# DEVELOPMENT OF AN AUGMENTED REALITY BASED FACILITY LAYOUT PLANNING AND OPTIMIZATION


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## UNIVERSITY OF MALAYA
## ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: TAN CHEE HAU

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Name of Degree: Master of Engineering Science

Title of Project ~~Paper/Research Report~~/Dissertation/~~Thesis~~ ("this Work"):

DEVELOPMENT OF AN AUGMENTED REALITY BASED FACILITY LAYOUT PLANNING AND OPTIMIZATION

Field of Study:

Facility layout planning and optimization using Augmented Reality (AR) technology.

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# DEVELOPMENT OF AN AUGMENTED REALITY BASED FACILITY LAYOUT PLANNING AND OPTIMIZATION

## ABSTRACT

This study presents an augmented reality (AR) based facility layout planning (FLP) system with an optimization algorithm to assist facility layout designers in decision making. AR is a technology that blends virtual data such as 3 Dimensional (3D) model into the actual world. FLP is about the allocation of facilities to achieve smooth, efficient and effective processes. FLP's research can be divided into the procedural approach, algorithmic approach, Virtual Reality (VR) and AR-based approaches. AR-based FLP effectively addressed the traditional FLP issues such as facilitating the addition of a new machine in an existing production floor, rearrangement of machines' sequence, etc. The advantages of AR-based FLP approach over the other approaches are the shorter time taken to build its model and its flexibility in the design modification. Previous studies in AR and FLP had shown that the digitalization of existing objects is needed. The simple plane, blocks and cylinders are used to overlay onto the actual objects as representation in this research. An AR assisted FLP software was built with 4 modules to locate a new machine in an existing layout, to utilize a space given and optimize a production schedule, to locate a shared facility in an existing layout and to optimize a loop layout robotic cell process. The space occupied and the parts' travelled distance are compared to support in decision making. Production line commonly used algorithm such as shortest processing time (SPT), longest processing time (LPT), cycle time optimization and centre of gravity (CoG) algorithm are coded in this system which enables the production schedule and sequence to be optimized. Four cases studies have investigated this research whereby case study-1 is to evaluate the most suitable position and orientation of a new machine to be placed in an existing production floor, case study-2 is to maximize the area given and further maximize the productivity by optimizing the production sequence, case study-3 is about identifying the best position of a shared facility whereas the case study-4 identified the most effective production sequence in a robotic conveyor cell. The developed AR-based FLP software allows users to re-configure the suggested layout by moving the facilities in the AR environment and the results are reflected in real-time. This research is useful for production line which requires flexibility and agility. The developed AR-based FLP software is fast and effective.

Keywords: Factory Digitalization, Augmented Reality, Real-Time, Process Sequence, Space and Production Time, Optimization.

**PEMBANGUNAN SEBUAH PERANCANGAN DAN OPTIMISASI SUSUN ATUR KEMUDAHAN BERASASKAN REALITI TAMBAHAN**

## ABSTRAK

Kajian ini membentangkan sistem perancangan susun atur kemudahan (FLP) berasaskan Realiti Tambahan (AR) yang berasaskan algoritma optimisasi yang dilaksanakan untuk membantu pereka susun atur kemudahan dalam membuat keputusan. AR adalah teknologi yang menggabungkan data maya seperti model 3 Dimensi (3D) dalam dunia sebenar. FLP adalah mengenai susunan kemudahan yang lancar, cekap dan berkesan. Penyelidikan FLP merangkumi penyelesaian berasaskan prosedur, algoritmik, Realiti Maya (VR) dan AR. FLP berasaskan AR amat berkesan dalam menangani isu-isu tradisional FLP seperti penambahan mesin baru di kilang, penyusunan semula urutan mesin, dan lain-lain lagi. Kelebihan penyelesaian FLP berasaskan AR adalah masa yang diambil lebih pendek untuk membinakan modelnya dan kelenturannya dalam pengubahsuaian reka bentuk. Kajian yang lepas menunjukkan digitalisasi objek sedia ada dalam alam AR diperlukan. Satah, blok dan silinder digunakan unutk melapisi barang sebenar sebagai gambaran dalam penyelidikan ini. Sebuah perisian FLP yang dibantu AR dibangunkan dengan 4 modul untuk mencari posisi yang sesuai untuk mesin baru dalam ruang yang sedia ada, untuk menggunakan ruang yang diberikan sepenuhnya dan mengoptimumkan jadual pengeluaran, untuk menempatkan kemudahan dikongsi bersama dalam ruang yang sedia ada dan untuk mengoptimumkan proses sel robotik bentuk gelung. Ruang yang dipenuhi dan jarak antara objek dibandingkan untuk membuat keputusan. Beberapa kriteria yang lazim digunakan dalam bidang pengeluaran seperti masa pemprosesan terpendek (SPT), masa pemprosesan terpanjang (LPT), optimisasi masa kitaran dan pusat graviti (CoG) diprogramkan sebagai algoritma optimisasi dalam sistem ini yang membolehkan jadual pengeluaran dan urutan pengeluaran dioptimumkan. Empat kes kajian telah diselidiki di mana kes pertama adalah untuk menilai kedudukan

dan orientasi mesin baru yang paling sesuai ditempatkan di tempat pengeluaran yang sedia ada, kes kedua adalah untuk memaksimumkan ruang pengeluaran dengan menempatkan stesen kerja sebanyak mungkin dan selanjutnya memaksimumkan prestasi pengeluaran dengan mengoptimumkan urutan pengeluaran, kes ketiga adalah mengenal pasti kedudukan terbaik bagi kemudahan kongsian manakala kes keempat adalah mengenal pasti urutan pengeluaran yang paling berkesan dalam sel penghantar robotik. Perisian FLP berasaskan AR yang dibangunkan boleh dikonfigurasi semula susun atur yang disyorkan dengan memindahkan kemudahan di alam AR dan hasilnya ditunjukkan secara langsung. Penyelidikan ini agak berguna untuk barisan pengeluaran yang memerlukan kelenturan dan ketangkasan. Perisian FLP berasaskan AR yang dibangunkan adalah cepat dan berkesan.

Keywords: Kilang Digitalisasi, Realiti Tambahan, Segera, Urutan Proses, Ruang dan Tempoh Pengeluaran, Pengoptimuman.

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List of Symbols and Abbreviations

| | | |
|---|---|---|
| AC | : | Ant Colony |
| AR | : | Augmented Reality |
| AGV | : | Automated Guided Vehicle |
| CA | : | Construction Algorithm |
| CAD | : | Computer-Aided Design |
| CAE | : | Computer-Aided Engineering |
| CAM | : | Computer-Aided Manufacturing |
| CAVE | : | Cave Automatic Virtual Environment |
| CNC | : | Computer Numerical Control |
| CoG | : | Center of Gravity |
| DMU | : | Digital Mock-Up |
| DIY | : | Do It Yourself |
| FLD | : | Facility Layout Design |
| FLP | : | Facility Layout Planning |
| GA | : | Genetic Algorithm |
| GUI | : | Graphical User Interface |
| HA | : | Heuristic Algorithm |
| HMD | : | Head-Mounted Display |
| IA | : | Improvement Algorithm |
| IDE | : | Integrated Development Environment |
| LPT | : | Longest Processing Time |
| MR | : | Mixed Reality |
| PTAM | : | Parallel Tracking and Mapping |
| QA/QC | : | Quality Assurance/Quality Control |

| | | |
|---|---|---|
| R&D | : | Research and Development |
| SA | : | Simulated Annealing |
| SDK | : | Software Development Kit |
| SLAM | : | Simultaneous Localizing and Mapping |
| SPT | : | Shortest Processing Time |
| TS | : | Tabu Search |
| ToF | : | Time of Flight |
| GPS | : | Global Positioning System |
| VR | : | Virtual Reality |
| 2D | : | 2-Dimensional |
| 3D | : | 3-Dimensional |

# CHAPTER 1: INTRODUCTION

## 1.1 Background study

Augmented Reality (AR) technology is an advanced approach that blends the virtual models, data with the real environment seamlessly (Azuma et al., 2001). Marker-based AR system uses a printed marker as a reference to superimpose virtual objects or data onto the real environment (Kato & Billinghurst, 1999). By doing this, an AR environment is created. In AR simulation, users can view the AR scene in real-time. AR has been rapidly grown since it was introduced in early of 1990. With the advance achievement and popularity rises of gadgets, smartphone and tablets, AR has been recognized as one of the famous fields in research. There are many AR software available on the internet, some are open-source and some are commercial (Kovach). With the aid of this software, AR application development can be done easily and rapidly. Some examples of the open-source AR software are ARToolkit, Argon, A-Frame, ArUCO, DroidAR, ARma, Mangan, GeoAR, PTAM, mixare, GRATF, ATOMIC Authoring Tool, Augment, Goblin XNA, etc. The popular brands of commercial AR development kits are Kudan AR, Vuforia, Wikitude, Layar, MAXST, etc.

On the other hand, Facility Layout Planning (FLP) deals with the arrangement of facilities (machines, workstations, operators, etc.) in general to maximize the production output, minimize the production cost, minimize the process, minimize the production time and fully utilize the resources and space (Shahin & Poormostafa, 2011). FLP at the design stage of a brand new shopfloor is relatively easier where criteria and constraint are lesser. In real-world, most of the cases are to re-design the existing layout. The existing shopfloor is usually difficult to be formulated in a mathematical formula. The complex mathematical formula will take a long time to be solved. Efforts have been done by researchers to find creative, innovative ways to solve FLP, especially on existing shopfloor re-design (Hadi & Mohamadghasemi, 2013; Hu et al., 2007; Lee, 2011; Menck et al., 2012).

## 1.2 Problem statement

FLP is a research topic that has been studied for many years since early 1950. Researchers were focused on the new facility layout design, which assuming the facilities are built on an empty shopfloor (Lee & Moore, 1967; Murther, 1961; Reed, 1961; Seehof & Evans, 1967; Dilworth, 1996). There are many options for facility layout planner to apply for designing a new facility layout. With the criteria and constraint of the facilities formulated correctly based on the production data, the layout planning can be implemented well normally. For instance, the procedural approach, algorithmic approach and Virtual Reality (VR)-based approach are feasible to be developed to solve new facility layout design problem (Jiang, 2013). The expertise and experience of the planner/designer will affect the result of these approaches.

Modern industry has new expectations for FLP for an organization to stay competitive in the market. Adding machines or removing machines to change the existing facility layout is very common in the production plant. The request from the market to have a wide variety of products to suit every layer of the targeted customer has also triggered the requirement of a flexible, re-configurable production line. When FLP involved existing machines reconfiguration, additional constraints have to be defined accurately. As such, FLP using procedural, algorithmic, VR-based approach maybe not suitable. These approaches are time-consuming and have less adaptability when formulating the criteria and constraints of the existing layout.

The AR-based approach could be used to solve FLP for existing layout re-design. In the AR system, virtual data are integrated into the real environment. By using this technology, an existing shopfloor can be planned, analyzed, re-designed and adjusted virtually. Difficult tasks such as re-locating existing machines, breaking existing barriers can be avoided at the design stage. On the other hand, planning task for electrical wiring for machines and machine's safety barriers can be made in the AR environment easily.

## 1.3 Research objectives

From the problems stated in Section 1.2, this research is aimed to utilize the currently available AR technology with the aid of real-world space, object and process digitalization method to effectively design, plan and simulate a facility layout. The objectives of this research are summarized below:

- To develop an Augmented Reality (AR) assisted factory layout planning system.
- To integrate the Factory Layout Problem (FLP) decision model making by comparing a layout's area, distance and cycle time.
- To simulate the real-time reconfiguration of the digital factory using AR assisted decision support system.

## 1.4 Scopes and limitations

This research aims to develop a marker-based AR assisted decision support system in FLP. This system is aimed at space and process optimization. Existing elements at the shopfloor are to be defined by the user in the AR program. To assist users' in decision making, the main considerations are on the area occupied, the total material travel distance and the production cycle time. The proposed system is targeted on a small scale facility layout only. It is not suitable to analyze a large scale facility planning where several departments are involved.

## 1.5 Structure of the thesis

Chapter 1 of this dissertation gave a general overview of this study and covered the scope and limitations, objectives, methodology and contribution of the study. Chapter 2 covered the literature review of previous researches, related technologies through journal papers, articles and books. Chapter 3 presented on the detailed methodology, including the research flow, procedures, modules developed, algorithms and the programming architecture. Chapter 4 presented the results and case studies regarding the modules developed to check the practicality and usability and discussed the findings and observations. Finally, Chapter 5 concluded the study and discussed some possibilities for future studies.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Introduction

A thorough review of the AR technologies and FLP solutions are presented in this chapter. The AR technology and its related devices, tracking systems are first discussed. Next, the possible applications of AR technology and AR in FLP and optimization are studied and reviewed as well. The literature review followed by the discussion of the objectives and design considerations of the facility layout design. The facility layout design is to minimize the space, minimize the processing time, minimize the production cost and maximize the production output. The literature on the virtual/digital facility layout design has been studied next. The advancement in computer technology has improved the effectiveness of facility layout design and the digital factory makes the design and analysis of a facility layout design easier and effective. The design time is greatly reduced and the design mistake is minimized as well by implementing virtual/digital facility layout design. Finally, some studies and reviews on the methods used in FLP and optimization are completed. FLP can be categorized into 4 classes, namely procedural approach, algorithmic approach, VR approach and AR approach. It is common in the research field where these approaches were combined and introduced as a hybrid method. A summary of the previous research, the capabilities of the AR and FLP technologies and the gap to be filled are concluded in the final part of the literature review.



## 2.2 Augmented reality

Milgram, 1994 has proposed a Reality-Virtuality (RV) Continuum idea where a 100% real environment is situated at one side while the other end is a completely fake virtual environment generated by the computer which generally known as VR. In between real and virtual environment, there is where AR and Augmented Virtuality (AV) located. AR and AV are the environments where virtual data and real environment exist together, AR is where the real environment covers most of the environment while AV has the most virtual data in the environment. Everything falls between AR and AV is called Mixed Reality (MR) where reality is mixed with virtual data. Figure 2.1 explains the RV continuum (Milgram, 1994).

