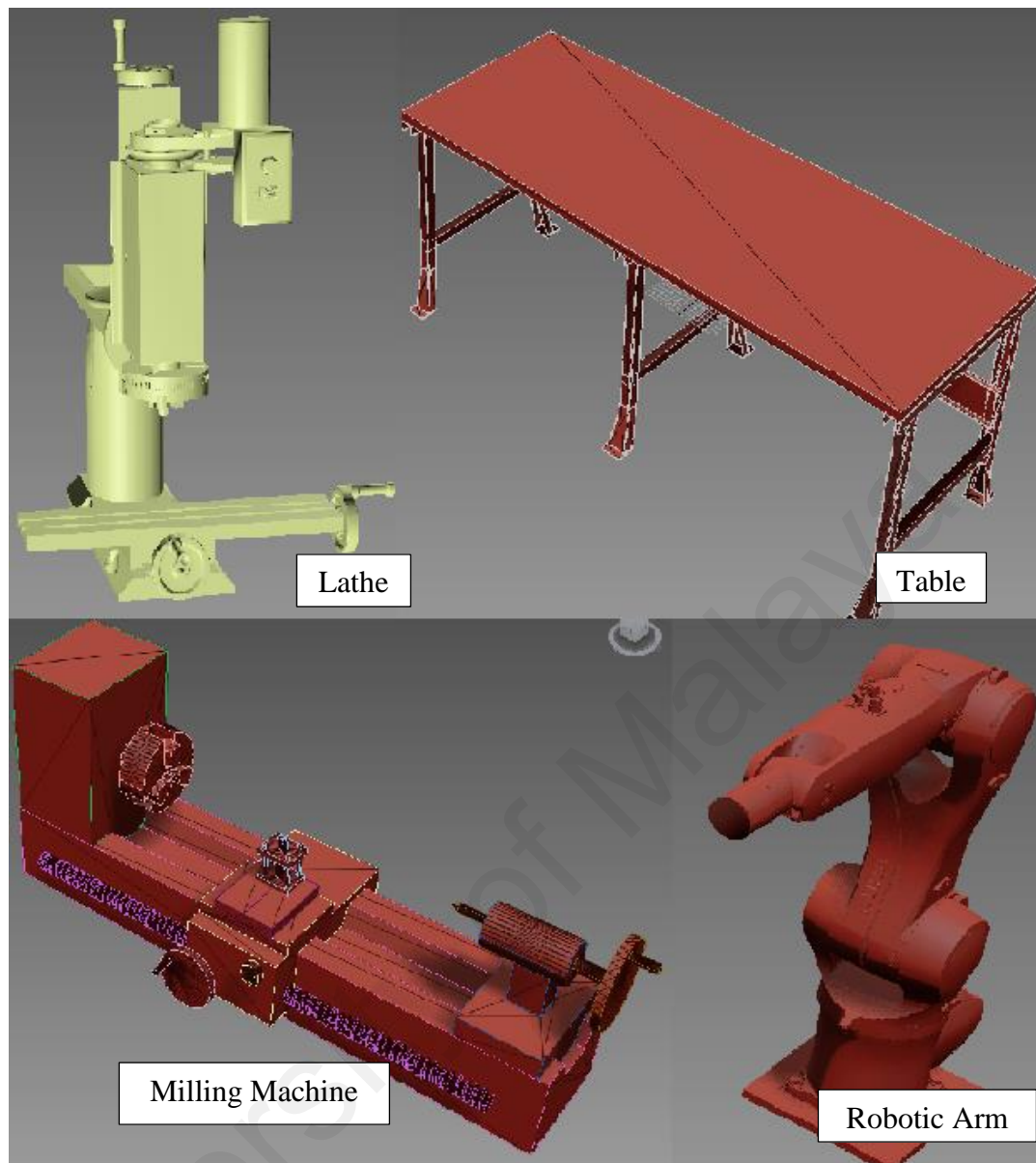


Figure 3. 7 Lathe, Milling Machine, Robotic Arm and Table in 3ds max

### 3.2.3 Phase 3: Virtual Environment Development (EON Reality)

All 3D models are imported into the VR software to create a virtual robotic work-cell model (Figure 3.8). This is a pure visualization of the constructed virtual robotic work-cell according to the following ratio: virtual ratio in 1mm: 1 virtual unit where the geometry of each need to be set (Figure 3.9)

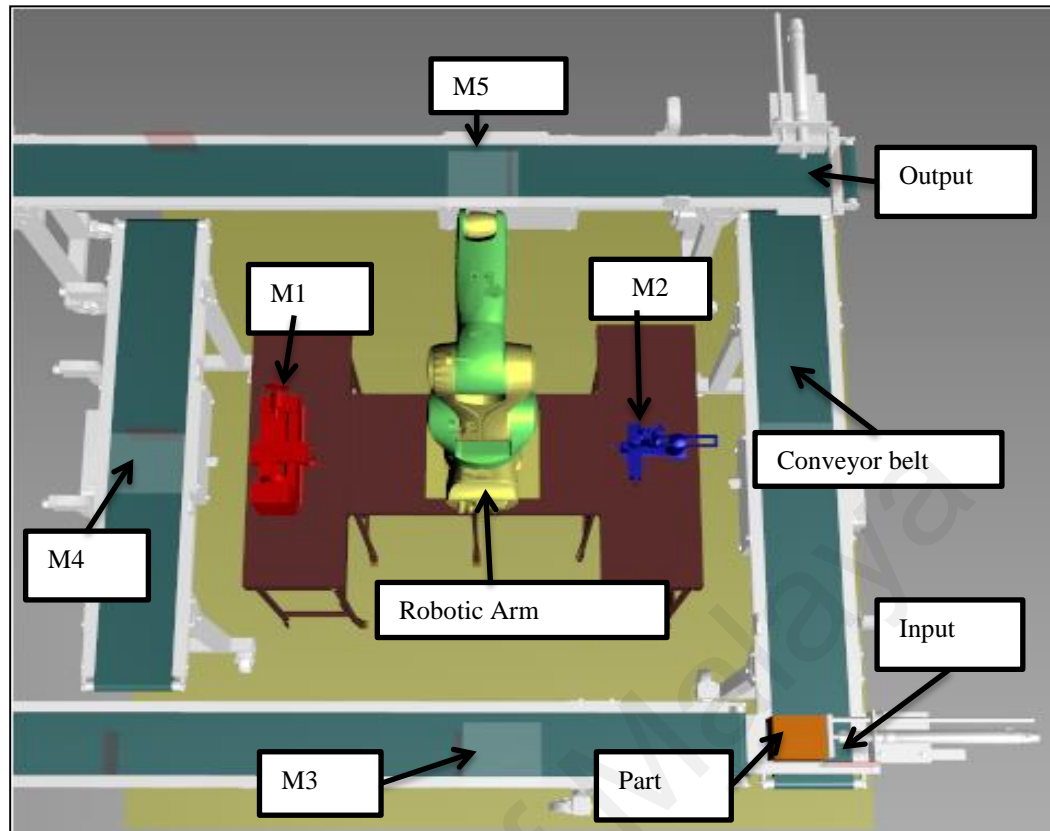


Figure 3. 8 Virtual Robotic Work Cell

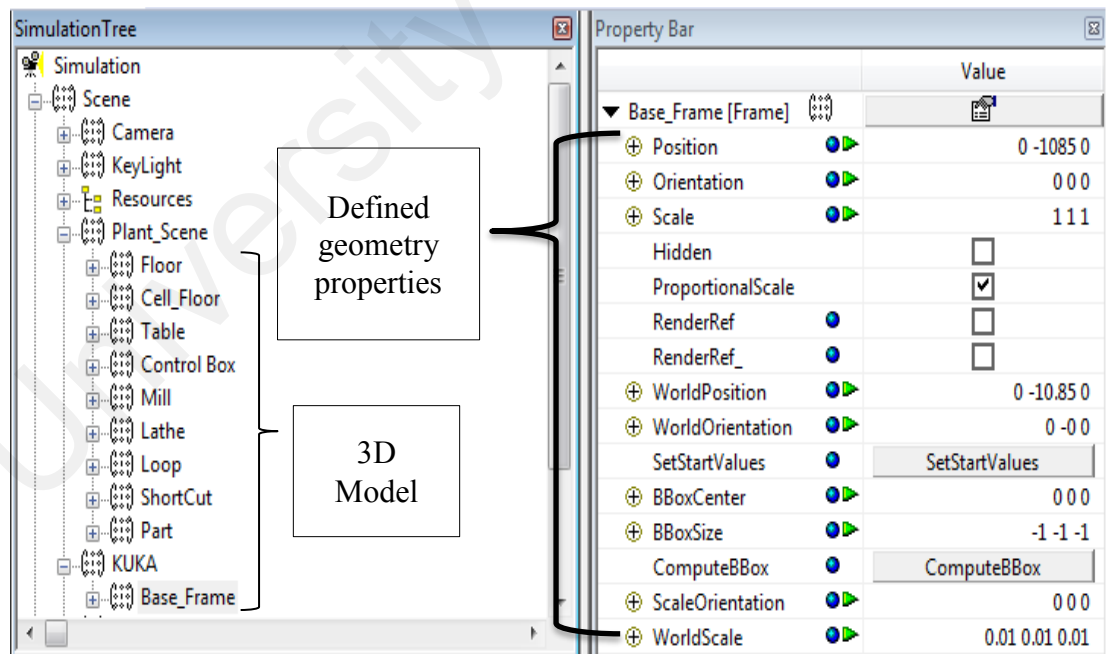


Figure 3. 9 3D Model Properties Setting in EON Reality

### 3.2.4 Phase 4: Virtual Model Behaviour

For the simulation to run, the behaviour of each 3D model needs to be pre-programmed. The main behaviour of the 3D model is listed in Table 3.5:

Table 3. 5 Virtual Robotic Work-Cell Behaviour Mode

Behaviour	Example in Simulation
Event based	<ul style="list-style-type: none"> <li>• Robotic arm automatically moves to the desired machine once the machine is selected to pick the part from the current machine</li> <li>• Once the part finishes its machining process, the robotic arm automatically picks the part to the next machine</li> <li>• Figure 3.10 show the method of event based behaviour programming. The script is written to receive the data of the previous event (selection on <math>M_1</math> or <math>M_2</math>). Once the previous event is completed, the next event is triggered where the robotic arm moves to the selected machine.</li> </ul>
Sensor based	<ul style="list-style-type: none"> <li>• The part stops exactly in front of each machine as a sensor is placed in front of each machine as a stopping alert.</li> <li>• Once the part is on the conveyor belt, it can move automatically as a sensor is placed along the conveyor belt for the part to move automatically.</li> <li>• Figure 3.11 show how the sensor works in the virtual environment.</li> </ul>

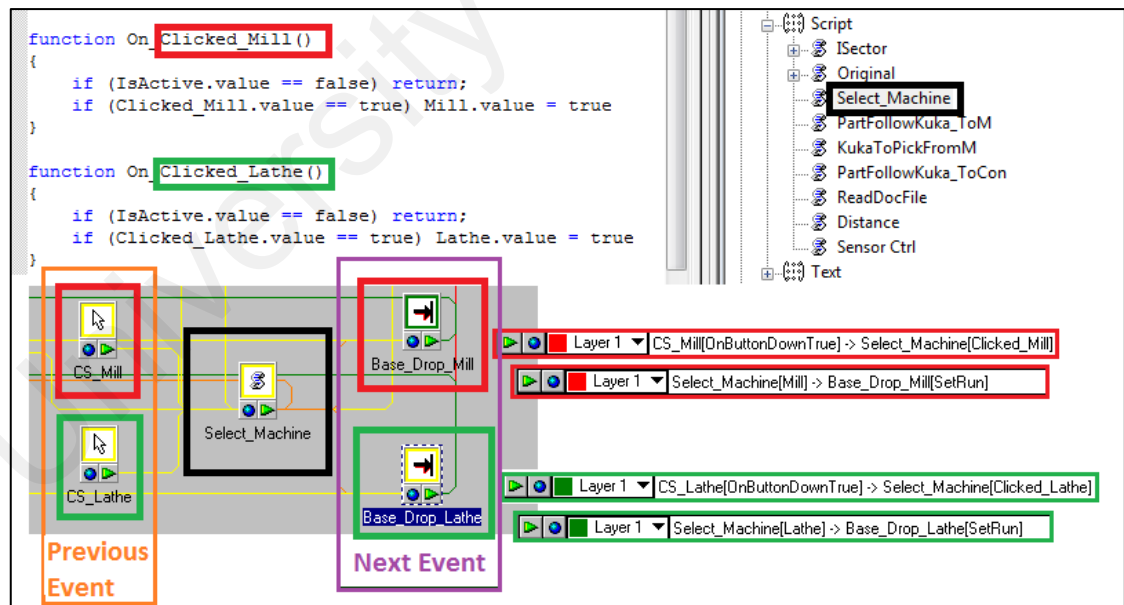


Figure 3. 10 Event Based Behaviour example in Virtual Robotic Work Cell

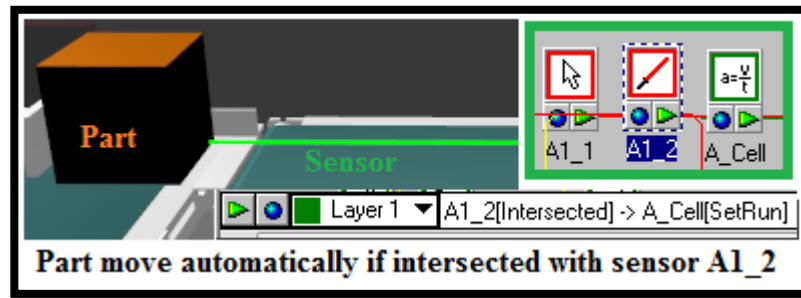


Figure 3. 11 Sensor Based Behaviour example in Virtual Robotic Work Cell

### 3.2.5 Phase 5: User Interface Design

After the setting for the interactive features between virtual objects, the user interface was created for the user to control the virtual environment is described in Table 3.6.