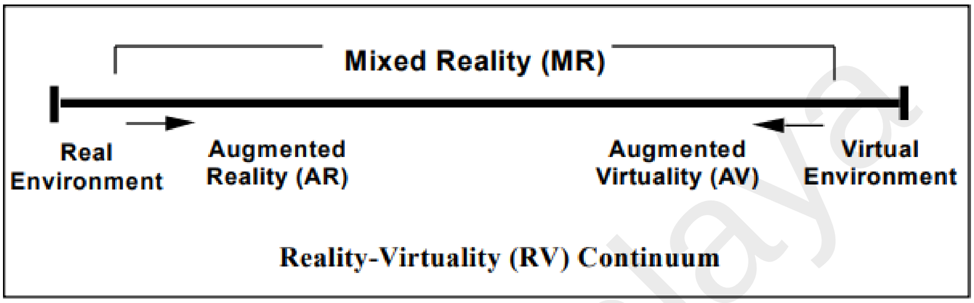



**Figure 2.1: Simplified representation of a RV Continuum (Milgram, 1994)**

AR technology is a technology to mix virtual data (computer-generated data) to the real world. In the AR environment, a virtual object can be superimposed in a real-world environment and the interaction between human and virtual objects are possible. AR system is defined by Azuma (1997):

- The real and virtual objects are combined with an actual environment at the background.
- Run interactively in real-time.
- The real and virtual objects are registered or aligned with each other.

Figure 2.2 shows the working principle of the general AR system, explain how virtual object is projected on a marker detected by a webcam of the computer. The computer's webcam is used to feed a live image of the real environment to the AR system. This is a typical marker-based AR solution. There is marker-less AR solution which uses a 3D scanner to search for a flat surface and project virtual object on it, gyroscope and accelerometer to detect the horizontal plane of a camera and project virtual object on it and etc.

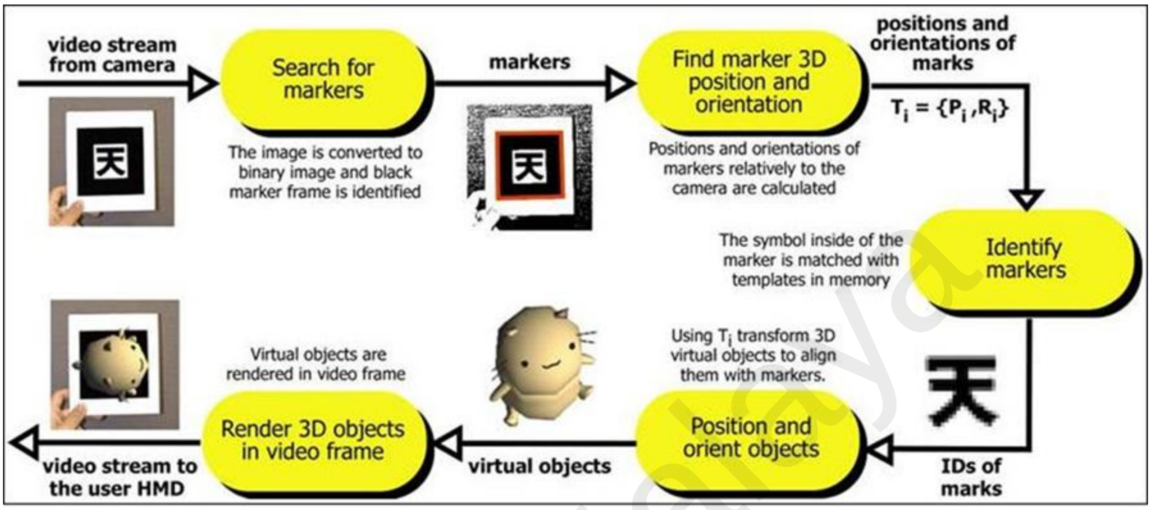



**Figure 2.2: Working principle of the AR system (Lamb)**

To build up an AR system, a computer is needed to run the programming code (as the brain of the system), a camera to capture background video and search for AR markers (as AR system's eye) and a display projected virtual model as well as the live video to view the AR environment. The visual display examples are video see-through, optical see-through and projective display. Video see-through is an AR approach where the AR system is viewed from a screen, optical see-through is viewed from goggles or spectacles while the projective display is a concept to project the virtual models in the real environment (example hologram). Figure 2.3 shows the basic setup of an AR system.

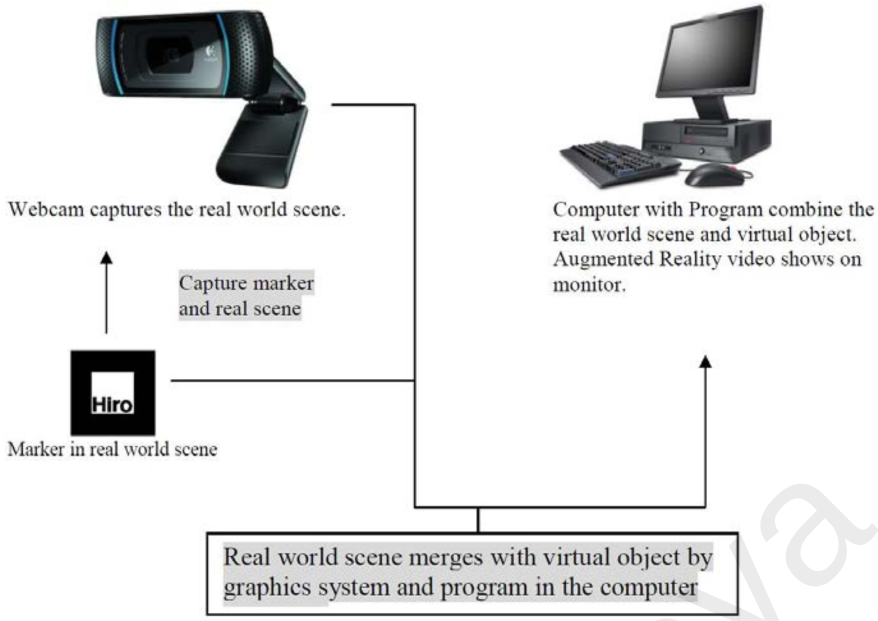



**Figure 2.3: Basic Architecture of an AR system (Pai, 2015)**

### 2.2.1 AR System Display Types

(a) ***Video See-through display:***

In this display system, the real world image is first captured. Then, the captured information is blended with the virtual data rendering by the graphics processor. The blended image will be presented to the users in real-time. These processes will take a millisecond to complete. It is a similar concept as VR technology by replacing the virtual environment with the video captured as background. The real environment is digitized and virtual data overlaid on the digitized real environment. With video see-through display, the virtual models in the digitized real environment can be easily manipulated, replaced or removed, the brightness and contrast of the display can be adjusted easily and the display enables the matching of virtual and real environment without delay. However, this type of display has low resolution and limited field of view that will cause parallax error and cybersickness. Furthermore, the display's focus distance is fixed. It is not suitable for everyone. The design of the display's focus distance should be adjustable.

(b) ***Optical see-through display:***

The similar method as the video see-through display but the real environment is not rendered. Instead, the optical see-through method projects virtual data on a semi-transparent glass in front of users' eyes. These virtual data were presented "floating" in the air with the real environment as background. This type of setup is relatively cheap setup with fast processing time if compared to video see-through. It is parallax free where no eye-offset happened due to camera positioning. The most notable advantage of this device is users are still able to see the real environment even when the device is having a power failure. It is best for medical and military uses where a second power failure may cause death. Optical see-through type display has a limited field of view (limited by the size of the holographical transparent mirrors and lenses and the clips which hold the mirrors and lenses) and it is not suitable to use for outdoor activities due to the sunlight will reduce the brightness and contrast of the AR images when holographical transparent mirrors and lenses project the virtual data. Optical see-through devices require extra input devices such as the camera to recognize marker registration, as well as a sensor for the interactive input.

(c) ***Projective display:***

AR data is projected and overlaid onto the real-world objects. This idea is working like the hologram concept. Users do not need to wear special optical equipment to view the AR environment, the field of view of this type of display is wide. However, this system if not perfect as a holographic projector is required to present the AR effect and it is expensive. Extra input devices are needed for users' interactive input. To avoid the error of projected AR view, calibration is needed to be carried out from time to time before a simulation is started. The resulting projected images have low brightness and contrast, this system is not suitable for outdoor usage.

**Table 2.1: Comparison of AR system display types (Tang, 2016)**

| AR system display types | Advantages | Disadvantages |
|---|---|---|
| Video See-through | • Easily remove or alter objects from reality<br>• Easy brightness and contrast matching<br>• Head tracking for better virtual object registration | • Low resolution.<br>• Limited field of view.<br>• Parallax error.<br>• The display's focus distance is fixed, not suitable for everyone.<br>• Users may experience cyber-sickness. |
| Optical See-through | • Cheap setup<br>• Fast processing time<br>• Parallax-free<br>• Users are able to see when device power failure | • Requires extra devices<br>• Not good for outdoor used<br>• Limited field of view |
| Projective display | • No special optical equipment is required<br>• Wide field of view | • Need to have a holographic projector<br>• Extra input device is required<br>• Calibration from time to time<br>• For indoor use only |

Table 2.1 summarizes the comparison of the three types of general AR system displays. Optical see-through and video see-through displays are widely used in research while the projective display is still very new (Weng et al., 2012).

Optical see-through and video see-through AR can be displayed in three types of devices, namely head-mounted display (HMD), handheld display and spatial display. HMD is where the display (video see-through or optical see-through) is mounted on the head, the handheld display is where the users have to hold the screen on hand while the spatial display is projected on the screen to view the AR system. Figure 2.4a shows an example of HMD type AR, the demonstrator in the photo is wearing a North Star headset designed by Leap Motion. Figure 2.4b is showing a tablet with AR ability to show tags of respective products. Figure 2.4c shows an example of spatial display type hologram AR.

**(a) HMD North Star** **(b) Handheld display AR** **(c) Spatial display AR**

**Figure 2.4: AR system display types**

Table 2.2 shows the market available HMD for the AR application. Other than those listed in the table, there are several Do–It-Yourself (DIY) AR HMDs, for example, North Star by Leap Motion. DIY AR HMDs require users to have deep knowledge of hardware calibration and software setup. It needs a longer time to master and even more efforts in developing AR simulation. Generally, these HMD have a small field of view and very sensitive to ambient lighting that causes the users not feeling good in AR experience. Bulky design and the heat dissipated from the HMD might as well make the users do not like wearing it.

**Table 2.2 Market available HMD**

| Manufacturer – HMD model | Display |
|---|---|
| Cybermind – hi-Res800 (2D/3D) | Stereo |
| Cybermind – Visette45 SXGA | Stereo |
| Dreamglass | Stereo |
| eMagin – Z800 3DVisor | Stereo |
| Epson Moverio BT-300 | Stereo |
| Magic Leap one | Stereo |
| Meta 2 DK | Stereo |
| Microsoft Hololens | Stereo |
| NVIS – nVisor ST | Stereo |
| NVIS – nVisor SX111 | Stereo |
| ODG R7 | Stereo |
| Trivisio – ARvision-3D HMD | Stereo |
| Trivisio – ARvision-S HMD | Stereo |
| Vuzix – Tac-Eye LT | Mono |
| Vuzix – Wrap 920AR | Stereo |

While for the projector to project the AR environment on screen, the listed models are small portable projectors. In order to have a good AR projection, the light intensity should be high (>200 lumens) or users will need to control the AR environment in a dark environment. Table 2.3 shows the mini projectors available in the market.

**Table 2.3: Example of a mini projector**

| Manufacturer – projector model | Pros |
|---|---|
| AAXA – P1 Jr Pico projector | Small size |
| AAXA – P2 Pico projector | Small size |
| LG Electronics Minibeam | High light intensity |
| MicroVision – Pico projector | Low cost |
| Optoma ML750 | 3D ready |
| Pico projectors with DLP technology | High light intensity (8-300 Lumens), Filter free, Lamp free, Good readability |
| Viewsonic M1 | High light intensity |

Haptic devices are commonly attached to the AR application to allow users to interact with the virtual object further create an immersive environment. These devices are used as input and output of the computer in the virtual environment. Haptic devices can be used to pick and move virtual objects in simulation and meantime create feedback to the users with force, vibration and motion. Table 2.4 shows the example of haptic devices available in the market. The haptic device is needed for users to interact with virtual data, it provides a real interaction feeling as compared to the mouse and keyboard of the computer.

**Table 2.4: Example of haptic devices in the market**

| Manufacturer – haptic model (Type) | Pro |
|---|---|
| CyberGlove – CyberGrasp<br>(Exoskeleton type) | • Adds on to CybleTouch for fingers' force feedback<br>• Lightweight |
| CyberGlove – CyberTouch<br>(Vibration tactile actuator type) | • Tactile feedback on each finger and palm<br>• Flex sensors to provide real-time output data<br>• Wearable<br>• Lightweight<br>• Wireless connection |
| Geomagic – Touch X<br>(Actuator type) | • Touch and manipulate virtual objects with Handler<br>• Force feedback<br>• Small size<br>• Lightweight |

### 2.2.2 AR system tracking type

User tracking is important in the AR system. In order to project the AR images correctly for the users to view, a proper tracking system is required. The tracking system should be able to identify the location and orientation of the real-world object (a flat plane or an AR marker), then only the virtual objects can be superimposed in the real world to create the AR environment. Basically, the tracking system can be classified into 2 types, vision-based and sensor-based (Rolland et al., 2001). They have reviewed sensor-based tracking that includes electromagnetics, electronics, and mechanics sensors with an explanation of the working principle of those sensors. Example of the sensor-based tracking system are systems that use Time of Flight (ToF) principle, spatial scan analysis, inertial sensing, mechanical linkage system, phase difference technique, direct field sensing method as well as the hybrid systems. ToF tracking systems use ultrasonic or pulsed infrared laser diode to measure the distance of the target. Global Positioning System (GPS) is a kind of big-scale ToF tracking system where satellites and ground stations are used to measure the position of user. Optical gyroscope uses a laser to calculate the time of propagation to extract the angular velocity of a target. Spatial scan trackers are based on the analysis of the image (2-Dimensional (2D) projections) or analysis of sweep-beam angles to calculate the target's position and orientation. Typical spatial scanning systems are outside-in type, where camera as a reference to detect target; inside-out type, where the target is the camera to sense the references; videometric technique where several cameras are placed on a target to acquire the image of the known target (example, ceiling) and the beam scanning technique where the optical beam is emitted to target and sensor on the target will sense the reflected beam from the reference surface. Inertial sensing systems may use mechanical gyroscope to detect the angular velocity of the target, an accelerometer to measure the linear acceleration of target and finally convert the data collected to the position and orientation of an object. Mechanical linkage tracking system uses mechanical joints to determine the position and orientation of a target. Phase difference systems use a relative phase of the signal from a target and compare to the same frequency signal received from the signal source located on the reference. The direct field sensing system can be magnetic field sensing system, where the strength of the magnetic field is used to determine the distance of an object from a reference point or gravitational field sensing that apply the principle of a pendulum. While the last option is the hybrid system of the above-mentioned techniques. Table 2.5 shows the market famous sensor-based tracking system list. There is a trend in AR applications where vision-based tracking is becoming more popular than sensor-based tracking. This is because sensor-based tracking with bulky hardware restricts the users' movement. In term of economic, vision-based tracking is more cost-effective than hardware-based tracking.

**Table 2.5: Example of tracking systems in the market (Rolland et al., 2001)**

| Manufacturer – Tracking system model (Type) | Pros |
|---|---|
| Ascension – driveBay (Magnetic) | • Miniaturized passive sensor<br>• 6DOF movement tracking<br>• No inertial tracking<br>• No distortion |
| InterSense – InertiaCube BT and Wireless InertiaCube3 (Inertia) | • Small size<br>• Wireless connection<br>• No restriction in user movement |
| InterSense – IS-900 (Inertial + ultrasonic) | • Easy manipulation<br>• 6DOF movement tracking |
| InterSense – IS-1200 (Inertial + optical) | • Small size<br>• 6DOF movement tracking |
| Xsens MTx (Inertia) | • Small size<br>• Drift-free orientation data<br>• Kinematic data included |

Vision-based tracking method can be categorized into 3 categories, namely marker-based tracking, natural feature tracking and model-based tracking (Nee et al., 2012). An example of successful vision-based tracking method AR system is AR Toolkit (Kato & Billinghurst, 1999). 2D black and white markers can be easily detected due to its unique geometric features. The tracking of a 2D black-and-white marker is stable and robust. The other natural feature tracking system uses natural pictures as a marker where the natural features of a picture are detected and matched with the pattern library. One of the examples of natural feature tracking AR system is Vuforia (Blanco-Pons et al., 2019). It enhances the tracking stability and range. While the model-based tracking AR system identifies the 3D model as a marker and then overlays the virtual object on it. There is also a new technique where no marker is used in the AR system, called marker-less AR system (Lee, Shin & Hwang, 2007). Marker-less AR does not need markers to appear in the AR scene. Simultaneous Localizing and Mapping (SLAM) technique can be applied to calculate the camera position and update point cloud of the environment and then build a marker-less AR environment (Jiang, 2013). Parallel Tracking and Mapping (PTAM) is another tracking and mapping method that can be used to map the 3D environment and that can be used in the marker-less AR environment as well (Klein & Murray, 2007).

### 2.2.3 AR development tools

To develop AR applications, there are many available AR development tools or Software Development Kit (SDK) nowadays. Most of the SDKs available in the market nowadays offer commercial license as well as a free license with a logo watermark on the screen. AR technology is still new to the market and it requires end-users to try, hence these free SDKs are available for the developers to encourage them to develop AR contents. This is a step to explore the AR's possibilities and test the end-users' acceptance of AR technology. Table 2.6 shows the popular AR SDKs nowadays. ARToolKit is an open-source AR software library made available for free and non-commercial used under GNU General Public License. EASYAR is developed by a China company that offers a plugin to be used in Unity as well as Android Studio and iOS xCode. It is aimed at AR mobile app development. Vuforia is quite similar to EASYAR in the way of their marketing. The plugin is available for Unity, Android and iOS as well. CRAFTAR is another option for AR mobile app developer. It offers similar specifications as Vuforia and EASYAR but it has its own Content Management System (CMS) online. Where their clients can manage their AR content without any programming skills. Wikitude does provide a commercial license for a public and free license for new startup companies with terms and condition. D' Fusion, an AR SDK produced by Total Immersion company is free for everyone to use. Its strength is in face tracking. KUDAN is another major AR SDK used in the market, it provides both free and commercial usage. SDK needs to be compiled with the Integrated Development Environment (IDE) platform and packaged into an executable program. Based on the review from the above-mentioned SDK, Unity and Unreal Engine are the most widely used IDEs in the AR industry. Unity is a real-time 2D, 3D content development platform. It is widely used in creative industries to create 2D, 3D, VR & AR visualizations for games, simulations, animations, etc. It is a cross-platform engine, nowadays it supports building for more than 25 different platforms (iOS, Android, Universal Windows Platform, Windows, Mac, Linux, etc). Unreal Engine is Unity's with the advantage of the better graphic solution.

**Table 2.6: Popular AR SDKs list (Kovach)**

| AR SDKs | License | Feature tracking |
|---|---|---|
| ARToolKit | • Open Source<br>• Free<br>• Commercial | • Square marker<br>• 2D barcode marker<br>• Multiple marker tracking<br>• Natural feature tracking |
| EASYAR | • Free<br>• Commercial | • 2D image<br>• 3D object (Commercial version only)<br>• Surface tracking<br>• Natural feature tracking |
| VUFORIA | • Free<br>• Commercial | • 2D image<br>• 3D object<br>• Text target<br>• Surface tracking<br>• Natural feature tracking |
| CATCHOOM CRAFTAR | • Free<br>• Commercial | • 2D images<br>• 3D objects<br>• SLAM<br>• Barcodes<br>• Natural feature tracking<br>• LLA marker |
| WIKITUDE | • Commercial | • 2D image<br>• Barcode<br>• GPS<br>• IMU<br>• Natural feature tracking |
| TOTAL IMMERSION D' FUSION | • Free<br>• Commercial | • Face tracking<br>• 3D objects<br>• GPS<br>• Marker-less tracking<br>• Multi-target |
| KUDAN | • Free<br>• Commercial | • SLAM<br>• Unlimited marker<br>• 3D environment tracking |

## 2.3 Augmented reality applications

AR technology is very common in research area nowadays. researchers proposed several possible applications in design and manufacturing using AR technology. AR can be used to assist the engineering design, design review (Back et al, 2010; Carmigniani et al., 2011; Gausemier, Fruend & Matysczok, 2002; Nee et al., 2012; Chi, Kang & Wang, 2013). To review the digital prototype of a design, the designer can wear an AR HMD and observe the Digital Mock-Up (DMU) of the design (Abeykoon et al., 2012). AR can also be used to design a product (Lu et al., 1999). Instead of having 3D Computer-Aided Design (CAD) software, AR CAD software is used in this case. The designer can create a new DMU or modify the existing DMU in AR CAD software. For example, one to design a fixture bracket to hold a component in the place where the component is a real object while the fixture bracket is a virtual object. The AR engineering application can be extended to Finite Element Analysis (FEA) and Computational Fluid Dynamic (CFD) area (Nee et al., 2012). Figure 2.5 is showing Volkswagen engineers reviewing the CFD analysis of their product in AR.

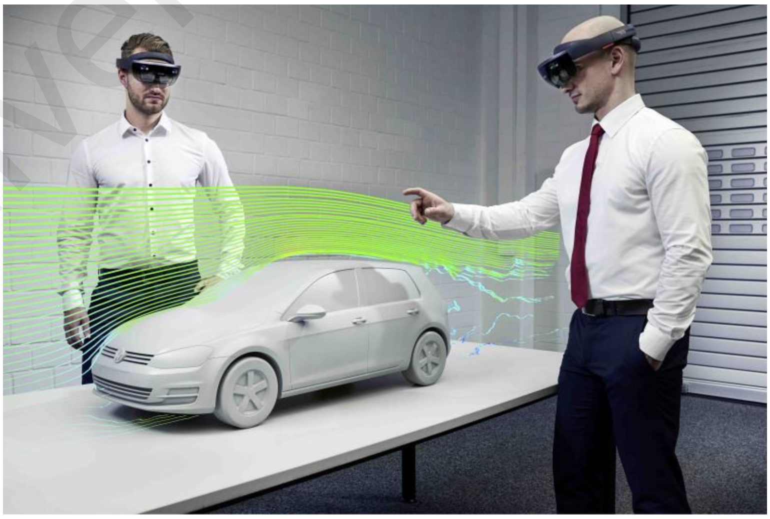


**Figure 2.5 Volkswagen CFD review in AR (Osterman)**

AR is also useful in robotic application. Robotic programmer can teach a robot to move offline in an AR environment, the robot will then follow the design path in the actual environment (Webel et al., 2013). Chong et al., 2009 have shown an interactive way to plan the robot's path to avoid collision with the aid of AR. Figure 2.6 shows an AR system that connects people to robots developed by New York University Tandon School of Engineering (Frank et al., 2016). Through this AR system, the user can understand the robotic coordinate system easily. The user is able to manipulate the robot arm to conduct some tasks.

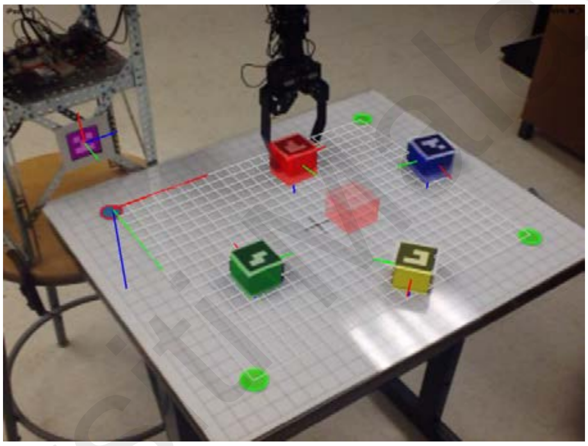


**Figure 2.6: AR robotic showcase (Frank et al., 2016)**

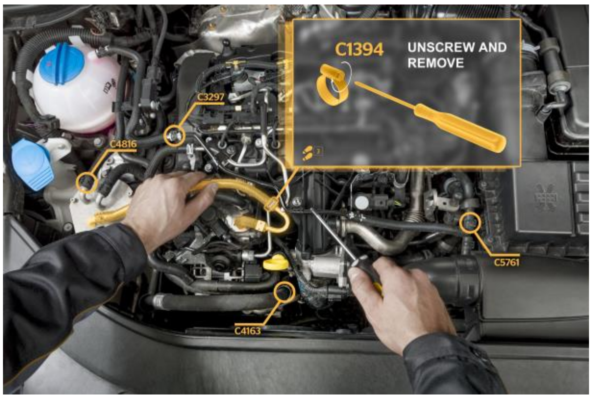



**Figure 2.7: Automobile maintenance guidance in AR (Teslenko)**

AR can be as well be used to assist the technician in doing maintenance jobs (Siltanen et al., 2007). When a new technician is working, this is a very useful technique to guide the technician. Sometimes, the product range is so wide that a human cannot recognize all the products so as the maintenance method. AR can be used to help this situation. Figure 2.7 shows an AR application that guides the mechanic to conduct a maintenance job (Teslenko).

AR is found to be helpful in computational numerical control (CNC) machine teaching. Similar to that of AR robotics, AR can be used to teach the CNC machine tool path (Pai et al., 2016). AR application in CNC teaching removed the risk of a new CNC programmer to learn CNC machine operation and save the cost of material as the CNC operation is in AR. Figure 2.8 shows the AR CNC simulation concept. AR can be used in FLP to design a new layout or redesign an existing layout easily. There are some researchers proposed AR assisted FLP solutions (Wan et al., 2010; Pai et al., 2014; Jiang & Nee, 2014). The said AR assisted FLP solutions have touched on the superimpose method of the 3D virtual data to the actual environment, the constraint of the machine or equipment allocation. There is a need to have an embedded system with an algorithm to check all the layout possibilities, analyze and propose a good layout design in the AR assisted FLP solution.

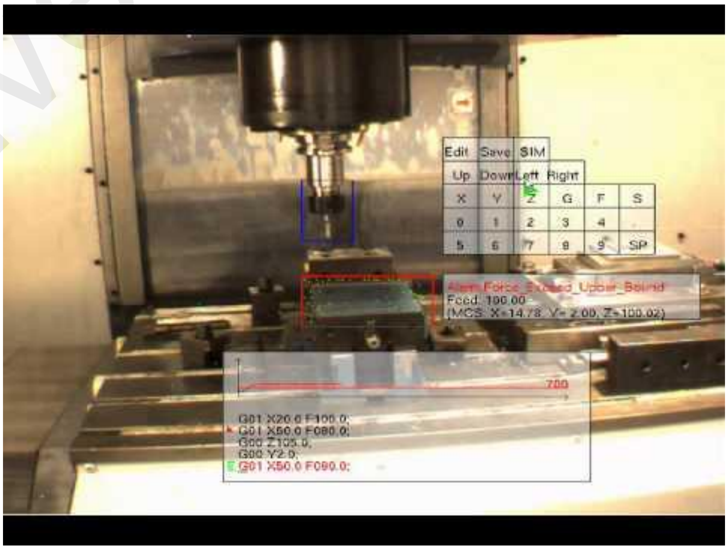



**Figure 2.8: AR CNC Simulation (Pai et al., 2016)**

## 2.4 Facility layout design

Facility Layout Design (FLD) is important in an organization operation. It involves the design of material handling path arrangement, machine and workstation layout with sequences. The basic objectives of the FLD are to achieve a smooth workflow with a systematic arrangement. The facility layout should be effective in terms of space, time and ultimately cost. A good facility layout is the integration of the output needs, material supplies and the production system. It should be smooth in process or production flow, simple but efficient material handling and safe for the users. Commonly, the market is facing challenges to have wide product variety, short product life cycle, product design change due to rules and regulations. Hence, the facility layout design should be flexible and easy to modify as well to adapt to the market changes.

The design on facility layout is associated with the arrangement of machines, workstation and workers. Static and dynamic items need to be identified clearly. Static items are those not moving items. For example, the machine needs a power plug, it must be static there since power plug is fixed there. Dynamic items are those that can move. For example, the automated guided vehicle (AGV) that handle material in a production line. It is dynamically moving around the factory space, the moving path must be cleared or it will be blocked and its performance or productivity will be dropped.