Table 3. 6 Virtual Robotic Work Cell User Interface Design

User Interface	Example in Simulation
Virtual Button	<ul style="list-style-type: none"> <li>• Virtual buttons are created to start, end and reset the simulation</li> <li>• Figure 3.12 shows that when the user clicks the button “Original”, the virtual button sends a signal to a script to reset other scripts and restart the whole simulation</li> </ul>
Device Input	<ul style="list-style-type: none"> <li>• The user can select the desired machine sequence by clicking directly on the virtual model using the mouse.</li> </ul>
Text based	<ul style="list-style-type: none"> <li>• A written script enables the VR system to read a Microsoft Word file to retrieve the sequence of a part and simulate it directly without any extra control on the virtual environment. The user can edit the sequence in the text file for it to simulate.</li> <li>• Figure 3.13 shows how the script works. The script reads the text file through ActiveXObject method, and then it will detect the number in the designated array. In this case, the first array of data refers to the M<sub>2</sub> machine, triggering Pick_B feature to activate the robotic arm to move to M<sub>2</sub> machine.</li> </ul>

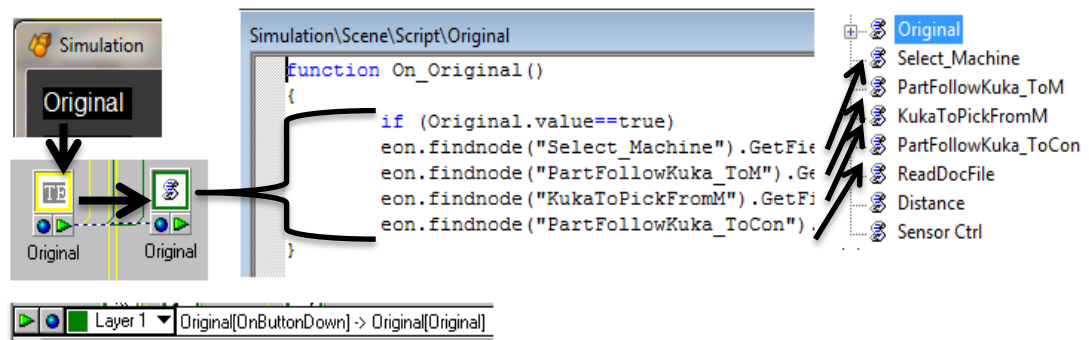


Figure 3.12 Virtual Button example in Virtual Robotic Work Cell

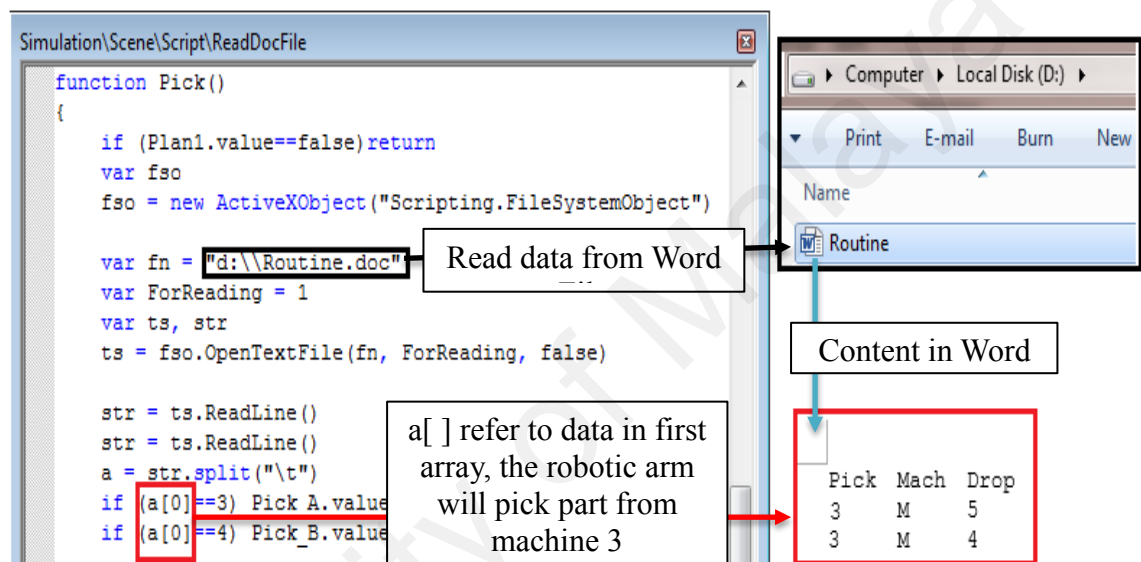


Figure 3.13 Text Based Interface example in Virtual Robotic Work Cell

### 3.3.6 Phase 6: Simulation Flow and Data Feedback System

After scripting the interactive features for the virtual robotic work cell, the simulation flow (Figure 3.14) needs to be designed. The simulation can be initiated using two methods:

- I. Virtual control - user selects all three machines in the virtual environment
- II. Text file – user can edit a text file for the system to read and run the simulation without any further control.

Once the simulation starts, the user can select the first machine ( $M_i$ ) or read the selection from the text file. Then, sensors for the selected machine is activated to stop the

part at the selected machine. The second machine ( $M_{i+1}$ ) is then selected by the user. Once the second machine is selected, the robotic arm automatically collects the part from the first machine and sends it to the second machine. The same procedure is repeated for the third machine ( $M_{i+2}$ ). As the part finished all three machining processes, the simulation window can be reset for a new simulation.

A data feedback system (Figure 3.15) was design for the completeness of the manufacturing system simulation. The objective of the data feedback system is to collect the total travel distance of the part in the robotic work cell. Several assumptions were made for the data feedback system:

- I. The distance calculated is based on equation (3.1):

$$\text{Distance from } A(a_i, b_i) \text{ to } B(x, y) = |x - a_i| + |y - b_i| \quad (3.1)$$

- II. The calculated distance is limited to the distance of part travel on conveyor belt.
- III. The distance of part through the robotic arm is not included as it involves 3D axes.
- IV. The distance unit is virtual unit.