The FLP problem can be generally introduced as the assignment of facilities (departments) to a site such that a set of criteria are satisfied or some objectives are minimized (maximized). Hence, it can be considered as a multi-criteria problem due to presence of the qualitative criteria such as flexibility and the quantitative criteria such as the total cost of handling material (Hadi-Vencheh & Mohamadghasemi, 2013). The facility can be a department in a large-scale FLP task (block layout) or a machine in a small-scale FLP task (detailed layout). A summary of the mathematical approaches to solve FLP issues since recent years and the suggested directions in FLP research was reported (Anjos & Vieira, 2017). As far as row FLP is concerned,  three properties need to be defined:

- Assign the departments into a row
- Mathematical representation distance between departments (centre to centre)
- Space occupied including empty space in between departments.

## 2.5 Virtual facility layout design

The facility layout design is a complicated task and it involves several parties in a large organization (engineering, production, procurement, quality assurance and quality control (QA/QC), logistics, research and development (R&D) departments and so on). Every party has different interests in contributing the facilities layout design and they are from different background. Hence, it is necessary to present the factory layout design in a good method so that each party will be able to visualize the design easily. Here comes the existence of virtual factory layout design or digital factory layout design. The conventional way of designing the factory layout is by sketching the concepts on a floor plan paper. This is less effective if compared to virtual/digital data presentation (3D models) (Dwijayanti et al., 2010). Technical 2D drawings are meant for professional personnel, which are not easy to understand. And, somehow mistakes or miscommunication always happen. 3D spatial constraints are difficult to define and explain through 2D drawings, may need to have several extra detailed views to explain the constraints well. With the aid of the computer, FLP design and redesign is rather easier. With just a click, users are able to undo the changes made. Many design versions can be saved for a comparison purpose. Sharing of data is very convenient. Virtual factory layout helps in evaluating plant layout before actually building it and saving cost in conducting a physical re-layout. It also allows the user to get a better perspective than what could be achieved in 2D CAD solutions. Re-location of the machines can be done such that the material handling cost is reduced as well as bottlenecks are removed. Some issues like the safety, aisle and other layout problems can be reviewed and modified using factory layout problem-solving techniques. Re-layout can be done until a satisfactory result is achieved. Researchers used eM-Plant for modelling and simulating optimization for digital factory (Jia et al., 2010). It is concluded that virtual factory concept helps in optimizing a facility layout design before establishing the actual system as shown in Figure 2.9.

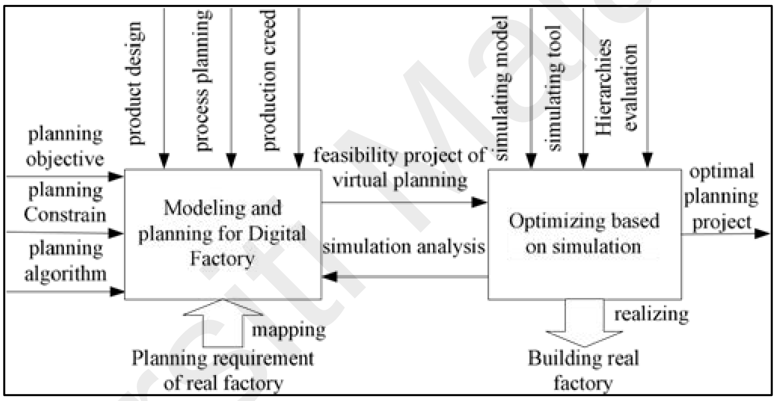



**Figure 2.9: Relationship of planning, modeling and simulation of manufacturing system (Jia et al., 2010)**

Facility layout must be considered carefully in the early stage because constantly redesigning the facility is undesired (Heragu, 1997). It will be too late if the layout design is started after the factory has built, and most of the time constraints are fixed and not changeable. Factory layout design has become easier with the aid of CAD software. 2D drawings, 3D models can be generated easily in the CAD software. The so-called digital factory and digital manufacturing have been introduced to support the factory layout design. The digital factory is the generic 2D drawing or 3D model of a factory with its manufacturing system model. However, these data can only be seen in computer and it might take times to model the environment. In some cases, the 3D environment is not real enough to simulate the process. There is a limitation where some non-technical personnel do not understand 2D drawings and not everyone can understand 3D models. Iqbal and Hashmi, 2001 expressed that the facility layout problem-solving technique can be implemented in the 3D virtual environment. This will be helpful to engineers to solve existing layout problem and improve the layout visualization. Since all the data handled are virtual data, quick changes can be implemented and simulated. Results can be compared in a short period to assist engineers to design, to make the decision. Anyhow, there are some limitations in the virtual facility layout where the users may find difficult to understand the simulation model or data shown. There comes the necessity where VR, AR and MR can be used to present the simulation model or data. Users will immerse in the VR, AR or MR system to review as if the models are real. The development of the trend of FLP solutions is aligned with all the CAD, Computer-Aided Manufacturing (CAM) and Computer-Aided Engineering (CAE) software. The history was to design on the 2D plan view, analyze by using the graph. Then, with the aid of computational technology, the design was improved to 3D model design and computation simulation technique was implemented. Now with the rising of VR, AR and MR technologies, the FLP software is able to work further to improve the FLP design visualization and reduce the design mistake and error.

## 2.6 Facility layout planning and optimization

There are a few challenges for FLP. For example, the market tends to have quick product change due to the rules and regulations, short product life cycle and wide product variety. These challenges require the layout designed to be flexible, easily change. It is necessary for the facility layout designer to handle all the possible layout modification at the design stage. By having a virtual factory, the algorithmic tool can be implemented to optimize the layout design. Dwijanyati et al., 2010 proposed to evaluate a layout arrangement using a combination of heuristic method and simulation technique. The popular heuristic methods used by researchers and designers for facility layout design are Tabu Search (TS), Simulated Annealing (SA) and Genetic Algorithms (GA) (Singh & Sharma, 2006). Each method has advantages and disadvantages, depends on the nature of the problem to be solved. Aside from the heuristic method, simulation technique is another option. Common simulation tools used are Arena, QUEST, IGRIP, ProModel, Witness and Flexsim (Dwijanyati et al., 2010). Many of the simulation tools present the simulation result in 2D. Some had 3D visualization for better viewing, understand and evaluate. Generally, simulation technique needs the user to define the relationship between the workstations, sequential arrangement of the workstations and finally link the workstations to become an operating system. By then, efficient work and procedures are achieved. The computer calculation will continue to check for a few alternative arrangements and save as proposal.

The request for the factory layout to be easy to visualize and understand by audiences does not stop at virtual factory layout design. Further efforts had been done in recent years to bring the VR, AR and MR technology to assist in facility layout design and optimization. In the market, there are few commercial products for Factory Layout Planning (FLP) systems, example Tecnomatix Factory (Factory Layout Simulation) by Siemens, Teamcenter Manufacturing Plant Simulation by UGS and MPDS4 Factory Layout by CAD Schroer. These systems are actually VR based. The systems provided a virtual on-line layout planning platform to simulate the layout plan, to refine the results before implementation. These systems have one disadvantage in common, which is the tedious design process. Every single part of the layout needs to be modelled. Figure 2.10 shows the VR assisted FLP tool and Figure 2.11 shows AR assisted FLP tool.

**Figure 2.10: VR-assisted FLP tool (Advice Manufacturing)**

**Figure 2.11: AR-assisted FLP tool (Advice Manufacturing)**

Jiang, 2013 summarized that there are four existing approaches to tackle FLP issues, namely, (a) procedural, (b) algorithmic, (c) VR-based and (d) AR-based approaches. Each approach is discussed below.

(a) Procedural approach

The procedural approach is a systematic method of using sequential general steps to solve FLP issues. The criteria can be addressed from the qualitative and the quantitative aspects. In the beginning, the data of the facility layout are collected including product type, product quantity, material flow, process flow, machine quantity, machine size, cycle time, etc. Then, the activity relationships are created based on the material flow analysis. Based on the activity relationships, the spatial locations of the facilities are determined (Shahin & Poormostafa, 2011). This approach can generally incorporate a large variety of design objectives. The effectiveness of this approach depends on the expertise and experience of the designer. Procedural approach is an old technique to solve FLP developed from the year 1950 to the year 1980. Table 2.7 summarizes the procedural approach FLP methods namely Immer's basic steps, Naddle's ideal system approach, Reed's plant layout procedure, Muther's systematic layout planning and Apple's plant layout procedure (Jiang, 2013).

**Table 2.7: FLP procedural approaches**

| Method | Methodology | Mathematical analysis method |
|---|---|---|
| Immer's basic steps (1950) | 1. Identify the problem<br>2. Show lines of flow<br>3. Convert flow lines to machine lines | • No |
| Naddle's ideal system approach (1961) | 1. Aim for a theoretical ideal system<br>2. Conceptualize the ultimate ideal system<br>3. Design the workable ideal system<br>4. Install the recommended system | • No |
| Reed's plant layout procedure (1961) | 1. Analyze the product<br>2. Determine the process<br>3. Prepare layout planning chart<br>4. Determine workstations, storage area<br>5. Establish minimum aisle widths, office requirements<br>6. Consider personnel facilities and services<br>7. Survey plan services<br>8. Provide for future expansion | • Layout planning charts |
| Muther's systematic layout planning (1961) | 1. Gather data<br>2. Draw activity relationship diagram<br>3. Draw space relationship diagram<br>4. Modifying considerations, adjusting according to limitations<br>5. Develop alternative layouts | • Activity relationship diagram<br>• Space relationship diagram |
| Apple's plant layout procedure (1977) | 1. Basic data collection and analysis<br>2. Design the production process<br>3. Check the equipment required<br>4. Plan individual workstations<br>5. Design activity relationships<br>6. Determine storage, space requirements<br>7. Evaluate, adjust and check the layout | • Activity relationship diagram |

(b) Algorithmic approach

The algorithmic approach is about the development of the mathematical model as FLP solutions' algorithm. FLP problems seldom have an exact solution due to the complex constraints and criteria. Singh & Sharma, 2006 and Drira, Pierreval & Hajri-Gabouj, 2007 classified Construction Algorithm (CA) and Improvement Algorithm (IA) as Heuristic Algorithms, while Genetic Algorithm (GA), Tabu Search (TS) algorithm, Simulated Annealing (SA) algorithm, and Ant Colony (AC) algorithm as Meta-Heuristic Algorithms.

CA applies trial-and-error method to design a new layout plans by adding in facility one by one into the new space, while IA starts the layout design with a random plan and refines the plan by changing the facilities. Heuristic Algorithms were widely used at the beginning stage of algorithmic researches to solve FLP issues (Armour & Buffa, 1963; Lee & Moore, 1967; Seehof & Evans, 1967; Dweiri & Meier, 1996). The mathematical models are the abstracts of the FLP task and normally present in 2D layouts. It is useful at the conceptual design stage.

Meta-heuristic Algorithms are dealing with more complex FLP problems. Various constraints can be applied in Meta-heuristic Algorithms. Chiang and Kouvelis (1996) have studied the TS algorithm in FLP, while Chwif et al., 1998 have applied SA in their FLP researches. Whereas Baykasoglu et al., 2006 have reported using AC and some researchers have reported GA in their FLP studies (Aiello et al., 2006; Shayan & Chittilappilly, 2005; Wang et al., 2005). There were FLP studies with hybrid approaches where algorithms were combined to solve FLP issues. For example, Chwif et al., 1998, Azadivar & Wang, 2000, Balakrishnan et al., 2005 and Aiello et al., 2006.

Computerised Relative Allocation of Facilities Technique (CRAFT) was used to solve FLP in Indonesia's universities library to meet the requirement for the digital native generation. An open space hub is the main requirement for its FLP design with easy access bookshelves for visitors to encourage them to cross-check the info gathered from the internet (Felicia et al., 2017). Covariance Matrix Adaptation Evolution Strategy (CMAES) combined with weighted sum and penalty technique was applied to solve constrained FLP where facility's placement must have enough clearance, certain facility has to be placed at the designated place, certain facility must not be rotated and certain facility is linked to certain facility side by side (Wen & Ting, 2018). CMAES is found to be similar to IA but with constraints well-defined at the beginning of the calculation. Table 2.8 shows the comparison of different algorithmic approaches.

**Table 2.8: Comparison of different algorithmic FLP approaches**

| Method | Algorithm | Hybrid | Features |
|---|---|---|---|
| CRAFT (Armour and Buffa, 1963) | IA | No | o Random layout pan<br>o Exchange two facilities<br>o Compare the material handling cost |
| CORELAP (Lee and Moore, 1967) | CA | No | o Define activity relationship<br>o Allocate facilities according to adjacency rates |
| ALDEP (Seehof and Evans, 1967) | CA | No | o Randomly place facilities<br>o Scan facilities' pattern<br>o Allocate facilities according to adjacency rates |
| Dweiri and Meier (1996) | CA | No | o Incorporate fuzzy set theory<br>o Analytic Hierarchy Process's prioritization |
| Chiang and Kouvelis (1996) | TS | No | o Dynamic Tabu list size<br>o Intensification criteria<br>o Diversification strategies |
| Baykasoglu *et al*. (2006) | AC | No | o Budget constraints<br>o Dynamic layout problem |
| Shayan and Chittilappilly (2004) | GA | No | o Slicing tree representation of the layout plan<br>o Avoid preparation procedures |
| Wang *et al*. (2005) | GA | No | o Space-filling curves for encoding<br>o Unequal size facilities |
| Azadivar and Wang (2000) | GA | GA and simulation technique | o Incorporate operational constraints<br>o Dynamic layout problem<br>o Simulation method as an evaluation |
| Chwif *et al*. (1998) | SA | SA and IA | o Equal size facilities<br>o Dynamic layout problem<br>o Combine SA and IA |
| Balakrishnan *et al*. (2003) | SA | SA and GA | o Combine SA and GA<br>o Unequal size facilities<br>o A user-friendly interface |
| Chen and Sha (2005) | IA | IA and prioritization technique | o Linear combination of different objectives<br>o A multi-pass and doubling procedure based comparison<br>o Correct the inconsistent matrix. |
| Aiello *et al*. (2006) | GA | GA and ELECTRE method | o Produce the entire Pareto solutions<br>o ELECTRE method (ELECTRE) search for the solution |
| Felecia and Wulandari (2017) | IA | No | o Identify the important facility to be placed at the centre<br>o Apply constraint where only same size facility can be switched |
| Wen and Ting (2018) | CMAES | CMAES, weighted sum and penalty method | o Randomly initialize a plan<br>o Evaluate the plan<br>o Update plan by adjusting mean vector and covariance matrix<br>o Evaluate the new plan<br>o Repeat until the end, get the best plan |

*Remarks:
IA: Improvement Algorithm
CA: Construction Algorithm
TS: Tabu Search
AC: And Colony
GA: Genetic Algorithm
SA: Simulated Annealing
CMAES: Covariance Matrix Adaptation Evolution Strategy

In solving the production scheduling issue, a study which refers to classical heuristic algorithms namely Longest Processing Time (LPT) and Shortest Processing Time (SPT) was reported (Jabbarizadeh et al., 2009). LPT sorts the products by prioritizing the products which have longer processing time first while the SPT prioritizes the shorter manufacturing time product. There is another method where production line balancing is concerned. This method emphasizes every station in the production plant to have balance workload. As for the concern of shared facility solution, a study has reported to combine CoG method and basic location structure method in locating a blood bank in the community (Çetin & Sinem, 2009). This concept locates the shared facility at the CoG of every other workstation, where this distribution of workstations has the best efficiency. In a way, the shared facility will be located nearest to the workstations which needed it the most.

The algorithmic approach provides the mathematical model as an efficient solution for FLP issues. But, the results may deviate from reality due to the simplification of constraints and objectives when defining the mathematical model (Yang & Kuo, 2003). This approach is lack of an effective evaluation mechanism as well.

(c) VR-based approach

VR technology has allowed users to experience an immersive virtual environment (Weidlich et al., 2007). It has been applied in FLP to facilitate the designers and decision-makers. It adopts an interactive design process which procedural and algorithmic approaches cannot provide. Travelling and manipulating objects in the virtual factory offers more natural and direct layout planning (Smith and Heim, 2010).

There were few VR related FLP researches reported, for example, a development of Cave Automatic Virtual Environment (CAVE) viewing platform for a virtual shopfloor

(Banerjee et al., 1996). There is also a proposal of an immersive VR-based approach to the planning and implementation of manufacturing cells (Korves and Loftus, 1999). In this VR-based approach, the users can move the facilities on the shopfloor, define the constraints of the facilities and visualize the result. There is another reported VR framework where the user can modify the layout in the VR environment by refining the original master layout (Calderon et al., 2003). Kuhn (2006) developed a hybrid VR-based FLP which integrates with the simulation technique. The digital factory concept was applied and integrated with the simulation schemes on different planning stages for production planning optimization. Nee et al. (2012) have done virtual experimentation approach to plan and train manufacturing processes. Current VR-based FLP development's direction is about the integration of simulation techniques with VR technology (Yang et al., 2008; Back et al., 2010). A VR based support system for layout planning and programming of Kuka robotic work cell is developed (Yap et al., 2014). The system allowed users to import 3D models into the VR system to study the differences of the layout arrangement in robot programming. Many commercial FLP software is available in the market, for example, Plant Design Management System (PDMS), Plant 3D, Plant Simulation and Flexsim. The software generally has similar functions, for example, collaborative multi-users function, standard parts library, automatic simulation, planning analysis, etc. Most of the software is the hybrid type where VR is paired with simulation techniques and genetic algorithm. Figure 2.12 shows the user interface of the VR programs mentioned above (screenshot images of the VR-based FLP software developed by Korves and Loftus, 1999, Calderon et al., 2003, Yang et al., 2008 and Back et al., 2010) while Table 2.9 shows the comparison of the above-mentioned VR-based FLP approaches.

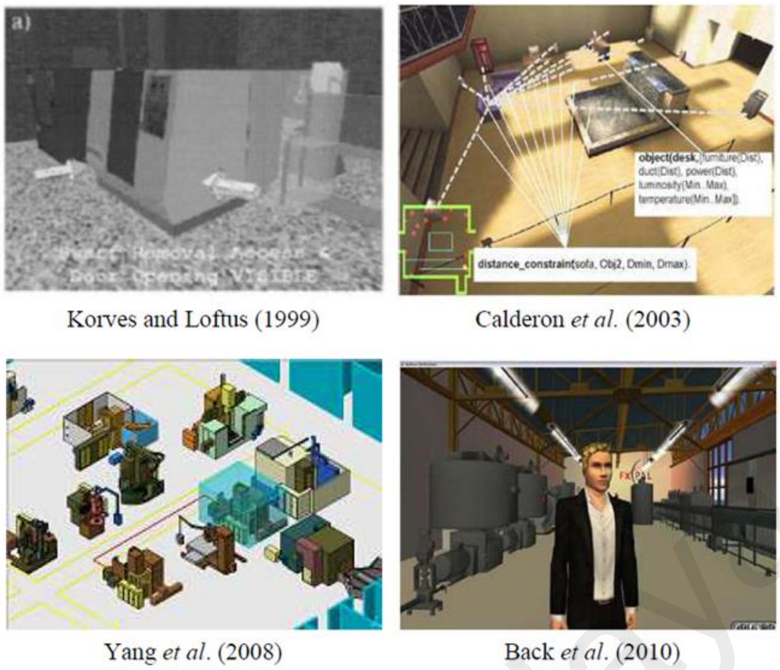



**Figure 2.12: VR-based FLP approach software screenshots**

**Table 2.9: Comparison of different VR-based FLP approaches**

| Method | Objectives | Functions | Hybrid |
|---|---|---|---|
| Korves and Loftus (1999) | o Quick visual assessment<br>o Lower users' skill requirement | o Standard shopfloor equipment library<br>o Animation<br>o Real-time feedback | No |
| Calderon *et al.* (2003) | o Alternative solutions based on domain knowledge for improvements | o Constraint logic integration<br>o Real-time constraint propagation<br>o New solution by refining the existing layout | VR and constraint logic programming |
| Kuhn (2006) | o Digital factory<br>o Integrate simulation processes at the planning stage | o Production and process simulation<br>o Manpower simulation<br>o Dynamic line balancing<br>o Dynamic machine planning | VR and simulation technique |
| Yang *et al.* (2008) | o Digital factory<br>o Simulation and optimization | o Object-oriented technology<br>o Construct resource library<br>o Dynamic simulation of production and process | VR and simulation technique |
| Back *et al.* (2010) | o Collaborate, control, and visualize with the VR system<br>o Enhanced collaboration | o Multi-client customizations<br>o Import contents<br>o Observation and monitoring remotely | VR and simulation techniques |
| Yap *et al.* (2014) | o Assign robot work cell layout design<br>o The safe robot programming environment | o 3D models (VRML) import, position and rotation can be modified in the program<br>o Simple and user-friendly robot control interface | No |

The VR-based approach is efficient for a new production plant but has limitations on the existing shopfloor re-planning. For a new production plant, the 3D models are made available readily and the layout is accurately created. But, the actual environment of the factory may vary from the 3D assembly model or drawing. For example, the flatness of the floor and the manufacturing tolerance of a machine's barrier fence. This is the main reason the existing shopfloor re-planning is less efficient if compared to brand new production plant planning.

(d) AR-based approach

There are several researchers about applying AR in FLP. Rauterberg et al., 1997 had developed an AR system named "Built-it" as one of the pioneers in the AR-based FLP application. The said system is a table-top device which superimposes the virtual shopfloor layout models on the real objects. By moving the real objects, users can make changes to the layout design. This feature allows users to design the layout cooperatively and interactively. Fruend & Matysczok, 2002 have applied AR in designing flexible manufacturing system. Dangelmaier et al. have presented AR in supporting discrete manufacturing system simulation. Gausemeier et al., 2002, Wan et al., 2010 have developed AR-based FLP tools, where facilities' 3D models were laid out on AR markers. Users can design the position of the 3D models (markers) in the AR environment intuitively. The environment and models were scaled down but the system responds in real-time. The assessment of the layout design is in real-time when the marker position changes. Figure 2.13 shows the AR planning tool developed by Gausemeier et al., 2002. while Figure 2.14 is the screenshot image from the AR FLP software designed by Wan et al., 2010.

**Figure 2.13: AR-planning tool (Gausemier et al., 2002)**

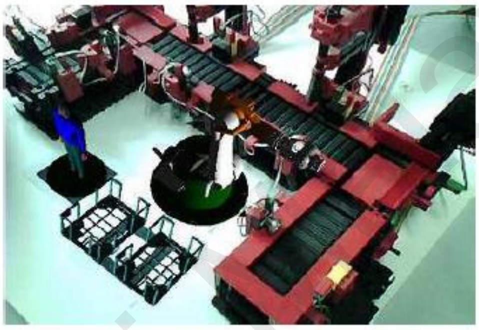


**Figure 2.14**: **AR-assisted FLP system (Wan et al. 2010)**

Poh et al., 2006 have reported a method to evaluate facility layout by assessing the criteria defined. Markers were used to represent the location of the facilities. Mathematical formula of the facilities' relationship was defined such as the total material travel distance, cost, electrical consumption, space occupied, etc. As the users move the facilities, these criteria can be updated in real-time. By comparing the value from the calculation, users are able to make the correct decision. Figure 2.15 shows the AR FLP system proposed by Poh et al., 2006 where the AR marker is used to represent the facilities and the distances between facilities are calculated respectively.

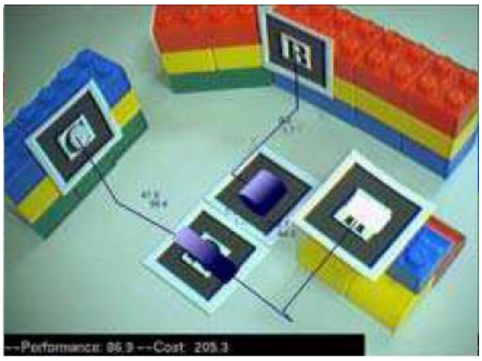


**Figure 2.15: AR-based FLP system (Poh et al. 2006)**

AR-Plan, a tool in ARVIKA is an FLP software (Doil et al, 2003) applies marker-based tracking where virtual data can be superimposed in a real shopfloor environment. It allows users to select and import the machinery and tools in the standard library. The collision of the virtual models and the real facilities can be identified visually. Based on this concept, locating a new facility in the existing layout becomes easier. ROIVIS, an AR-based system to support facility planning was proposed by Pentenrieder et al., 2008. The system adopts image processing technology for accurate measurement. Edge interference of facilities can be analyzed and compared to support decision making in FLP. Figure 2.16 shows ROIVIS used to plan the chilled water routing in a building.

**Figure 2.16: ROIVIS (Pentenrieder et al. 2008)**

Siltanen et al., 2007 implement AR in plant lifecycle management where AR is utilized to verify the layout. A client-server network was established and the layout plans were rendered in the real shopfloor with AR technology. The planners plan the layout operation while the operators can evaluate the plans on-site and communication can be done through the network. Figure 2.17 shows the screen of the AR assisted FLP program where the marker carries the info of a facility and showed in AR.

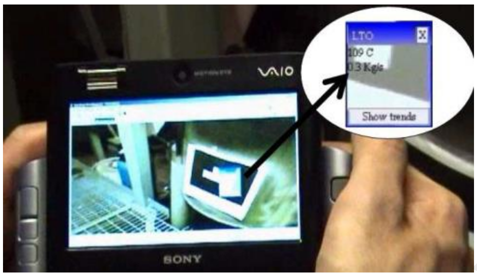



**Figure 2.17**: **AR-assisted factory layout planning (Siltanen et al. 2007)**

Lee et al., 2011 used AR to plan the installation of a robot arm. The virtual models of the existing facilities were built and shown in the AR FLP system to simulate the new robot's working envelope and to check the interference between the new robot and the existing facilities. The interaction between the real and virtual objects in AR-based FLP has been highlighted by the studies mentioned above. Figure 2.18 shows the robot arm placement planning in a factory developed by Lee et al., 2011.

**Figure 2.18: AR-based FLP tool (Lee et al. 2011)**

Researchers from the National University of Singapore (NUS) has developed an AR facility layout planning and optimization methodology (Jiang & Nee, 2014). AR is used to specifically solve FLP of the existing layout. Figure 2.19 shows the newly added machine is found collided with objects existed in the layout and hence warning window popped out to warn the designer.

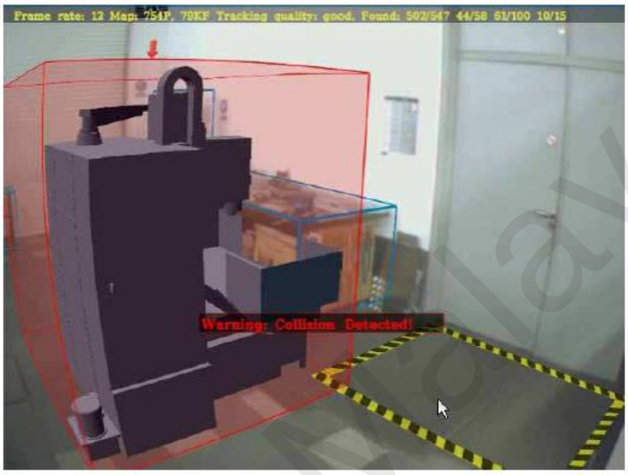



**Figure 2.19: AR FLP in the existing layout (Jiang & Nee, 2014)**

There is also a report on the application of AR in FLP for flexible manufacturing cell (Pai et al., 2014). Pai et al. used AR markers to represent the facilities in a layout. With the help of the AR system, the distance between the markers/facilities and the space occupied by the facilities are calculated. Several production line patterns were studied by Pai et al., namely straight line, U-shaped, V-shaped and W shaped production line arrangements. Figure 2.20 shows the five AR markers/machines used by Pai et al. in the distance and space occupied calculation study.