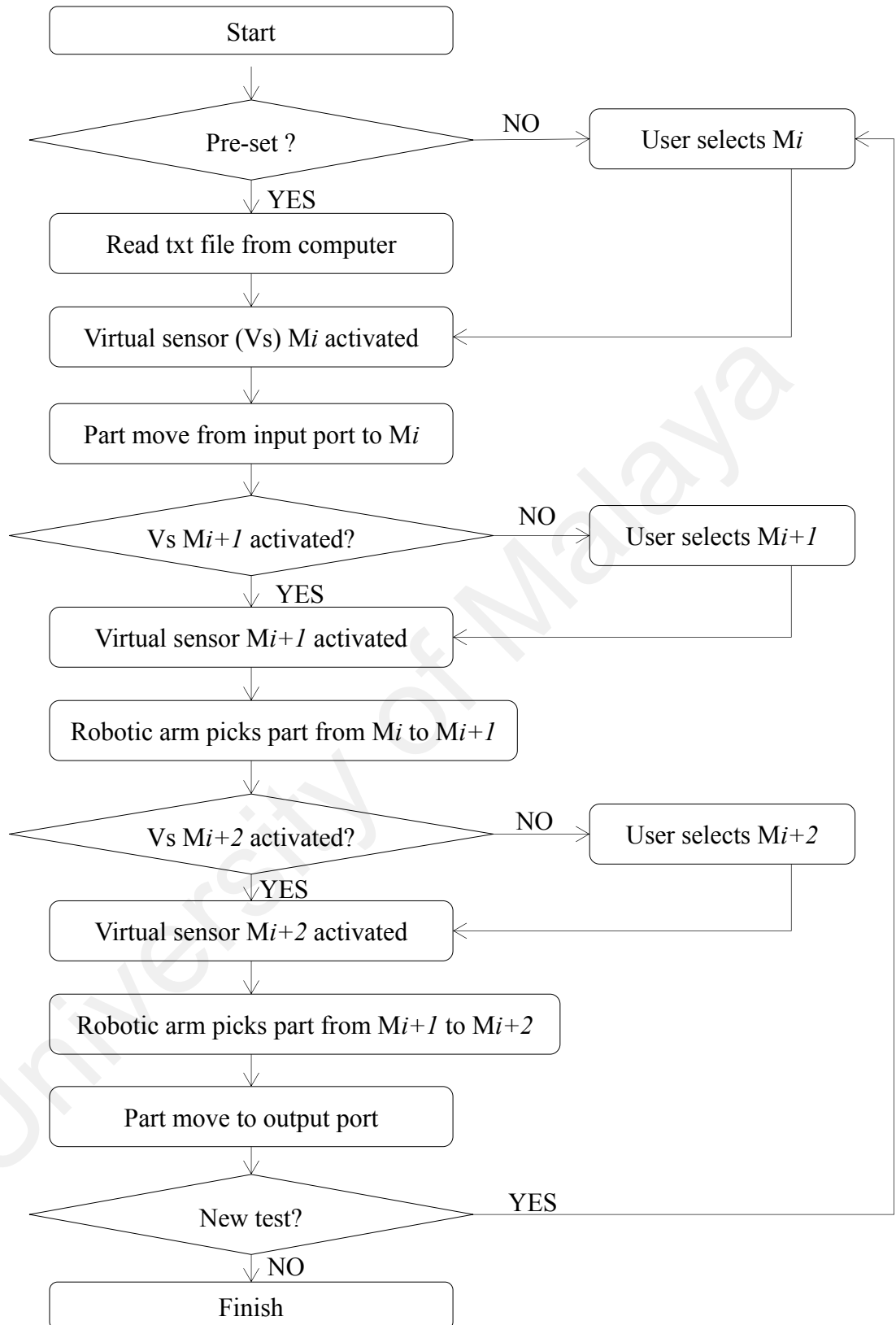


Figure 3. 14 Simulation Architecture of Virtual Robotic Work Cell

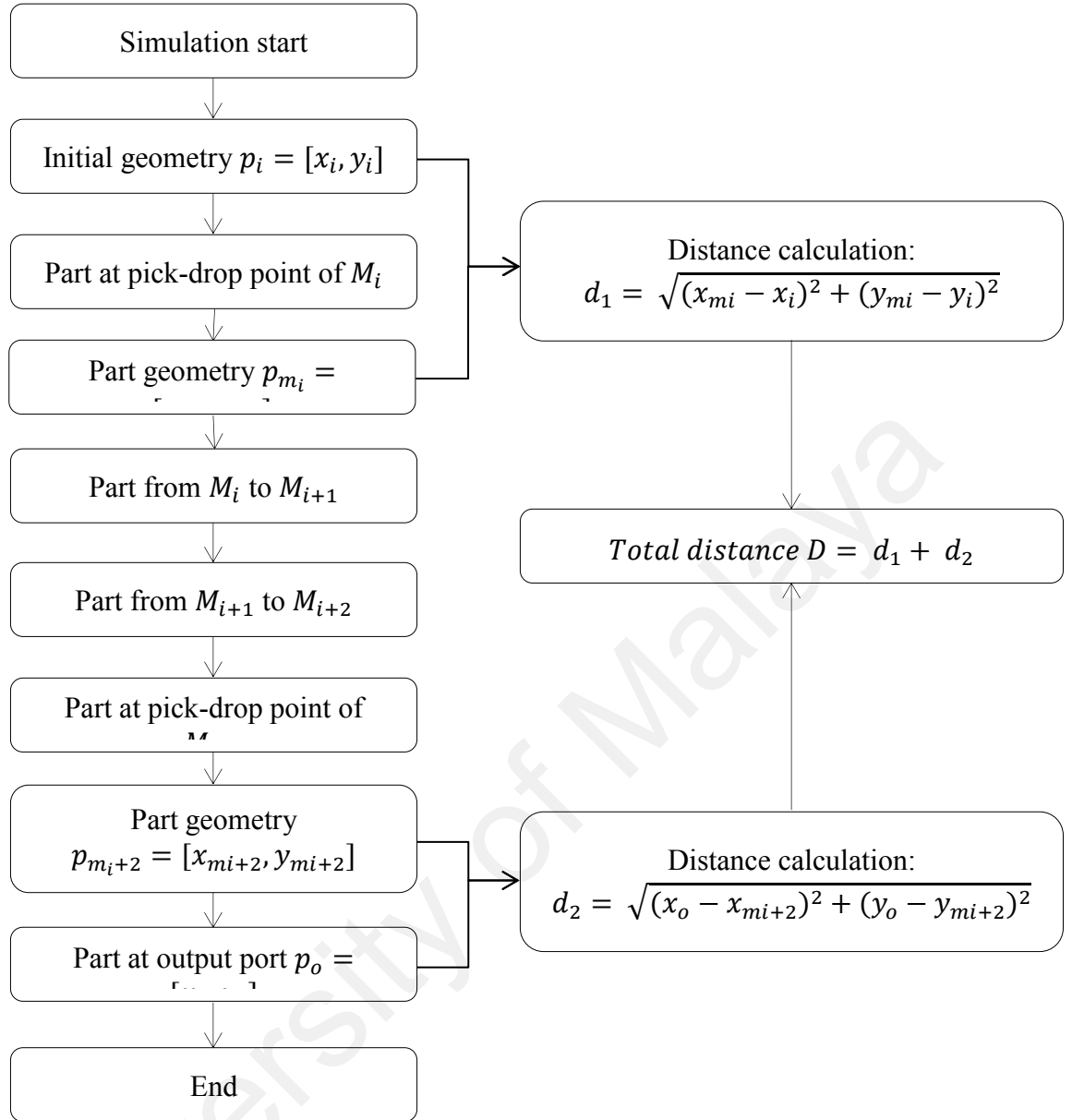


Figure 3. 15 Data Feedback System of Virtual Robotic Work Cell

### 3.4 Summary

This chapter covers the equipment required for this study, both the hardware and software. A general framework for generating virtual environment was also discussed which involve the six phases: 3D model designs, 3D model redefined, virtual environment design and the programming for the virtual object behaviour, creation of the user interfaces and the design of simulation flow and data feedback system. This framework was used to create the virtual robotic work cell with five machines and a

robotic arm and virtual loop layout with the benchmark test bed of ten machines and three production parts. The first phase of this study was the virtual robotic arm creation. This is a test model for the study on the possibility of using digital methodologies in modelling and simulation of a robotic work cell and getting manufacturing data from the digital factory platform.

University of Malaya

## CHAPTER 4

### METHODOLOGY: VIRTUAL LOOP LAYOUT

#### 4.1 Introduction

In this section, a development of virtual loop layout by using the framework design in Chapter 3 is explained. This virtual loop layout is design as an alternative tool for solving loop layout problem by virtual model simulation, testing, and improving proposed modification within simulation scene and analysis of multiple scenario of modification.

#### 4.2 Virtual Loop Layout

The construction of the loop layout problem involves the adoption of a benchmark test bed from Chapter 2 as the basic model of the simulation. The data feedback system of this simulation model is focused on obtaining the rectilinear travel distance of manufacturing part and traffic congestion of loop layout that described in Chapter 2.

##### 4.2.1 Phase 1: Benchmark Test Bed and 3D Model Design

The benchmark test bed used for evaluation in solving the loop layout problem described in Chapter 2 is adopted for the virtual environment construction. The details of the test bed such as the specification of machines (Table 4.1), specification of production parts (Table 4.2) and the machining time for each part (Table 4.3) were used by previous researchers to evaluate the efficiency of the numerical method. The exact same test bed

is also used for the virtual model in which all units is measured in virtual unit (1mm in physical). The conceptual design is shown in Figure 4.1.

Table 4. 1 Machine Specifications

Machine Number	1	2	3	4	5	6	7	8	9	10
Length (unit)	5	1	6	1	5	4	7	5	3	4
Clearance (unit)	1	1	1	2	2	1	1	1	3	2

Table 4. 2 Part Specifications

Part Type	Quantity	Label	Processing Sequence
1	1	Red	2-1-6-5-8-9-3-4
2	1	Green	10-8-7-5-9-6-1
3	1	Blue	9-2-7-4

Table 4. 3 Parts Processing Time

Part	Processing Time (virtual second)									
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
1	3.4	2.6	5.3	6.7	5.2	6.4	-	7.2	3.0	-
2	6.0	-	-	-	4.8	3.8	3.1	6.5	2.5	7.2
3	-	4.3	-	6.3	-	-	3.6	-	4.2	-

Assumptions on the layout design is made based on the following details:

- I. The placement of machines is around a loop conveyor belt with five machines at the top and bottom.
- II. Only one loading and one unloading station for input and output of parts.
- III. No robotic arms in included the loop and the part only travels through the conveyor belt.
- IV. The larger unit of space clearance is the exact space clearance of machines instead of the addition of both machines' clearance.
- V.

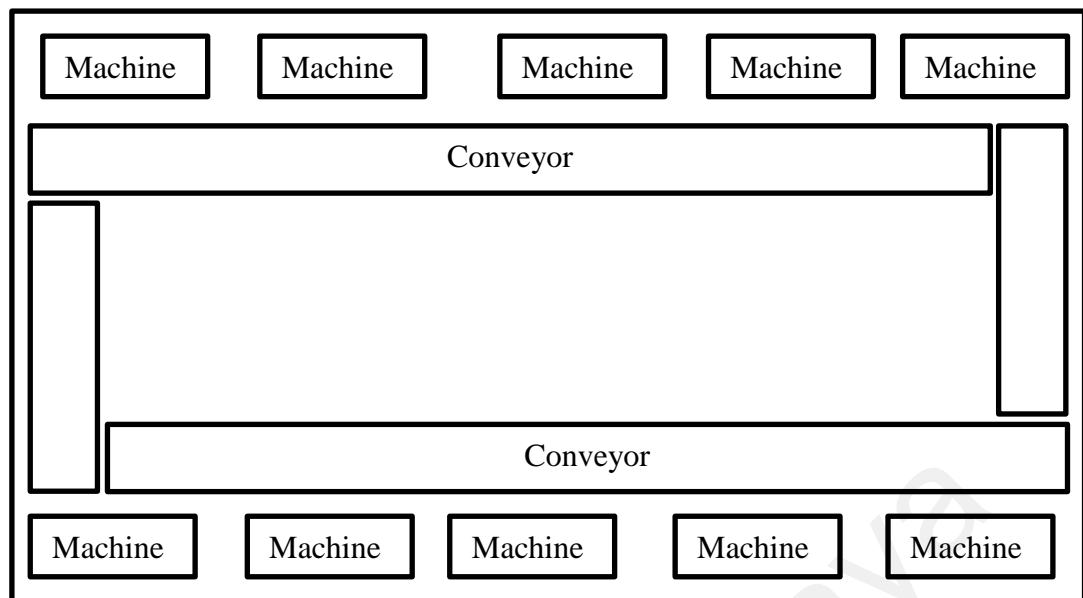


Figure 4. 1 Conceptual Design of Virtual Loop Layout

#### 4.2.2 Phase 2: 3D Model Refine (3ds max)

All the machines in the virtual loop are designed according to the conveyor scale and texture. The machine is treated as dummy machines (Figure 4.2) and the numbering or label of the machine design is located at the top of machine (Figure 4.3)



Figure 4. 2 Virtual Machine Design

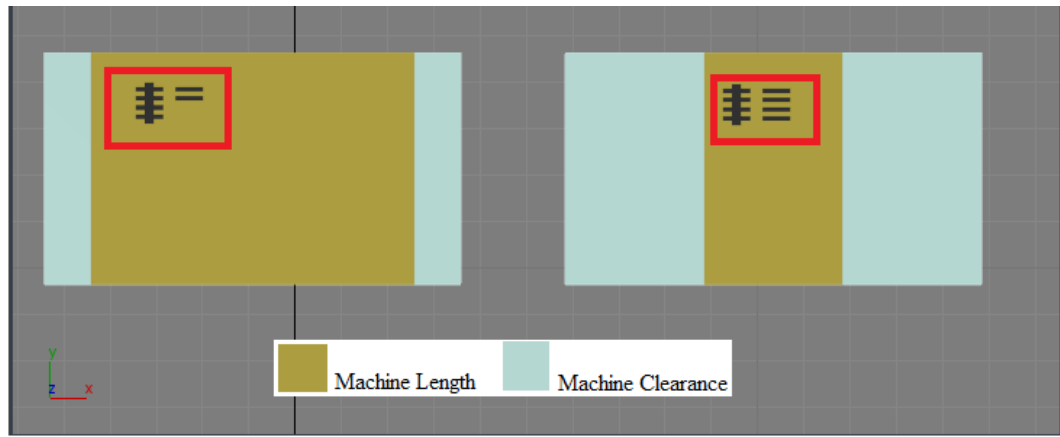


Figure 4. 3 Machine Label Design

#### 4.2.3 Phase 3: Virtual Environment Development (EON Reality)

All of the 3D models are exported into the VR software to create a virtual robotic work-cell model (Figure 4.4). This is a pure visualization of the constructed virtual loop layout according to the virtual ratio in 1mm: 1 virtual unit.

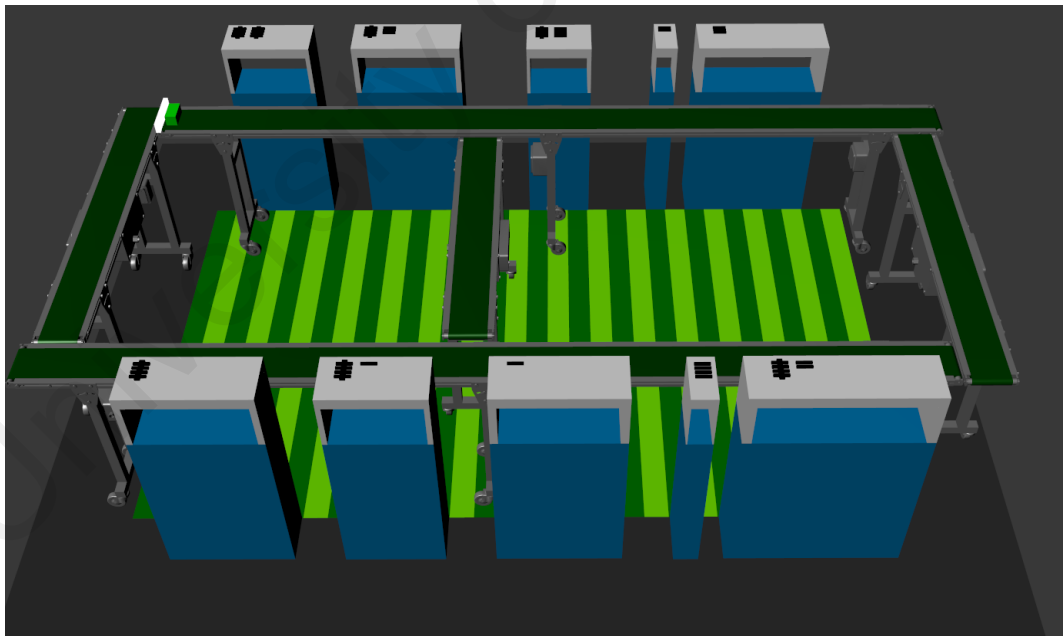


Figure 4. 4 Loop Layout in Virtual Environment

#### 4.2.4 Phase 4: Virtual Model Behaviour

In this virtual loop layout, three main behaviour forms exist (Table 4.4):

Table 4. 4 Virtual Loop Layout Model Behavior

Behaviour	Example in Simulation
Sensor based	<ul style="list-style-type: none"> <li>The part stops exactly in front of each machine as a sensor is placed in front of each machine as a stopping alert</li> <li>Once the part is on the conveyor belt, it moves automatically as a sensor is placed along the conveyor belt for the part to move automatically</li> </ul>
Time based	<ul style="list-style-type: none"> <li>Time based event such as the machine time for each part and each machine is scripted. (Figure 4.5)</li> </ul>
Event based	<ul style="list-style-type: none"> <li>The next processing machine is triggered after the previous machine completes the machining part</li> <li>Figure 4.6 show how the next event is triggered. Once part 3 is selected, it will trigger the part 3 script where the sequence of part is obtained. The sequence of part 3 is defined as a pre-set: 9-7-2-4, where machine 9 is the first to be triggered for processing. Once the machine 9 process is complete, the next machine in the sequence is triggered.</li> </ul>