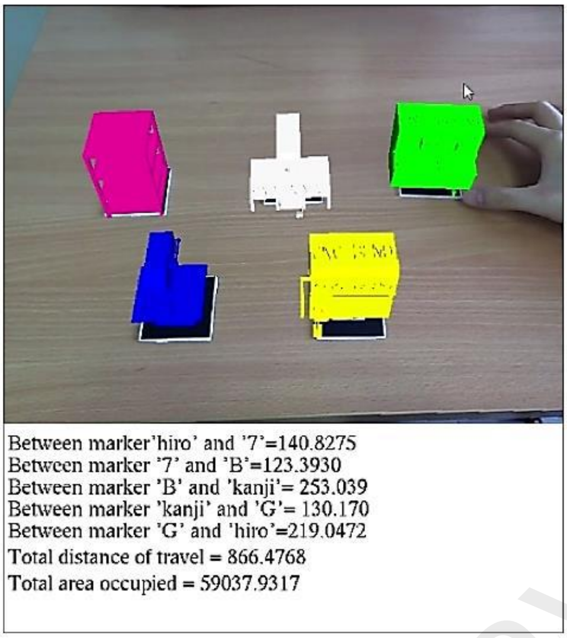



**Figure 2.20: AR FLP tool to check distance and space (Pai et al., 2014)**

By using AR technology, facility layout design can be conducted easier and more efficient. 3D data or 2D drawings can be mixed with the real environment for study and simulation purposes. AR technology makes facility layout design flexible, faster and efficient. The calculation for space and area needed for machine, forklift and storage rack is possible in AR. The marker used in an AR space can be used as a reference to check the size of inventories in an AR environment. With proper rigid body properties assigned to the AR virtual objects, collision detection method can be used to check if the virtual objects are crashing with each other. The collision of the virtual objects in AR can be simulated. Hence, the safety clearance can be maintained and the layout space can be optimized. By fixing the location of the machine where the operators have to do work or collect goods, the distance travelled by operators from one station to another can be checked and thus cycle time can be estimated for the layout designed. The process time reduction is possible from the very beginning stage. The process flow can be simulated as well to check the workflow's effectiveness. The layout design can be cost-effective.

Simulation can be run using the AR environment for the layout planning, machine path planning the work-cell process flow planning.

With the aid of AR technology, the 3D modelling of the full factory floor space can be eliminated. When dealing with FLP tasks, the factory floor space needs to be modelled using CAD software and this is a time-consuming job. Changes in the model position and orientation can also be done easily by adjusting the marker in the AR environment. Current FLP systems available, users need to choose the 3D object and adjust the position and orientation accordingly using the computer mouse or keyboard type in the command of the software. Moreover, any changes in AR environment will be reflected in real-time. It is not new to use AR in FLP. Several AR-based FLP, analysis and optimization works have been reported. Researchers have reported implementing AR in their research for facility layout design, analysis and optimization (Siltanen et al., 2007; Pentenriede, 2008; Lee et al., 2011; Jiang et al., 2014; Pai et al., 2014). The efforts done so far are digitized existing items, implement virtual objects in the real environment, constraint the virtual objects, add relationship in between items, evaluate the distance, space in between items and propose a better layout design. Nee and collaborators (2014) presented AR assisted FLP tool with four main modules. The tool will be defined by user experience or intuition by manually manipulating the virtual object position and orientation. User has to define the constraints of the components in the AR environment. On-site modelling is the main function to represent existing objects with boxes or pillars or add in 3D models from the library. Optimization modules which using analytical hierarchy process – a genetic algorithm to generate a good layout as the suggestion. Figure 2.21 shows the program user-interface of the ARFLP system developed by Jiang et al., 2014). Herr et al., 2018 have applied AR in FLP software named ARSAM, which computational FLP analysis was extended with AR. Other than the automated layouts suggested by ARSAM, users can visualize and review any critical paths in the layout as well.

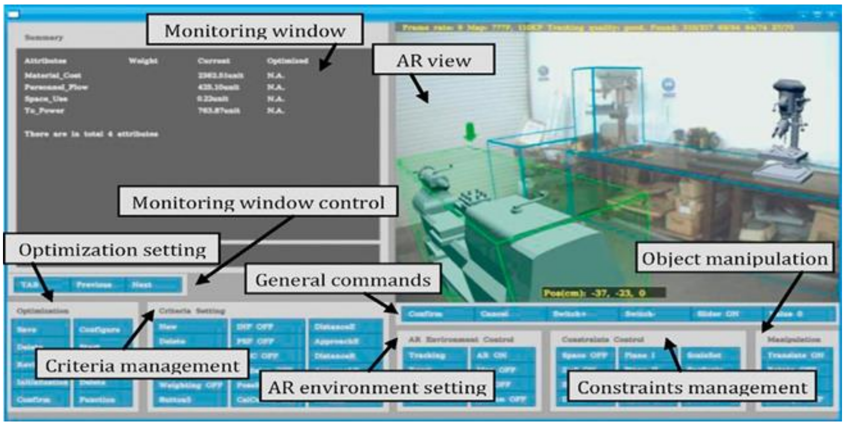



**Figure 2.21: ARFLP system user-interface (Jiang et al., 2014)**

The advantages of AR in FLP, analysis and optimization are accurate decision making, wide perspective consideration, flexible changes, less time consuming and cost-efficient. AR can be used to design the layout as a different situation can be simulated easily in the AR environment without disturbing the current production line. The reaction can be done in a very short time to change the production layout after checking in the AR environment. Since the AR is able to simulate the actual condition, the proposed changes should be very accurate and maybe no adjustment is needed when implementing the new layout design. The bottleneck of the processes can be detected in the early stage and necessary actions can be taken to optimize the production cycle time. The whole production line can be reviewed from time to time, the production engineer can plan the operators needed for the specific product production per day. Cost down can be achieved and production cycle time can be shortened. The decision can be made with few mistakes and more considerations in many perspectives in short time manner. Figure 2.22 shows the AR environment of a factory.

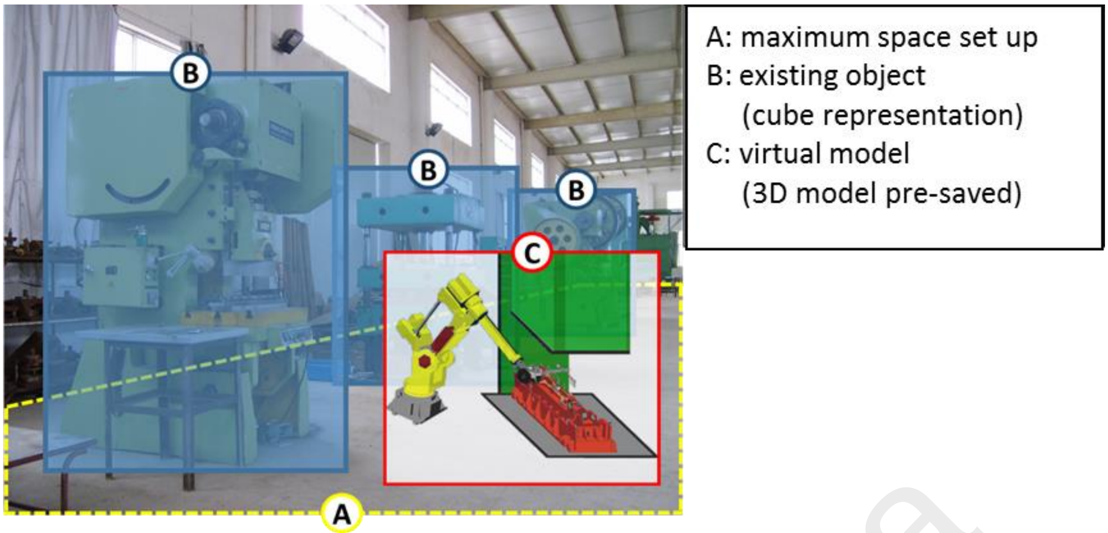



**Figure 2.22: AR environment of a factory**

Table 2.10 shows the comparison of AR-based approach for FLP. The above-mentioned AR-based FLP approach example is lack of proper evaluation mechanism. These systems require improvement in the interaction between real objects and virtual 3D models.

However, further improvement for the AR assisted FLP is required. Shariatzadeh et al., 2012 define that digital factory's or virtual factory's criteria should cover 3D visualization, interaction, immersion and real-time data manipulation. The digital factory must be able to verify and optimize the manufacturing processes of a product.

**Table 2.10: Comparison of AR-based approach FLP**

| Method | Objective | Functions | Hybrid |
|---|---|---|---|
| "Build-it" (Rauterberg *et al*, 1997) | o Production flow planning<br>o Team evaluation | o Table-top view<br>o Real bricks as interact handler<br>o Collaboration among team members | No |
| AR-Planning (Gausemeier *et al*., 2002) | o Production flow planning<br>o Layouts design with intuitiveness | o Collaborative planning<br>o Constraint, criteria definition<br>o Manipulate facilities with AR markers | No |
| Wan *et al*., (2010). | o Process optimization<br>o Production flow planning | o 3D model: WRL format<br>o Simulation data: XML format<br>o Layout planning by altering simulation data files | No |
| ARVIKA (Doil *et al*., 2003) | o Production flow planning<br>o Validation on-site | o Standard digital factory library<br>o Client-server framework<br>o Workspace ergonomics analysis | No |
| Poh *et al*., (2006) | o Minimize losses<br>o Maximize space | o Apply constraints on markers<br>o Evaluation criteria definition | No |
| ROIVIS (Pentenrieder *et al*., 2008) | o Process optimization<br>o Consistent reality and virtual data | o Client-server network AR application<br>o Stationary video-based AR system<br>o Mobile photo-based AR-system | No |
| Siltanen *et al*., (2007) | o Plant life-cycle management<br>o Management optimization | o Plugins (facility information, production data, AR simulation)<br>o Installation visual guidance | No |
| Lee *et al*. (2011) | o Cost minimization<br>o Process optimization<br>o Planning validation | o An image registration method<br>o Simulation data extraction and processing<br>o Collision detection between virtual facilities | AR and simulation technique |
| Jiang *et al*. (2014) | o FLP solution for existing factory<br>o FLP optimization<br>o FLP constraint definition | o Image recognition of existing objects<br>o Facility constraints mathematical representation<br>o Collision detection between virtual facilities | AR and simulation technique |
| Pai *et al*. (2014) | o FLP solution for flexible manufacturing cell<br>o Distance and space calculation for decision making | o FLP distance and space calculation<br>o Facility sequence definition<br>o Collision detection between virtual facilities | No |

Design, re-design, simulation of an FLP software must be quick, accurate and easy. The software must have a collaborative nature where people are able to talk, visualize and share information. Back to the objective of FLP, efficient and smooth process flow must be ensured. The optimized layout must fulfil space constraint, laws and regulations and workers' ergonomic comfort. The FLP software must contains the functional requirement such as layout geometry creation (create or modify 2D layout, 3D layout and interrelate the models), features, dimensions, constraint and tolerances definition (define geometric dimension, constraints in dimension and qualitative, interfaces between models definition, surface should attach to another surface, surface arrange parallel to surface, position for connector or insertion points for machine location and safety regulations constraint), non-geometrical information definition (annotation of objects, name, type, technical data, cost, weight, mean time to failure and mean time to repair), libraries of components creation (library with 3D models), import and export function (import models with different format, combine the newly added models to existing layout, the user interface), design presentation of properties and geometry (shows layout information, simulation walkthrough, save animation of moving components), layout analysis (measure and calculate distance, area, volume, quantitative and qualitative analysis whether the constraints are met, detect collision, calculate Center of Gravity (CoG) of model), model management (organize model structure, sequence of updating the model) and layout relation to other system and function (show and define material flow to another system, show and define manufacturing concept) (Jia et al., 2010).

## 2.7 Summary

From the literature review, it shows that AR is useful in FLP. The application of AR in the existing layout is even more useful. Literature has proposed in the early stage of designing, block representation can be used to speed up digital data development. But when the accuracy of the layout arrangement is expected, the detailed design of every item would be needed. The previous studies reported, there is a need to digitalize the existing objects in the existing layout with AR. Simple block representation can be used to represent the existing items. By doing this, FLP designers are able to cut down the time to model everything in CAD software or to generate a mathematical model for simulation. Meanwhile, the cost is also reduced. It is found that material travelled distance in a layout and space occupied are the two common concerns in FLP, followed by the production cycle time. Hence, these criteria should be used as judgement to support the FLP designers in decision making.

# CHAPTER 3: METHODOLOGY

## 3.1 Introduction

In this chapter, an AR-based FLP system for space and process optimization is proposed. There were 4 modules suggested in this AR-based FLP system. By employing the AR technology in an existing factory layout, the layout can be optimized in term of space and process. The evaluation data are in real-time to assist the user in decision making.

Hardware integration and software design are discussed as the research flow. The first module on AR-based FLP simulation for space optimization. The second module is on existing environment digitization and space optimization with the extension module where algorithm (LPT, SPT and total cycle time optimization) were implemented to suggest the production schedule. The third module suggests a location for a new shared facility by using the CoG algorithm. In the final module, it uses digitization from the second module to digitize a manufacturing conveyor belt system and design the process arrangement where some machines and robotic arm are added to replace the human workers.

## 3.2 Research flow

This research covered the building of AR environment, creating an interactive environment for the virtual and actual object, linking those objects as an operation system, loading algorithm to check for the possible arrangement of every object, optimizing the layout and finally sharing of the data. To create an interactive environment, the challenge is to digitize the actual items that are already existed. since the existing FLP may involve many types of object, it will consume a long time for the image processing part if the program needs to identify the objects automatically. Hence, the existing items will be represented by simple cubes or cylinders to assign properties to allow interaction in the AR environment in this research. Large and heavy objects are difficult to move in the real world, we may need the help of machines or vehicles to move them. However, since the cubes or cylinders are used to represent real objects in the AR environment, they can be moved and rotated easily in any ways the engineers want. Normally, machines need to have some clearance to ensure safety and heat dissipation. This is generally difficult for engineers to ensure the clearance is always enough in the real world. In the AR environment, the cubes or cylinders that represent real-world object can be designed in a bigger size cater to the clearance and make the design easier. The marker-based AR system is proposed in this research as a stable reference frame of the whole system. Unity and Vuforia are selected to develop the AR FLP system, due to its flexibility and C# programming language used for Unity and Vuforia is very common. On top of that, the ability of it to export executable program to Windows, Mac, Android and iOS has added value as well. For the AR hardware setup, the simplest video see-through display (computer with the webcam) is chosen in this research. This simplest setup needs only a minimal financial investment but it can effectively investigate the possibilities of AR in FLP solution.