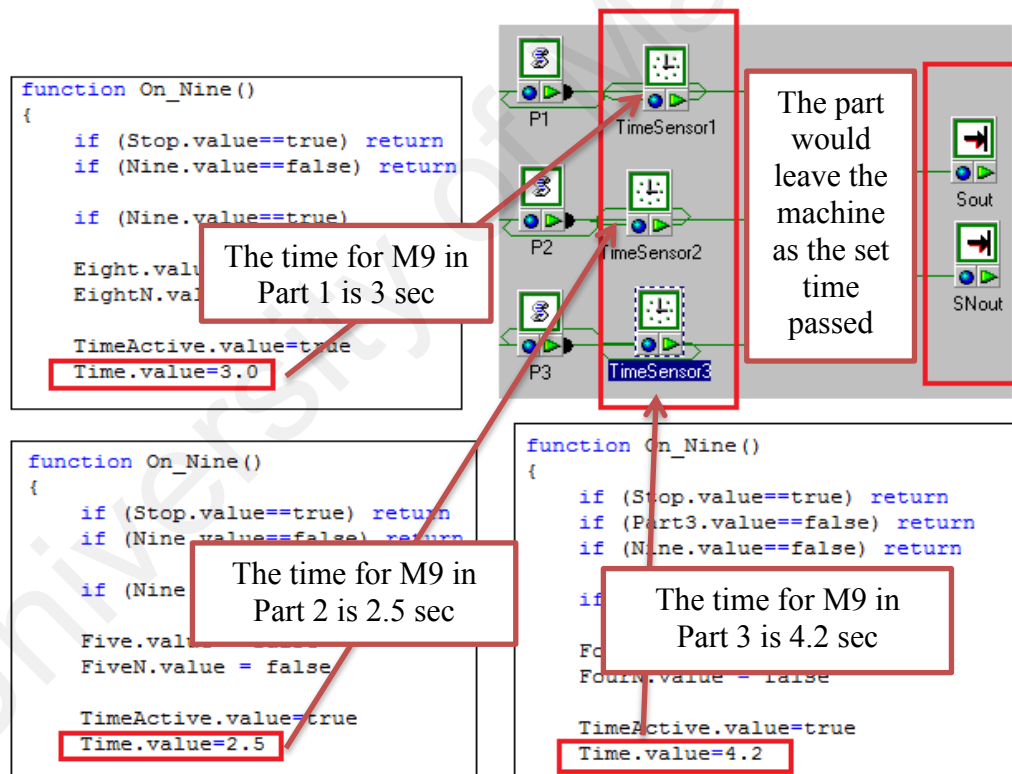


Figure 4. 5 Example Time-based Behavior in Virtual Loop Layout



```

function On_Part3()
{
    if (Part3.value==true)
    {Stop.value=false
    eon.findnode("9!Sense!stl object!9S!9s").GetFieldByName("Enabled").value=true
    eon.findnode("9!Sense_Num!stl object!9SN!9sn").GetFieldByName("Enabled").value=true}

    else
    {eon.findnode("9!Sense!stl object!9S!9s").GetFieldByName("Enabled").value=false
    eon.findnode("9!Sense_Num!stl object!9SN!9sn").GetFieldByName("Enabled").value=false}
}

```



The script for part 3 will call machine 9 as it is the 1<sup>st</sup> processing machine

```

function On_Nine()
{
    if (Stop.value==true) return
    if (Part3.value==false) return
    if (Nine.value==false) return

    if (Nine.value==true)

    Four.value = false
    FourN.value = false

    TimeActive.value=true
    Time.value=4.2

    eon.findnode("2!Sense!stl object!2S!2s").GetFieldByName("Enabled").value=true
    eon.findnode("2!Sense_Num!stl object!2SN!2sn").GetFieldByName("Enabled").value=true
}

```



The script for machine 9 will call machine 2 as it is the 2<sup>nd</sup> processing machine

```

function On_Two()
{
    if (Stop.value==true) return
    if (Two.value==false) return

    if (Two.value==true)

    Nine.value = false
    NineN.value = false

    TimeActive.value=true
    Time.value=4.3

    eon.findnode("7!Sense!stl object!7S!7s").GetFieldByName("Enabled").value=true
    eon.findnode("7!Sense_Num!stl object!7SN!7sn").GetFieldByName("Enabled").value=true
}

```

Figure 4. 6 Example Event-based Behavior in Virtual Loop Layout

#### 4.2.5 Phase 5: User Interface Design

After setting the interactive features between the virtual model of the loop layout, the user interface is according to Table 4.5 for the user to model the virtual loop layout.

Table 4. 5 Virtual Loop Layout User Interface Design

User Interface	Example in Simulation
Virtual Button (Figure 4.7)	<ul style="list-style-type: none"> <li>• Button Start: To start a simulation</li> <li>• Button Reset: reset simulation setting</li> <li>• Open and Save Icon: to save current layout or open previous saved layout</li> <li>• Number: select wanted part type</li> <li>• Move machine: Enable user to rearrange the machine layout</li> </ul>
Device Input	<ul style="list-style-type: none"> <li>• The keyboard controls the scene and reset the data (Figure 4.8)</li> <li>• The mouse moves the machine directly on the virtual world</li> </ul>

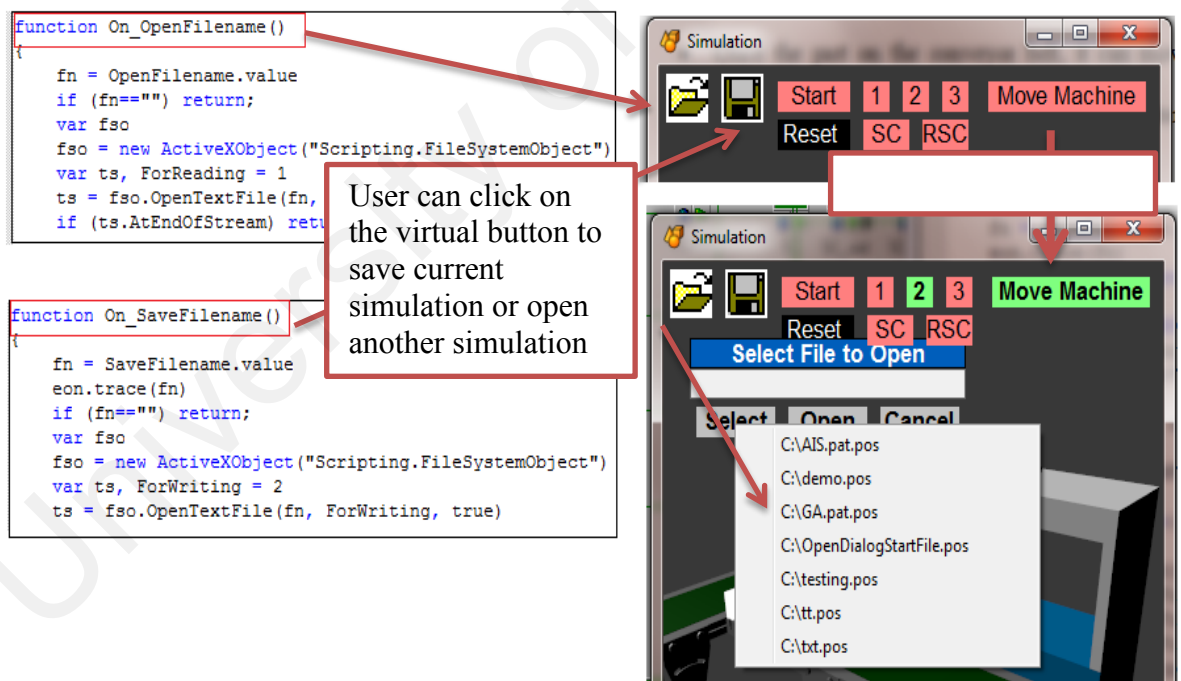


Figure 4. 7 Example Virtual Button in Virtual Loop Layout

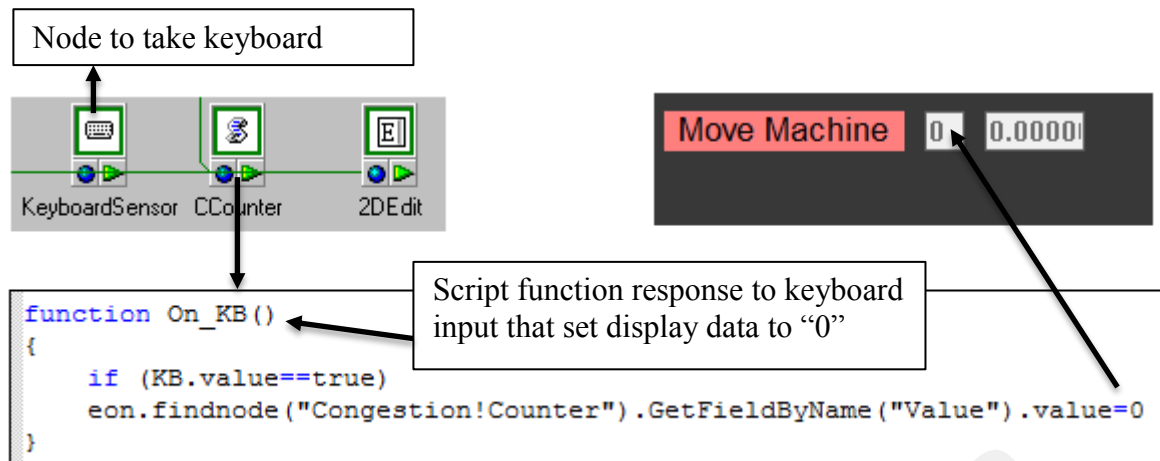


Figure 4. 8 Example Keyboard Input for Virtual Loop Layout

#### 4.2.6 Phase 6: Simulation Flow and Data Feedback System

For the simulation of the virtual loop layout, the user starts with a basic layout of 10 machines (designed according to specifications), which is a complete loop layout with pre-defined loading and unloading stations and a part. The user may rearrange the machine sequence according to the sequence obtained through numerical methods and save or open a previously saved layout. The complete flow for the simulation is illustrated in Figure 4.9.

The ActiveXObject function in JavaScript was used to save the virtual loop layout and to retrieve the saved layout by saving all the geometry properties (position and orientation) of each of the virtual model in \*.pos format. The code is explained in Figure 4.10.