Figure 3.1 shows the conceptual design of the AR FLP program designed with Vuforia and how it works. The proposed AR FLP program is marker-based which the webcam will stream live actual video and feed it to the AR program as background. The AR algorithm will look for any marker that appeared in the video fed as a reference point of every virtual data added to the AR program. As shown in the figure, the red dotted line plane is identified as the floor plane of everything in the AR environment. The existing objects captured in the video will be digitalized with cubes or cylinder 3D models. As shown in Figure 3.1, the forklift is digitalized as blue cube while the heat exchanger machines are represented as blue cubes as well. Finally a new facility, in this case, the

KUKA robot is placed into the AR environment to check for a suitable position and rotation.

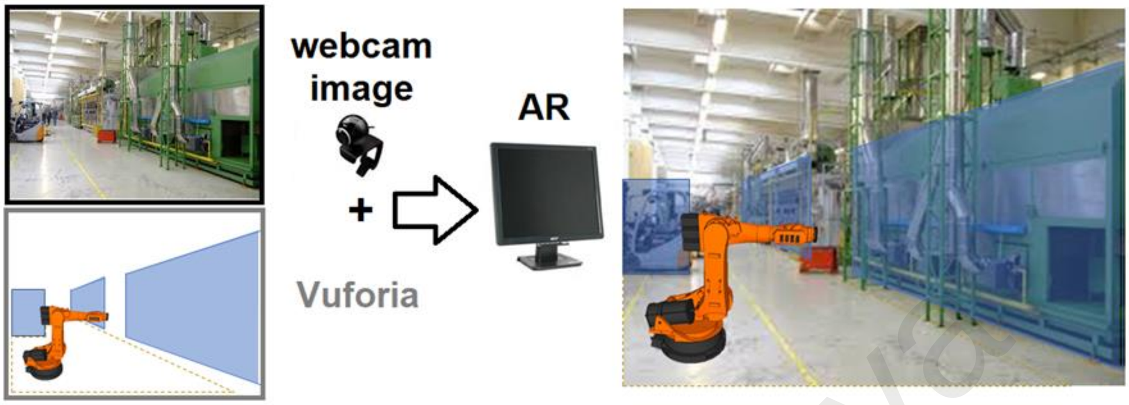



**Figure 3.1: Conceptual design of an AR FLP built with Unity and Vuforia**

The beginning of the study is the building of the AR system where the starting point is the setup of hardware and software. A laptop with a webcam is the minimum hardware requirement to build the AR system. The concern in this study is the ability of AR in optimizing FLP, there will be no difference if marker-based or marker-less AR is used. Marker-based AR was chosen as the AR system in this study due to its robustness and flexibility. In term of development time, marker-based AR consumes lesser time than that of marker-less AR. The development cost of it is much lesser than marker-less AR as well. From the AR SDKs review from Section 1.2.3, Unity and Vuforia are identified to be used in this research. Unity and Vuforia have to be installed on the laptop. Unity is a game creation software widely used in the gaming industries while Vuforia is a plugin for Unity to create AR application. The programming is the main thing that makes the AR environment work. C# programming language is the code used in this research.

The virtual data (3D models, blocks, cubes, spheres, etc.) to be blended in the AR environment should be pre-built in the computer. Unity can only use the 3D in **.obj* format. An **.obj* file is a 3D image format contains information like vertex coordinates, faces, texture that is only readable by CAD software.

The workflow of the program will start with the camera to capture the real environment of a factory. The program will then search for the AR marker, which pasted on the floor. Once the marker is detected, the user needs to set up the maximum space of operation. This will define the floor plan dimension, from wall to wall. Once space is set up, the virtual 3D model will then be loaded and place on the floor. Those objects which are known to be presented in the program are pre-saved. When there are existing actual objects which are unknown, a cube or a cylinder will be scaled to size and placed on the floor. The virtual objects' scaling and location setting are all controlled by mouse in the Unity environment. The cube or cylinder is partially transparent to allow the user to see the actual objects. Physics of the objects are defined. This part is to set up the digitalization of the existing space and objects in the AR-based FLP system. Up to this level, the actual objects will be recognized and able to interact with other virtual objects. Collisions between objects in the AR system can be detected, the distance between objects can be measured and the user is able to move the objects (virtual). Next, the optimization part of the AR-based FLP system will take place. The optimization algorithms will request the user to set the sequence for each workstation. Once this step is completed, the program will calculate the best layout and present the suggestion as a result. User can either choose to accept the layout design as it is or change the layout by pick and place the virtual objects. When there is a change, an algorithm will start and calculate the distance between workstation. The comparison will be made with the suggested layout earlier. Material handling path will be simulated and shown. In the end, the optimized layout suggestion will be printed as the top view floor plan. Figure 3.2 shows the workflow of the AR-based FLP program.

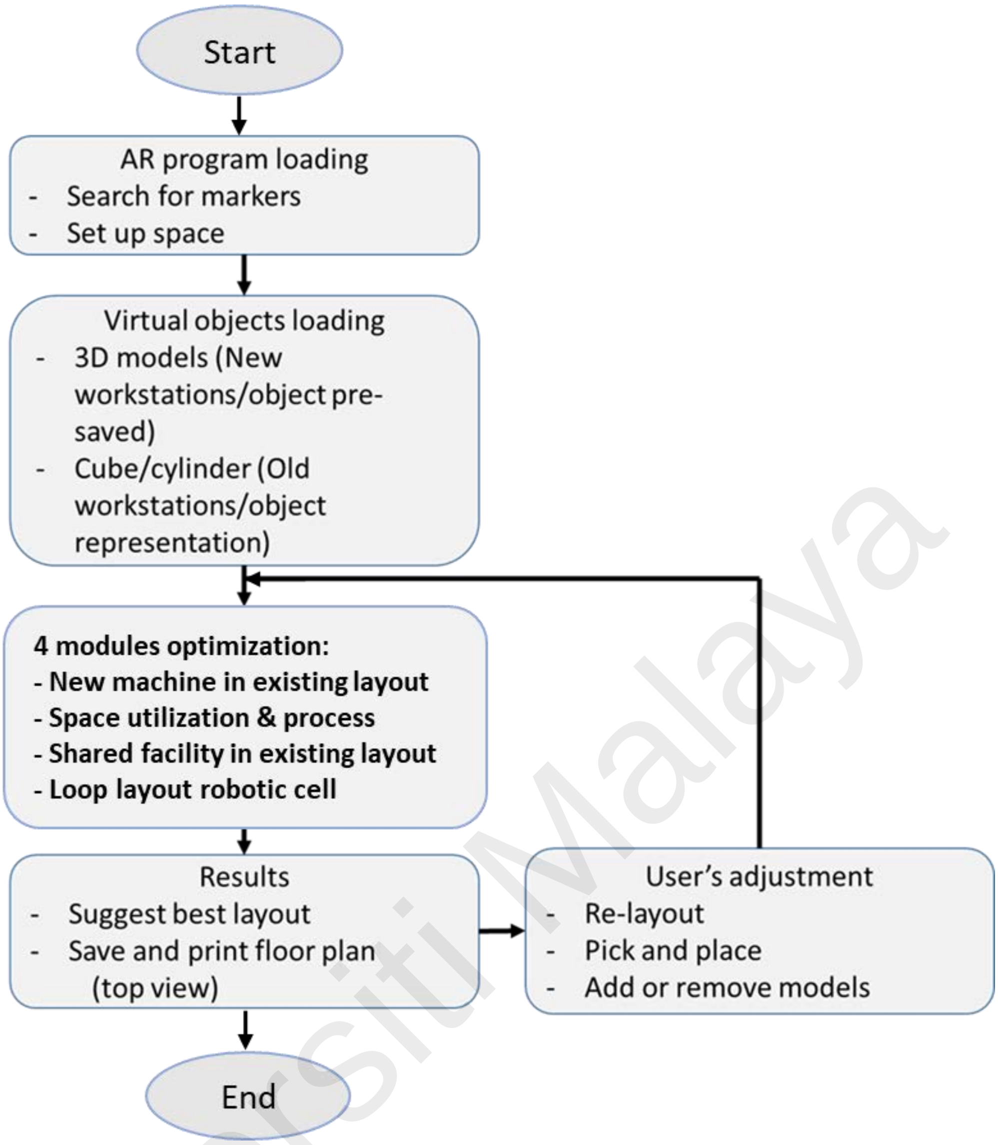



**Figure 3.2: AR Facility Layout Planning program structure**

### 3.3 AR markers design

Markers are used in this research for tracking and referencing. Black and white square images are designed as markers and print out on paper to be used as a target or reference point when running the AR-based FLP program. Figure 3.3 shows the list of markers used in this research. There are several criteria that must be fulfilled by an image to be a good and stable AR marker:

- Image contrast: The image must have good contrast for the camera to detect its edge. Black and white image has very good contrast.
- The markers must not be confusing. “O” marker and “0” marker cannot be used in the same program, the program may treat “0” as “O” tilted to the camera.
- The image should not be symmetrically the same. “O” is not a good marker because the top half is the same as the bottom half, as well as the left half, is the same as right half. “Q” is a better marker than “O”.


(a) CNC bending machine marker


(b) CNC shearing machine marker


(c) Inventory rack marker


(d) Drilling machine marker


(e) CNC punching machine marker


(f) New drilling machine marker

**Figure 3.3: Markers used in this research**



## 3.4 Module-1: Space optimization for the existing layout

An AR-based FLP program was developed. AR markers were designed without conflicting with each other. Each marker represents one unique facility. 3D data of the facilities were imported and overlaid onto the AR markers. Physical properties were assigned to the 3D models, the objects were set as rigid bodies.

### 3.4.1 Collision detection

In real production floor, there is always a safety zone for a machine where no other things are allowed to be placed in the machine safety zone. To implement this safety requirement, this AR program applies the collision detection method where the safety zone was represented by a box collider surrounding the 3D model. The AR program will check for the collision and sends a warning if the collision happens, 3D models will be highlighted in red colour if the collision is detected (Figure 3.4).

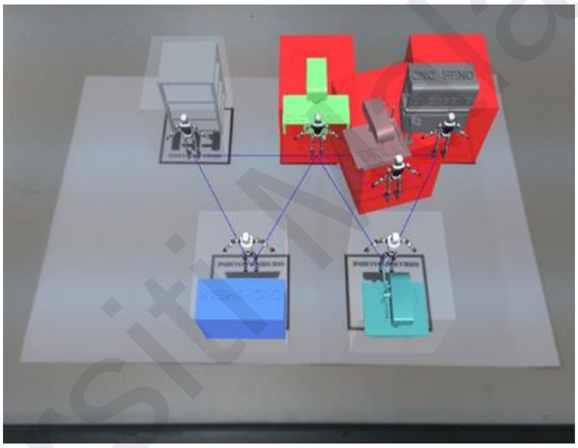


**Figure 3.4: Collision detection function**

Below is the function code used in Unity to check for collision. This boolean function will return true if the object is colliding with other objects, otherwise false.

```
public static bool CheckBox (
    Vector3 center,
    Vector3 halfExtents,
    Quaternion orientation = Quaternion.identity,
    int layermask = DefaultRaycastLayers,
    QueryTriggerInteraction
    queryTriggerInteraction = QueryTriggerInteraction.UseGlobal
    );
```

### 3.4.2 Material travel distance

Material travel distance and area occupied are the main considerations in this program. To calculate the material travel distance, this AR program is able to detect the position of the AR markers, machines as well as the operators. The material travel distance from one station to another station is presented as the distance between two subsequence machine operators.

$$\text{Total material travelled distance, } D_T = \sum_{i=1}^{max} \sqrt{(X_i - X_{i-1})^2 + (Y_i - Y_{i-1})^2} \quad (3.1)$$

where,

$L_i$ = i^th process material travel distance
$X_i$ = horizontal centre of the corresponding operator
$Y_i$ = vertical centre of the corresponding operator
$X_0$ = horizontal centre of the first operator
$Y_0$ = vertical centre of the first operator
$X_{max}$ = horizontal centre of the last operator
$Y_{max}$ = vertical centre of the last operator

Codes below calculate the material distance of a 5 machines production line and round up the distance calculated into 2 decimal places number.

```
line1_distance = (float)System.Math.Round(AB + BC + CD + DE + EA, 2);
        //total distance for original line
```

### 3.4.3 Space occupied

To calculate the area occupied, the AR program searches for width (distance between two machines which are farthest away from each other in the x-direction) and length (distance between two machines which are farthest away from the each other in the y-direction) of the layout. The area occupied is defined as the product of the width and length of the layout.

$$\text{Area, } A_T = ( x_{max} - X_0 + w ) * ( y_{max} - Y_0 + l ) \qquad (3.2)$$

where,

$X_0$ = horizontal centre of the first machine

$Y_0$ = vertical centre of the first machine

$x_{max}$ = horizontal centre of marker farthest away from the first machine

$y_{max}$ = vertical centre of marker farthest away from the first machine

$w$ = machine operation area width

$l$ = machine operation area length

Material travel distance and the total area occupied are recorded when a layout is confirmed. Re-layout can be conducted easily by moving and rotating the AR markers. Figure 3.5 explains the total material travel distance and area occupied in an example of AR facility layout.