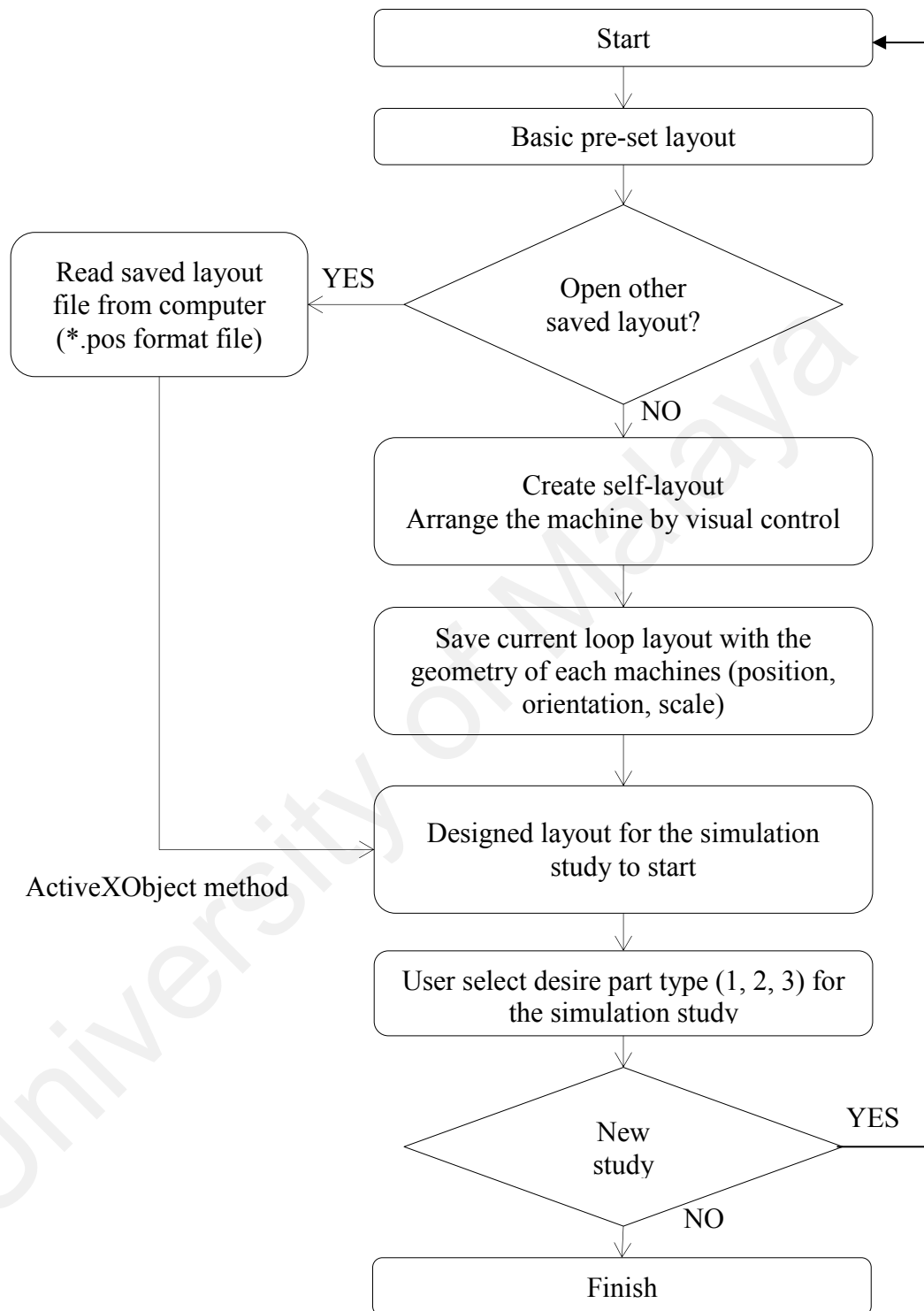


Figure 4. 9 Simulation Flow for Virtual Loop Layout

```

function On_SaveFilename()
{
    fn = SaveFilename.value
    eon.trace(fn)
    if (fn=="") return;
    var fso
    fso = new ActiveXObject("Scripting.FileSystemObject")
    var ts, ForWriting = 2
    ts = fso.OpenTextFile(fn, ForWriting)

    var nr, t, x, y, z, h, p, r, xs, ys, zs, tab
    tab = "\t"
    nr = Objects.GetMFCount()

    for (i=0;i<nr;i++)
    {
        var node = Objects.GetMFEElement(i)
        p = node.GetFieldByName("Position").value.toArray()
        q = node.GetFieldByName("Orientation").value.toArray()
        s = node.GetFieldByName("Scale").value.toArray()
        x = parseInt(p[0]*1000)/1000
        y = parseInt(p[1]*1000)/1000
        z = parseInt(p[2]*1000)/1000
        h = parseInt(q[0]*100)/100
        p = parseInt(q[1]*100)/100
        r = parseInt(q[2]*100)/100
        xs = parseInt(s[0]*1000)/1000
        ys = parseInt(s[1]*1000)/1000
        zs = parseInt(s[2]*1000)/1000
        t = x + tab + y + tab + z + tab + h + tab + p + tab + r + tab + xs + tab + ys + tab + zs
        ts.WriteLine(t)
    }
}

```

To save the layout

- Position in x, y, z axes
- Orientation in h(heading), p(pitch) and r(roll)
- Scale in x, y, z axes

```

function On_OpenFilename()
{
    fn = OpenFilename.value
    if (fn=="") return;
    var fso
    fso = new ActiveXObject("Scripting.FileSystemObject")
    var ts, ForReading = 1
    ts = fso.OpenTextFile(fn, ForReading)
    if (ts.AtEndOfStream) return;

    PosData.SetMFCount(0)
    do
    {
        str = ts.ReadLine()
        PosData.AddMFEElement(str)
    }
    while (!ts.AtEndOfStream)
    ts.Close()

    var nrd, nr, node, i, j, k, tab, nrr
    tab = "\t"
    k = -1
    nrd = PosData.GetMFCount()
    nr = Objects.GetMFCount()
    for (i=0;i<nr;i++)
    {
        node = Objects.GetMFEElement(i)
        pos = node.GetFieldByName("Position")
        ori = node.GetFieldByName("Orientation")
        sca = node.GetFieldByName("Scale")
        k = k + 1
        str = PosData.GetMFEElement(k)
        a = str.split(tab)
        pos.value = eon.MakeSFVec3f(a[3], a[4], a[5])
        ori.value = eon.MakeSFVec3f(a[6], a[7], a[8])
        sca.value = eon.MakeSFVec3f(a[9], a[10], a[11])
    }
}

```

To read the file from computer

Obtain the geometry data from the array

Figure 4. 10 Example programming Code for Virtual Layout Saving and Retrieved

This virtual loop layout aims to serve as the realistic evaluation platform for the numerical method in loop layout problem solving. Therefore, the data taken must be the evaluation criteria that is used in the numerical method and is comparative with the previous study. As discussed in Chapter 2, the criteria that is used for the evaluation is the number of congestion and rectilinear distance that is defined as the number of times a specific part traverses the loop before its processing is complete and the total length of the straight lines connecting two points while travelling in only one axial direction at a time respectively.

In this virtual platform, an intersection trigger sensor and counter is used to measure the congestion number as illustrated in Figure 4.11. The sensor sends a signal to the counter as and increment in number once the part passes through it. Through this mechanism, the total number of congestion is obtained from the simulation window.



Figure 4. 11 Data Feedback System in Traffic Congestion

Regarding the second criteria which is the rectilinear distance of a part, is limited to the distance on the conveyor, in which the distance from conveyor belt to machine or vice versa and the distance travelled within a machine is not be taken for the total distance calculation. The complete description of the data feedback system shown in Figure 4.12.

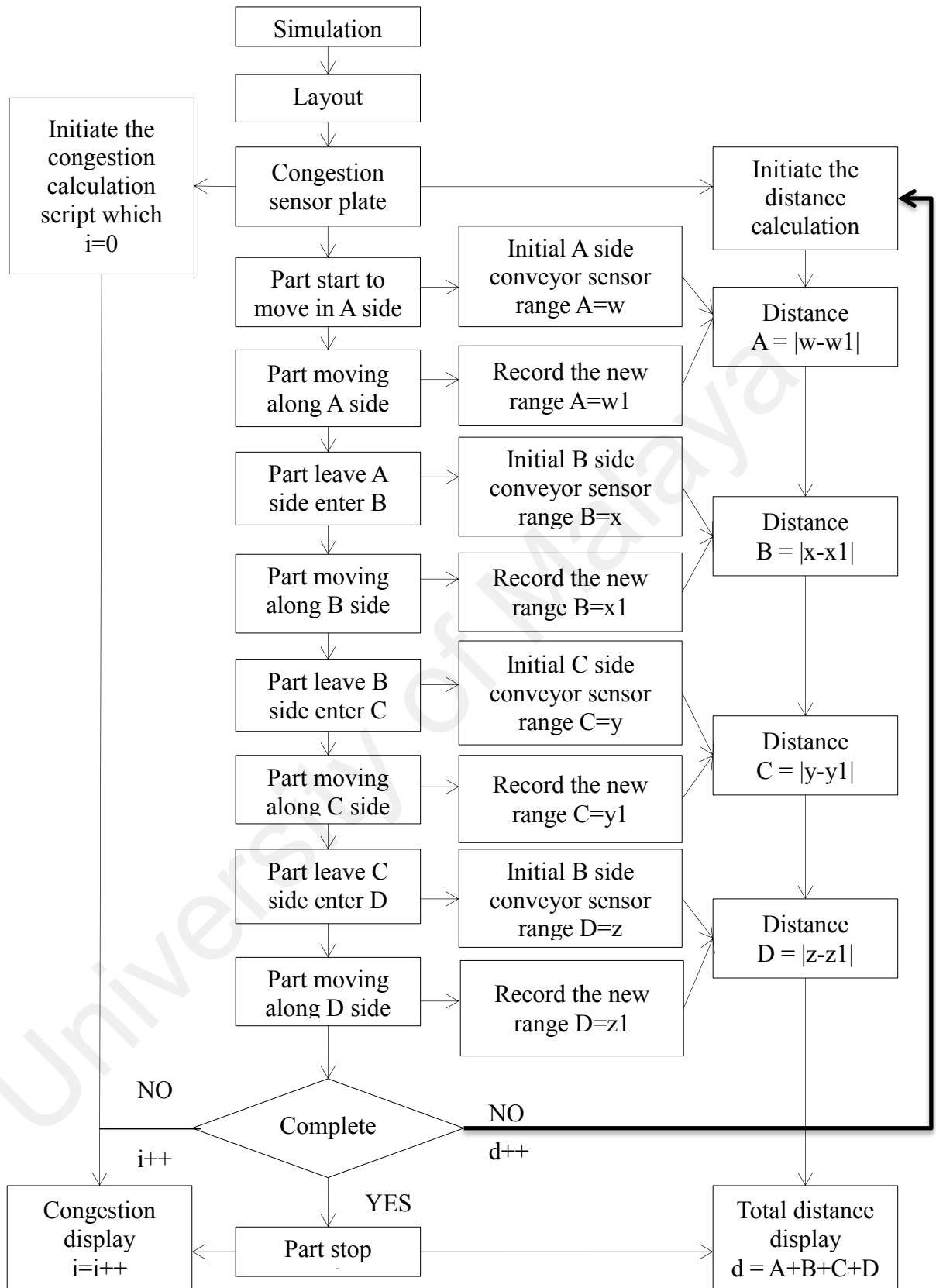


Figure 4. 12 Data Feedback System for Virtual Loop Layout

### 4.3 Summary

This chapter had covered the second stage of study which is the development of virtual loop layout. In the second phase, a virtual loop layout was created that functions as a digital factory platform that is not only limited to simulation and visualization purpose, but also consider the possibility of serving as a manufacturing system planning and evaluation tool in achieving optimum selection of machine sequences arrangement in loop layout as well. The next chapter discusses on the simulation model constructed, the data obtained from the simulation, validation of loop layout with previous numerical analysis and the case study of shortcut allocation in the virtual loop layout



## CHAPTER 5

### RESULTS, ANALYSIS, AND DISCUSSION

#### 5.0 Introduction

Based on the previous chapter, two virtual manufacturing systems (virtual robotic work cell and virtual loop layout) was developed in a digital factory platform. The data collected from the virtual manufacturing system is analysed in this chapter.

#### 5.1 Virtual Robotic Work Cell

The virtual robotic arm is built according to the initial conceptual design and the simulation data is collected for analysis. The developed virtual robotic work cell is capable of simulating the manufacturing system activities successfully and provide data feedback as per designed. The simulation activities achieved are as listed below:

- I. Movement of the robotic arm to the desired location (Figure 5.1)
- II. Movement of the part to the desired location (Figure 5.1)
- III. to the robotic arm can pick and place the part at the selected machine (Figure 5.1)
- IV. The virtual robotic work cell is responsive to user input (virtual button, mouse)
- V. The manufacturing data (part's travel distance) is retrievable (Figure 5.2)



Figure 5. 1 Part move to M3, Robotic Arm Pick Part from M3



Figure 5. 2 Part Travel Distance in Virtual Unit

The part is designed to go through three different machines to complete the manufacturing process. As stated in the previous chapter, the second stage is limited to M1 (lathe machine) and M2 (milling machine) M1 and M2 is excluded from being the first and third machine, while the selection of machine is non-repeatable. The total possible sequence of the part is defined using Equation 5.1 and listed in Table 5.1:

$$P(\text{part sequence}) = P(\text{first stage}) * P(\text{second stage}) * P(\text{third stage}) \quad (5.1)$$

Table 5. 1 Part sequence

Part Sequence No.	Part Sequence
1	M3 – M1 – M4
2	M3 - M1 – M5
3	M3 – M2 – M4
4	M3 – M2 – M5
5	M4 - M1 – M3
6	M4 - M1 – M5
7	M4 – M2 – M3
8	M4 – M2 – M5
9	M5 - M1 – M3
10	M5 - M1 – M4
11	M5 – M2 – M3
12	M5 – M2 – M4

As stated in the previous chapter, only the travel distance on conveyor is used, whereas the travel distance of part during pick and place by the robotic arm is not calculated. In this condition, the part sequence is reduced to half as the choice of machine in the second stage will not have any difference. The calculation of possible part sequences is shown as follow:

$$P(\text{part sequence}) = P(3) * P(1) * P(2) = 6$$

The collected data is show in Table 5.2 and in Figure 5.3.

Table 5. 2 Travel Distance of Part for Different Sequences

Sequence	1 <sup>st</sup> stage	2 <sup>nd</sup> stage	3 <sup>rd</sup> stage	Distance (virtual unit)
1	M3	M1	M4	2808.724
2	M3	M1	M5	1282.580
3	M4	M1	M3	5507.866
4	M4	M1	M5	2662.172
5	M5	M1	M3	6943.949
6	M5	M1	M4	5624.044

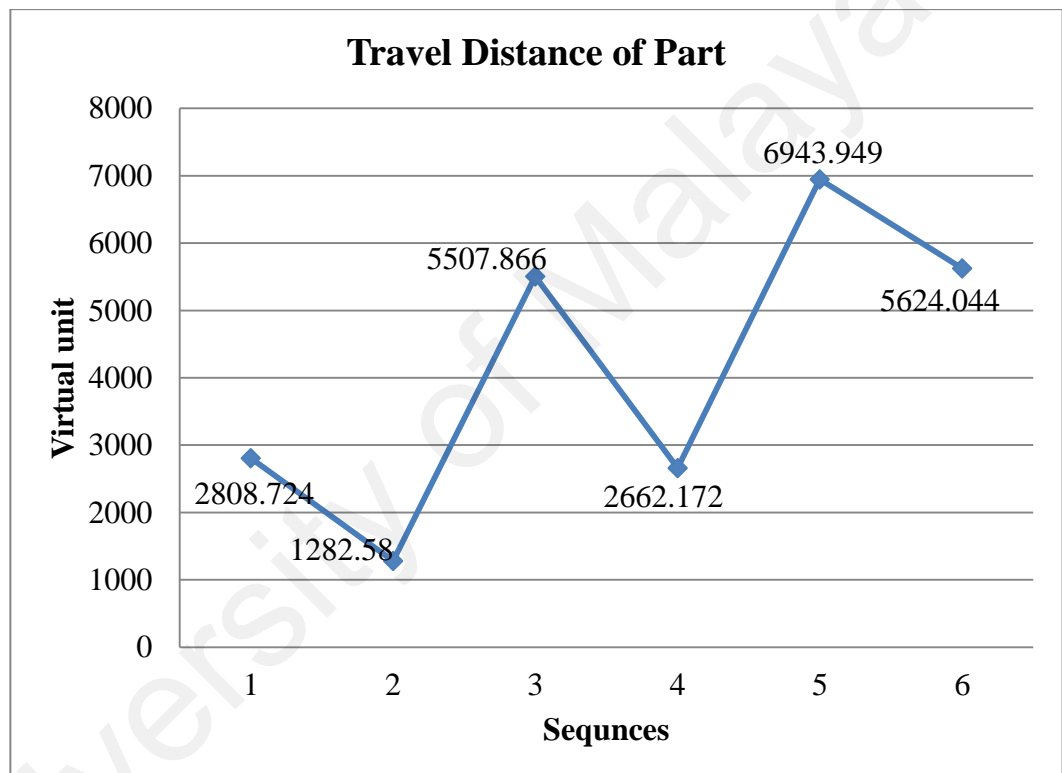


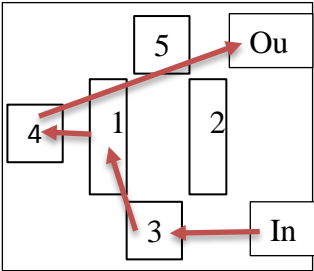
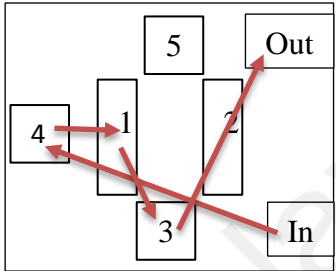
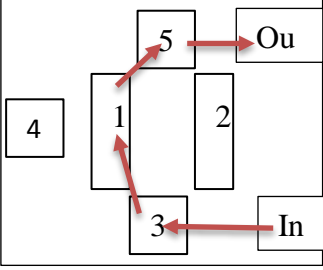
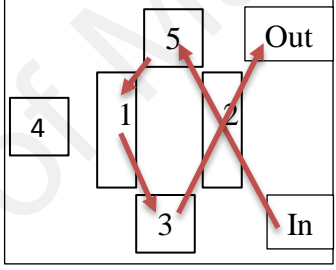
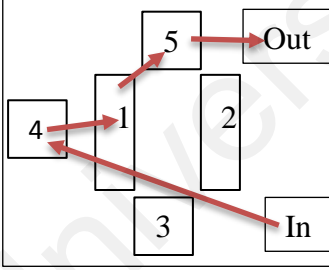
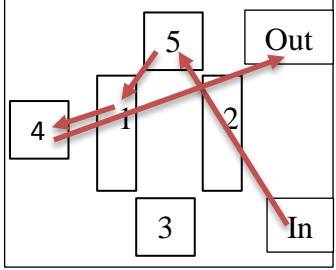
Figure 5. 3 Travel Distance of Part for Different Sequences

From the graph, there are three high values of travel distance and three relatively low travel distances. As observed in the part sequences, if the machine selected for third stage is further from the input station (nearer to the output station) compared to the machine selected in the first stage, the travel distance will be relatively high. Table 5.3 shows the comparison of the part sequence with the same machine but in different order, where the percentage of difference is calculated as equation 5.2:

$$\text{Percentage of difference: } \frac{\text{Higher value} - \text{Lower value}}{\text{Lower value}} * 100\%$$

(5. 2)

Table 5. 3 Process Sequence Comparison

Part sequence	Distance (virtual unit)	Part sequence	Distance (virtual unit)	Percentage of difference (%)
<p>M3 – M1 – M4</p> 	2808.724	<p>M4 - M1 – M3</p> 	5507.886	96.10%
<p>M3 – M1 – M5</p> 	1282.580	<p>M5 – M1 – M3</p> 	6943.949	441.96%
<p>M4 - M1 – M5</p> 	2662.172	<p>M5 - M1 – M4</p> 	5624.044	111.26%

The greatest comparison observed is the part sequence of M3-M1-M5 with the part sequence M5-M1-M3, where the travel distance of the latter is 4 times that of the former. This may be due to M3 being the first machine from the input station and M5 being the last machine before the output station. If the part travels according the sequence M5-M1-M3, the part travels almost the distance of two loops to complete the manufacturing process. While the percentage of difference for the other two pair is

relatively lower, it may be due to the machines in the first stage and third stage located next to each another, therefore the repeated travel distance is lower.

As the simulation obtain great differences of part travel distance even is involving same manufacturing process by comparing different scenario of process sequences, the sequence of a part being manufacture should be considering during the early stage of design. By applying the DFMA guideline, product design engineer shall design the part to be ease for manufacture by considering the manufacturing process sequences. Instead of designing the part go through process sequences of M5-M1-M3, product design engineer shall consider alternative design with DFMA guideline to made the part able to be process by M3-M1-M5 design. Through the collaboration from both manufacturing engineer (optimal process sequences) and design engineer (design for the ease of manufacture), the total part travel could be reduced and overall manufacturing cost would be reduced.

## 5.2 Virtual Loop Layout

The second phase of the study is to build and interactive virtual loop layout platform and validating simulation model with the results from numerical method. The interactive features of the simulation model which are built within the digital factory platform are listed below:

- I. The movement of the part on the conveyor with the control of virtual button (Figure 5.4)
- II. The part is sent to the dummy machine (Figure 5.5)
- III. The activation of shortcut conveyor in two directions of flow (Figure 5.6)
- IV. The re-allocation of machine and shortcut conveyor position with virtual control tool (Figure 5.7)

V. The ability to obtained data, save and open selected layout (Figure 5.8)

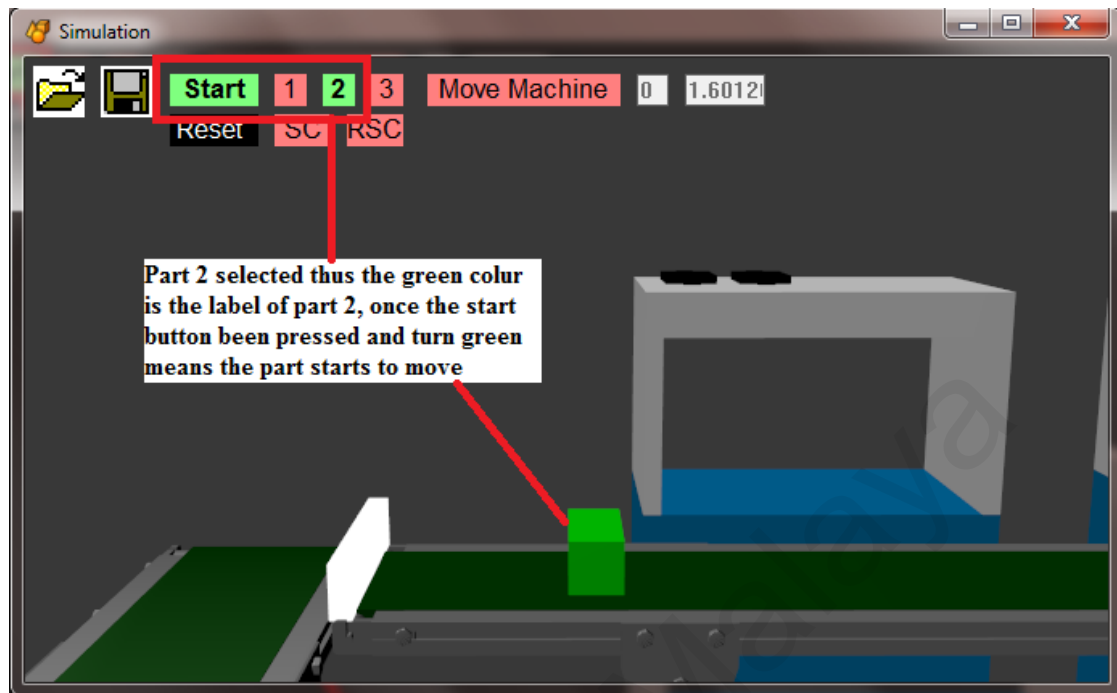


Figure 5. 4 Part Movement Simulation

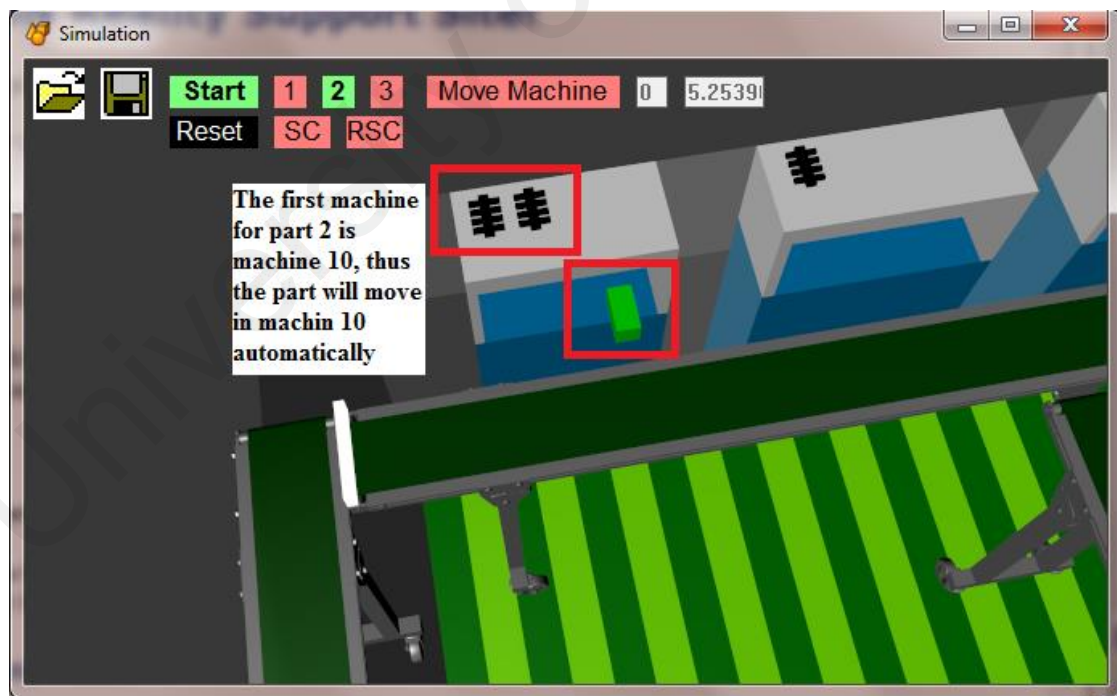


Figure 5. 5 Part Move in Machine Simulation



Figure 5. 6 Part with Shortcut Activation Simulation

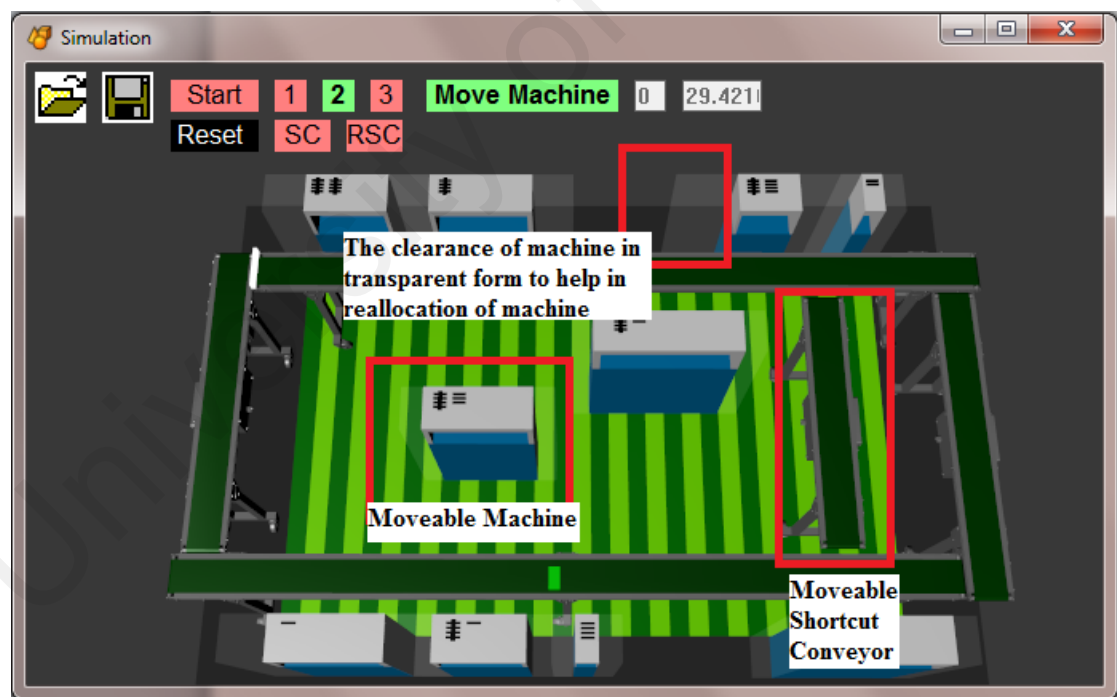


Figure 5. 7 Re-allocation of Machine and Shortcut Conveyor Position



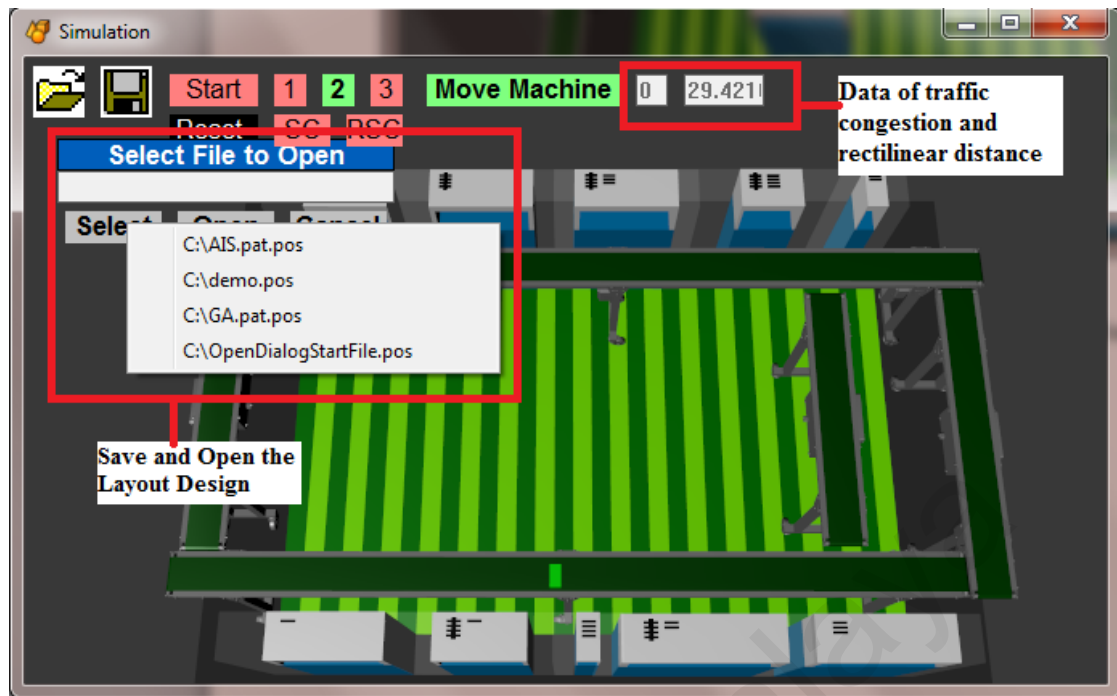


Figure 5. 8 Data Collection, Save and Open Layout Design

The validation of the simulation model is done by comparing the data from two previous researches that tested on the same benchmark test bed but in numerical analysis. The optimal machine sequence obtained through AIS and GA-RSMT with its traffic congestion and rectilinear distance (Table 5.4) been arrange in VR software respectively (Figure 5.9 AIS model, Figure 5.10 GA-RSMT model).

Table 5. 4 Loop Layout through Numerical Method

Numerical Method	Machine Sequence	Traffic Congestion	Rectilinear Distance
AIS	10-5-8-9-2-7-3-4-6-1	3	372
GA-RSMT	10-8-9-2-3-7-4-1-6-5	3	372

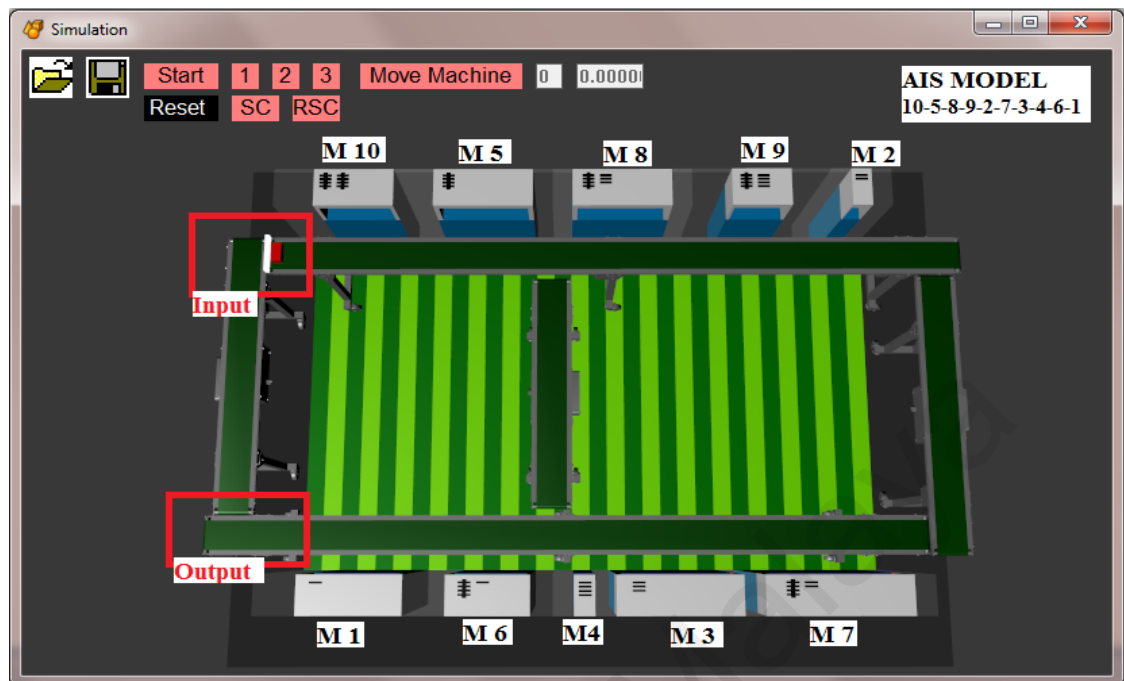


Figure 5. 9 Virtual Layout for AIS Model

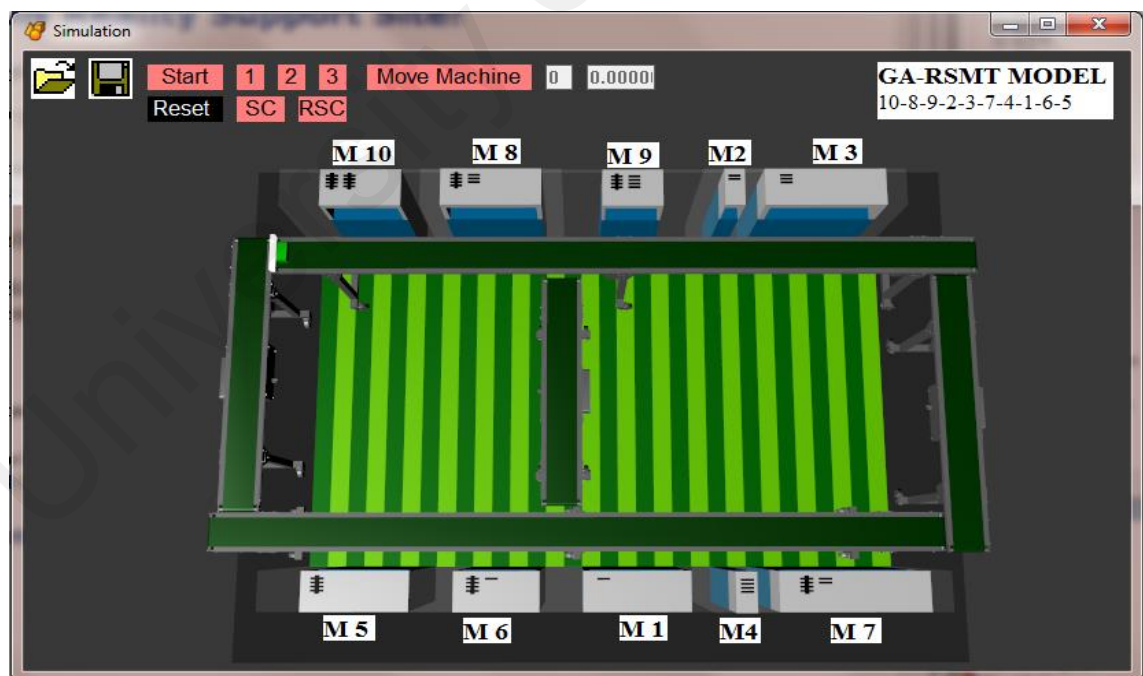


Figure 5. 10 Virtual Layout for GA-RSMT Model

The collected data from the simulation model (traffic congestion and rectilinear distance) for both layouts arrange by AIS model and GA-RSMT model are shown in Table 5.5.

Table 5. 5 Simulation data for AIS and GA-RSMT model

Simulation Model	Part Type	Traffic Congestion (number of times)	Rectilinear Distance (virtual units)
AIS Model	1	2	285.6
	2	1	185.1
	3	0	85.3
	Total	3	556.0
GA-RSMT Model	1	1	185.3
	2	2	285.6
	3	0	85.4
	Total	3	556.3

The measurement of rectilinear distance in the numerical method is the direct distance from machine to machine in which the distance for a part travels from the upper row machine to the lower row of machines or vice versa base on the clearance distance of the machine itself and as a whole number. In the simulation model, the distance of a part to travel from the upper row machine to the lower row of machines or vice versa (20 virtual units) is not considered by previous studies during rectilinear measurement. Figure 5.11 illustrated the condition of the simulation model.

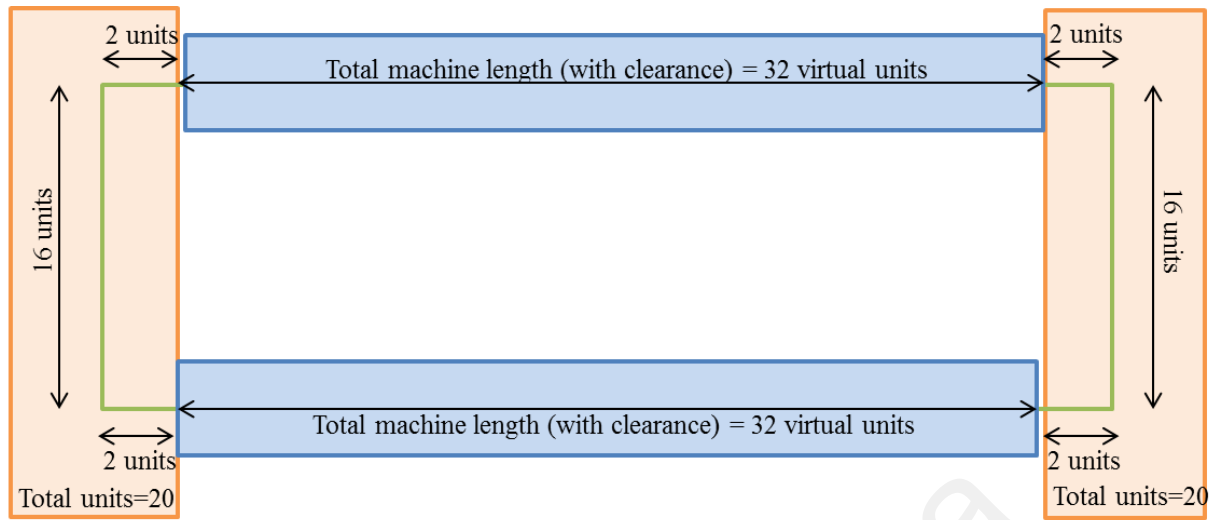


Figure 5. 11 Virtual Units Illustration

The collected simulation data is used to compare with the numerical data to investigate the percentage of difference. A calibration on the simulation data is needed for the data to fit the assumption used in the numerical method. The calibration equation is as follows:

$$\text{Distance} = \text{Simulation distance} - 20 \text{ units} * \text{times of part cross from row} \quad (5.3)$$

Table 5. 6 Simulation Data Calibration

Simulation Model	Rectilinear Distance (virtual units)	Times of part cross from row	Total units cross from row (virtual units)	Distance
AIS Model	556.0	9	180	376.0
GA-RSMT Model	556.3	9	180	376.3

The calibrated simulation data (Table 5.6) is compared to the numerical data (Table 5.7) and the percentage of difference is calculated as the following:

$$\text{Percentage of difference: } \frac{\text{Simulation distance} - \text{Numerical distance}}{\text{Numerical distance}} * 100\% \quad (5.4)$$

Table 5. 7 Simulation Data Calibration

Machine Sequence	Method	Traffic Congestion (Number of times)	Rectilinear distance
AIS Satheesh Kumar et al. (2008) 10-5-8-9-2-7-3-4-6-1	Virtual Simulation	3	376.0
	Numerical Simulation	3	372.0
	Percentage of difference (%)	0	1.0
GA-RSMT Zuhd (2013) 10-8-9-2-3-7-4-1-6-5	Virtual Simulation	3	376.3
	Numerical Simulation	3	372.0
	Percentage of difference (%)	0	1.2

Based on the analysis, the percentage of difference for the congestion number is 0%, which indicates that the simulation models an accurate measurement system in obtaining the traffic congestion data. The percentage of difference for the rectilinear distance obtained from the simulation model is only 1.0% in AIS model and 1.2% in GA-RSMT model. This indicates that the simulation system has a high accuracy for the situation simulation and the data from the simulation has a very low percentage of difference from the numerical method.

This section compared the simulation data with the numerical data; the low percentage of difference validates this simulation model as an evaluation platform for loop layout problem.

#### 5.2.1 Case Study: Shortcut Placement

In this section, a moveable shortcut conveyor is placed in the centre of the loop conveyor to improve the current material handling system. This fully utilized the

interactive feature of the virtual loop layout system to analyse and improve the loop layout through graphical simulation without any numerical tool. The machine sequence proposed by GA-RSMT is used as the simulation layout for the case study. Figure 5.12 show the proposed location of shortcut to minimize the total number of congestion and travel distance. Based on the provided machine sequence, there is only three possible location for the shortcut placement (labelled A, B, C). The space between a pair of adjacent machines must be more than 1 virtual unit for the part to have enough time to enter the shortcut.

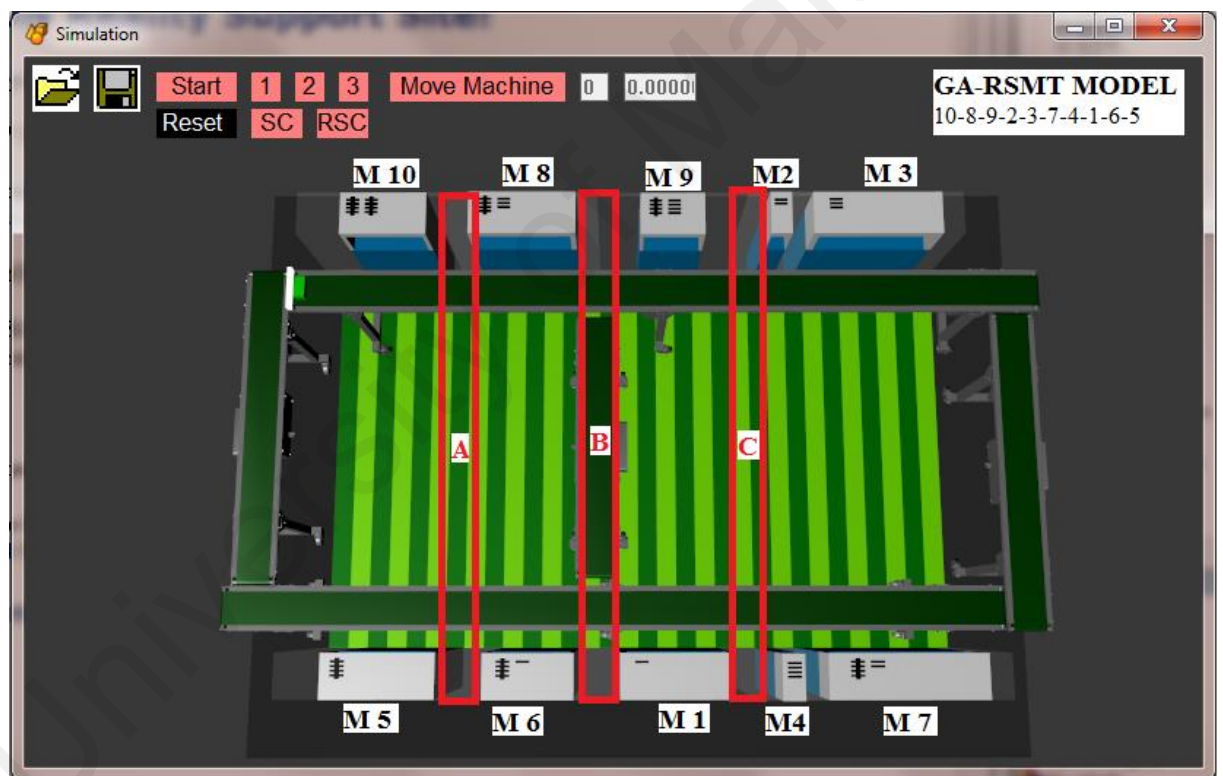


Figure 5. 12 Location of Shortcut Conveyor

Table 5.8 showed the traffic congestion and travel distance of each part for each location of the conveyor.

Table 5. 8 Simulation Data for Different Shortcut Conveyor Location

Measurement	Part	Without Shortcut	Shortcut Location		
			A	B	C
Traffic Congestion	1	1	1	1	1
	2	2	1	2	2
	3	0	0	0	0
Rectilinear Distance (virtual unit)	1	185.3	185.7	185.4	185.6
	2	285.6	255.2	285.1	232.0
	3	85.4	85.3	85.5	85.2

Based on the data, the shortcut location reduces the total congestion number and travel distance if allocated at the correct place. The A location of shortcut has reduced the total traffic congestion from 3 to 2 (33.33% reduction), which is the only location that can reduce the total congestion number compared to the other two location. For the travel distance, it reduces the part two travel distance by 10.64%, which was from 285.6 virtual units to 255.2 virtual units. The B location of shortcut had no improvement for both traffic congestion and travel distance of part. The B location was not suggested as it does not have any improvement and is a waste of manufacturing cost to set up a shortcut at that location. The C location of shortcut conveyor shows the reduction of travel distance by 18.77%, which is a reduction to 232 virtual units from 285.6 virtual units. Even though location C does not show any reduction in traffic congestion, this location reduced the most travel distance among the others positions.

### 5.3 Summary

This chapter described the two main phases of this research:

#### Virtual Robotic Work Cell

A virtual robotic work cell was successfully developed in a digital factory platform that enables modelling and simulation of robotic arm activities and processing sequence of part in the work cell. The virtual robotic work cell has been tested to simulate the effect

of part sequence on the total travel distance, and the data obtained from the simulation scene can be used as an evaluation data in selecting proper process sequence and as criteria to be considered in product design according to DFMA guideline.

- The same processing machines in different process sequence can greatly affect the travel distance in which the travel distance for M5-M1-M3 is 4 times (441.96%) higher than M3-M1-M5.
- The further the distance between two switching sequence machines, the higher the percentage of difference for travel distance.

#### Virtual Loop Layout

The virtual loop layout is developed using the design of benchmark test bed from previous literatures and validated through the comparison of numerical simulation data (previous literature study) and simulation data (virtual loop layout simulation). Thus, the virtual model is suited to be an evaluation platform for a manufacturing system solution. A case study in shortcut conveyor location selection was conducted and the results show that the virtual model is able to assist in decision-making for optimization purpose through scenario technique. The findings are as follows:

- The virtual loop layout is validated as the percentage of difference from its simulation result to numerical result having 0% in traffic congestion and 1-1.2% in travel distance of part.
- Virtual loop layout can be used as an interactive tool to select the optimal location of a shortcut conveyor location where the location can reduce the total number of congestion and reduce the travel distance by 18.77% (optimal result).



## **CHAPTER 6**

### **CONCLUSION AND RECOMMENDATIONS**

#### **6.0 Introduction**

This is the last chapter for the thesis. A summary of the thesis and recommendations for future work would be included in this chapter.

#### **6.1 Conclusion**

The main objective of this study is to develop a digital factory model of a robotic work cell and a loop layout based flexible manufacturing system. A framework of digital platform development for both robotic work cell and loop layout been design which involving six main stages which are 3D model design, 3D model redefine, virtual environment construction, virtual model behaviour programming, user interface creation and data feedback system programming. This work flow involving multiple software which form a network of digital methodology in building digital factory model of a robotic work cell and a loop layout based flexible manufacturing system. Both digital model was successfully build in this study, the virtual model able to simulate factory activities with physics properties, obtain manufacturing data such as travel distance and traffic congestion, real time modification on the virtual model for improvement and multiple scenario comparison. All these features allow user to simulation different scenario of different process sequence and layout design, obtain useful data from different scene in real time and utilize the data for obtaining the optimal decision for the manufacturing system before applying in physical factory. This was proven with the first stage of study that virtual robotic work cell able to simulate different scenario of varies

process sequence. Simulation data collected from scenario being analysed and showed the difference of part travel distance is up to 441.96% even though the part goes through the same machining processes (M1, M3, M5) in different order which is M3-M1-M5(1282.580 virtual unit) compared with M5-M1-M3(6943.949 virtual unit). This simulation data can be used together with DFMA guidelines in product design for robot assembly systems to reduce overall robotic cost.

Virtual loop layout was developed to achieve the second objective of this study which is to validate the virtual model with existing data in literature. The benchmark test from previous literature studies was used as the base design for the virtual loop layout. Then, the virtual loop layout was validated by comparing the virtual simulation results (traffic congestion, rectilinear distance) with the numerical simulation results from AIS and GA-RSMT method. The percentage of difference ranges from 0% to 1.2%, and thus, the virtual loop layout model is validated to serve as an accurate evaluation platform for loop layout planning simulation.

Third objective of study which is to apply the model in a case study of short-cut conveyor allocation in loop layout was achieved. A case study on the different location of shortcut conveyor was conducted to investigate the effectiveness of this platform for loop layout based flexible manufacturing system design and planning. The results showed that proper layout design could reduce loop traffic congestion by 33.33%, while the part travel distance could be reduced by 18.77%. Application of virtual manufacturing system in a digital factory platform is not limited to simulation and visualization purposes, it could also be used as an evaluation tool and as a major reference in decision making to optimise the manufacturing system performance.

## 6.2 Recommendations

The developed VR system allow users to interact with the virtual manufacturing system and enables them to plan and evaluate the plant layout and activities by providing a relatively high accuracy feedback data. However, this research may be improved and expanded in two main directions:

- I. Improvement in the immersion level and enhanced with ergonomics and safety study: The immersive level of this virtual environment could be improved to provide users a better experience through data glove and head-mounted display. Ergonomics and workplace safety study can be conducted with higher level of immersion in virtual platform.
- II. Physical model comparison with the virtual model to get precise data: This research could be improved through the comparison of simulation data with data from physical model to investigate the percentage of difference. A reduction in the gap between the virtual model and the physical model means that the virtual model could completely replace the physical mock up model in manufacturing system testing.

## PUBLICATION LIST

1. SY Phoon, HJ Yap, Z Taha, (2015) Modelling and Simulation of Flexible Manufacturing System in Virtual Reality Platform, International Symposium on Innovative Management, Information and Production, Malaysia, 29-31 October
2. SY Phoon, HJ Yap, Z Taha, YS Pai, Interactive solution approach for loop layout problem using virtual reality technology, The International Journal of Advanced Manufacturing Technology 89 (5-8) pg. 2375-2385, 2017

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