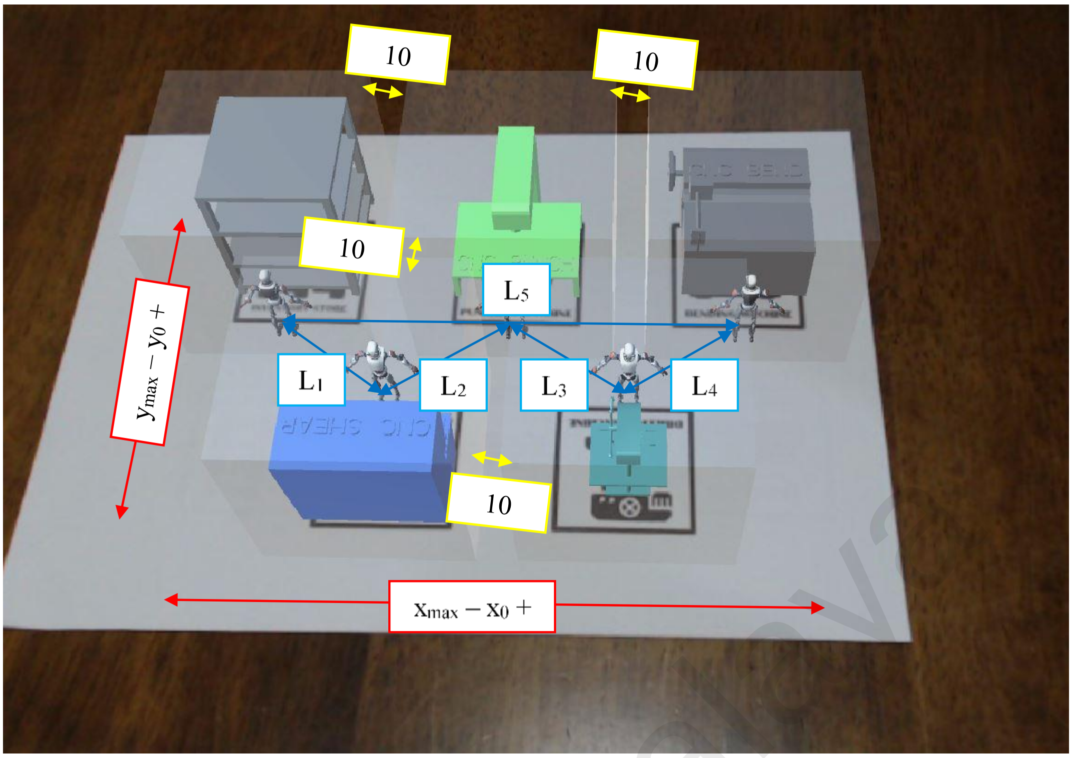



**Figure 3.5: Total material travel distance and area occupied calculation**

Codes below is a function that calculates the area occupied by 5 facilities placed on a shopfloor, where only the distance of furthest machine in x-direction and y-direction are recorded and the product of the two distances is the area occupied.

```
private void area()                        //calculate total area
{
   Xa[0] =   Mathf.Sqrt((center2.transform.position.x –
             center1.transform.position.x) *
             (center2.transform.position.x -
             center1.transform.position.x));

   Xa[1] =   Mathf.Sqrt((center3.transform.position.x –
             center1.transform.position.x) *
             (center3.transform.position.x -
             center1.transform.position.x));

   Xa[2] =   Mathf.Sqrt((center4.transform.position.x –
             center1.transform.position.x) *
             (center4.transform.position.x -
             center1.transform.position.x));

   Xa[3] =   Mathf.Sqrt((center5.transform.position.x –
```

```
            center1.transform.position.x) *
            (center5.transform.position.x -
            center1.transform.position.x));

Xa[4] =     Mathf.Sqrt((center6.transform.position.x –
            center1.transform.position.x) *
            (center6.transform.position.x -
            center1.transform.position.x));

Ya[0] =     Mathf.Sqrt((center2.transform.position.z –
            center1.transform.position.z) *
            (center2.transform.position.z –
            center1.transform.position.z));

Ya[1] =     Mathf.Sqrt((center3.transform.position.z –
            center1.transform.position.z) *
            (center3.transform.position.z –
            center1.transform.position.z));

Ya[2] =     Mathf.Sqrt((center4.transform.position.z –
            center1.transform.position.z) *
            (center4.transform.position.z –
            center1.transform.position.z));

Ya[3] =     Mathf.Sqrt((center5.transform.position.z –
            center1.transform.position.z) *
            (center5.transform.position.z –
            center1.transform.position.z));

Ya[4] =     Mathf.Sqrt((center6.transform.position.z –
            center1.transform.position.z) *
            (center6.transform.position.z –
            center1.transform.position.z));

float Xmax = Xa.Max();
float Ymax = Ya.Max();

Total_Area = (Xmax + 70) * (Ymax + 70);
Total_Area = (float)System.Math.Round(Total_Area, 2);
}
```

As an entry point of the AR-based FLP program, the user has to set up the AR production line by defining the AR markers to be used and importing the 3D models of the facilities. There are 2 constraints need to be defined in this program, namely facility spatial constraint and process sequential constraint. Facility spatial constraint is the definition of the machine dimension and machine working space as well as the physical properties of the 3D models. Process sequential constraint is where the relationship of the machines is defined. The machines should be arranged in a way to follow the process sequence. The AR-based FLP program allows an option for the users to do on-site re-layout by moving and orientating the markers in the AR environment. The analysis involved is collision detection among the 3D data, total material travel distance and total area occupied. These data will be recorded and tabulated. Users must decide which layout is the best based on the data analyzed. (Figure 3.6 explains the AR-based FLP program framework)

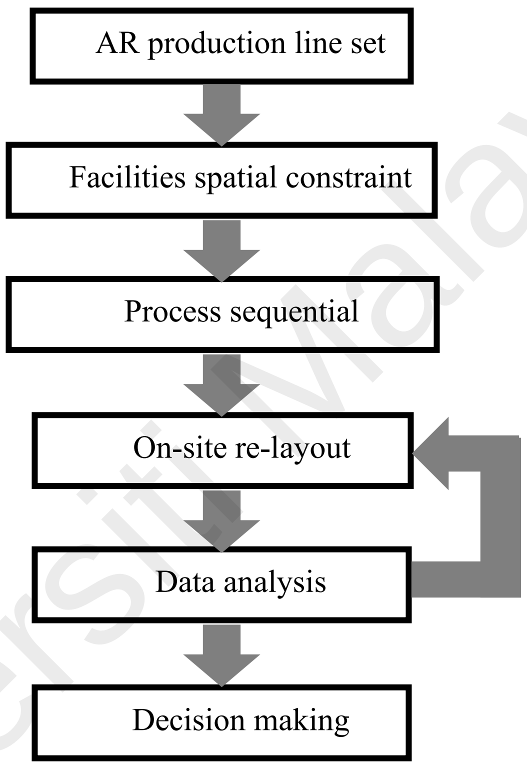



**Figure 3.6: AR-based FLP program framework**



The case study was about machine layout planning when new machines are added to the existing production floor. The orientation of the machines is one of the important aspects to be considered. To achieve the shortest material travel distance, the orientation of the machine should be optimized. The proposed AR program provides users to easily visualize and manipulate the position and orientation of the machines. Hence, the shortest material travel distance can be achieved. On the other hand, the total area occupied is another important consideration in FLP. The proposed AR system is able to capture and record the area occupied by the machines easily. The best layout is the one with the minimum area occupied.

## 3.5 Module-2: Space and production schedule optimization in an empty layout

An AR-based FLP program for optimization is proposed in this section, specifically for an empty shopfloor. The program starts with the marker registration and working space definition. The proposed AR working system is a marker-based AR system. The program will first search for the marker that is placed on the working space floor. This marker will act as the working space origin. Next, the user has to set up the working space by adjusting the floor plane position, orientation as well as the scale. Four walls will then automatically be generated at the edge of the floor plane. By using the floor as the reference plane, all the existing actual objects in the actual environment can be digitized into virtual data by overlaying blocks, cylinders, prisms, spheres, etc. onto the objects. The added virtual objects must be moved, oriented and scaled to overlap with the actual objects. The steps basically are to register the actual objects in the AR systems. In this system, the simple shapes used to represent the actual objects are wireframe models. Wireframe models can be easily and accurately overlaid onto the actual objects in the AR environment. If the 3D data of the existing objects are imported, the representation of the actual models is more accurate as compared to the simple shapes. Physics of the objects must be defined. Upon following these steps, the actual objects will be able to interact with those virtual objects. Collisions can be detected, the distance between objects can be measured and the objects can be moved and manipulated.

The layout can be optimized by applying relevant algorithms in this system. This system is aimed to maximize the working space by adding maximum amounts of machines or workstations in the available working space. The facilities will be loaded in the system as long as there is no collision of objects detected in the system. In this system, the user can move the facilities in the layout. Adding or removing machines or workstations are possible in this system as well. When the solutions provided by the program is not applicable, the user can amend or adjust the layout based on his judgement. Data of the proposed layout (distance between facilities, area occupied and production schedule) can be saved and exported as a text file while the floorplan can be saved and exported as a drawing. This last step of the data export is for reference and sharing purposes. Figure 3.7 shows the workflow of the AR-based FLP for space optimization program.

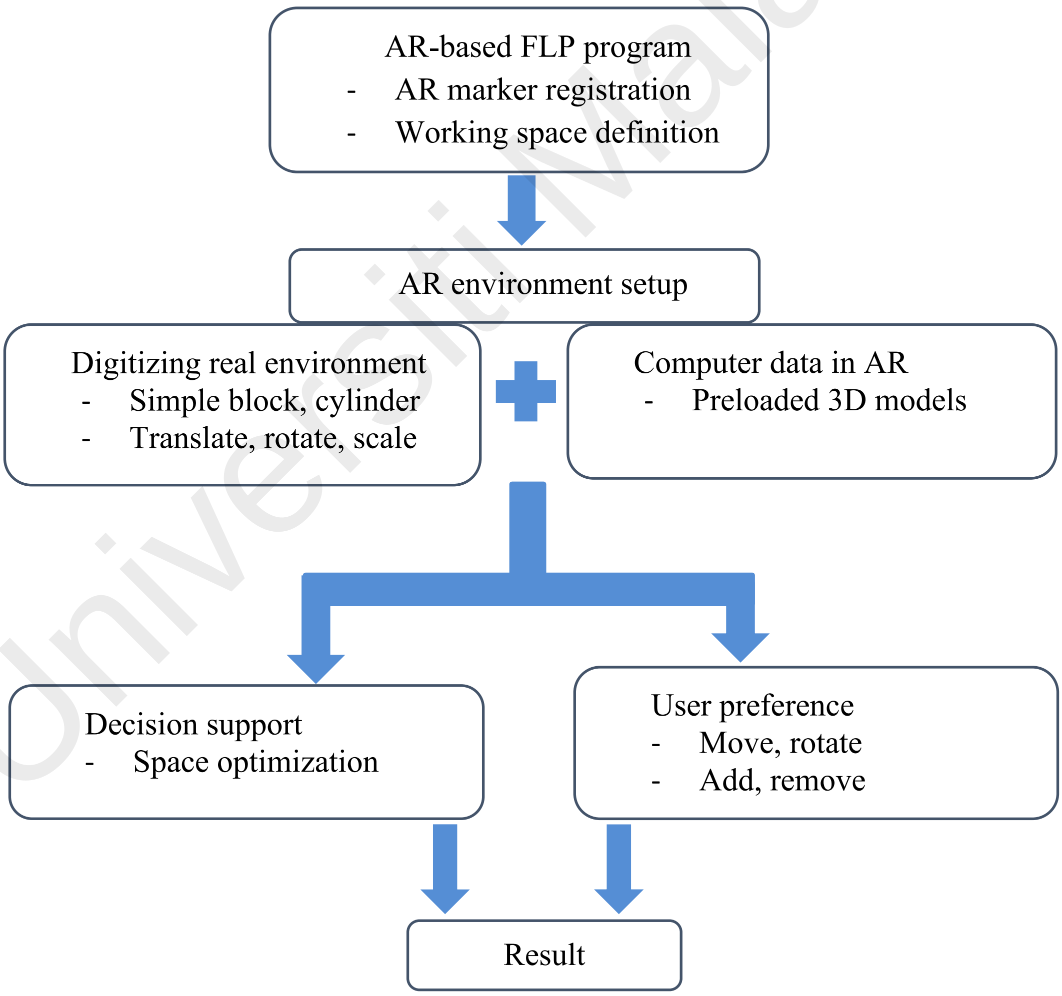



**Figure 3.7: AR-based FLP for space optimization program structure**

Production sequence can be simulated to find out the best production arrangement. In this system, all the methods applied are the same as Module 2a with an extension on the simulation of the production schedule. The production schedule can be sorted in ascending or descending manner or with cycle time optimized method based on the production cycle time. The production scheduling methods are referred to classical heuristic algorithms namely LPT and SPT. The cycle time optimization method is to minimize the time difference for the completion time of each facility which is referred to the production line balancing method.

### 3.5.1 LPT algorithm

First, a product list is built by sorting the products in descending cycle time order. Next, the maximum number of the workstation (X) to run the production is identified. For the first cycle process, the products are assigned to the corresponding workstation based on the list built earlier (top to down). The products from the list are picked continuously for cycle N production, fill the longest cycle time workstation first until all the product in the list has been chosen. Figure 3.8 shows the flowchart of the LPT algorithm.

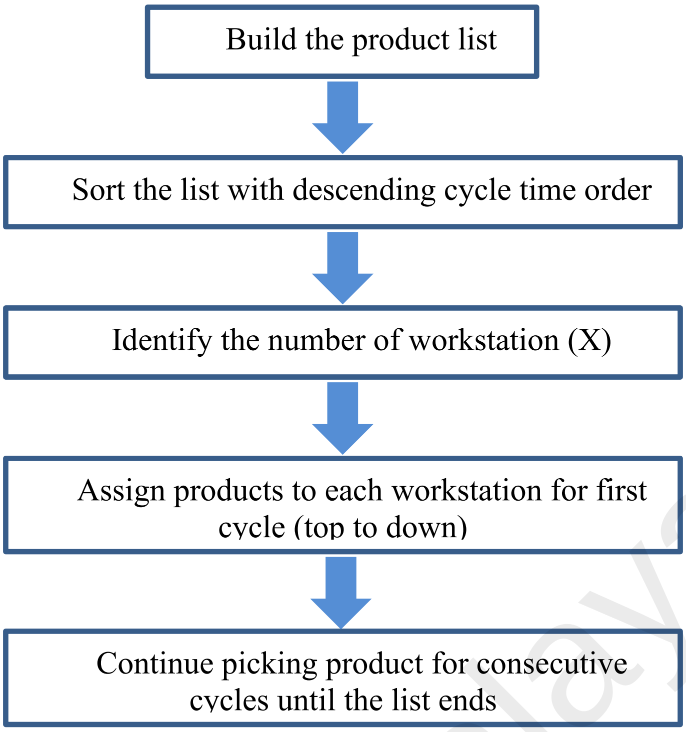



**Figure 3.8: LPT algorithm flowchart**

### 3.5.2 SPT algorithm

First, a product list is built by sorting the products in ascending cycle time order. Next, the maximum number of the workstation (X) to run the production is identified. For the first cycle process, the products are assigned to the corresponding workstation based on the list built earlier (top to down). The products from the list are picked continuously for cycle N production, fill the shortest cycle time workstation first until all the product in the list has been chosen. Figure 3.9 illustrates the flowchart of the SPT algorithm.

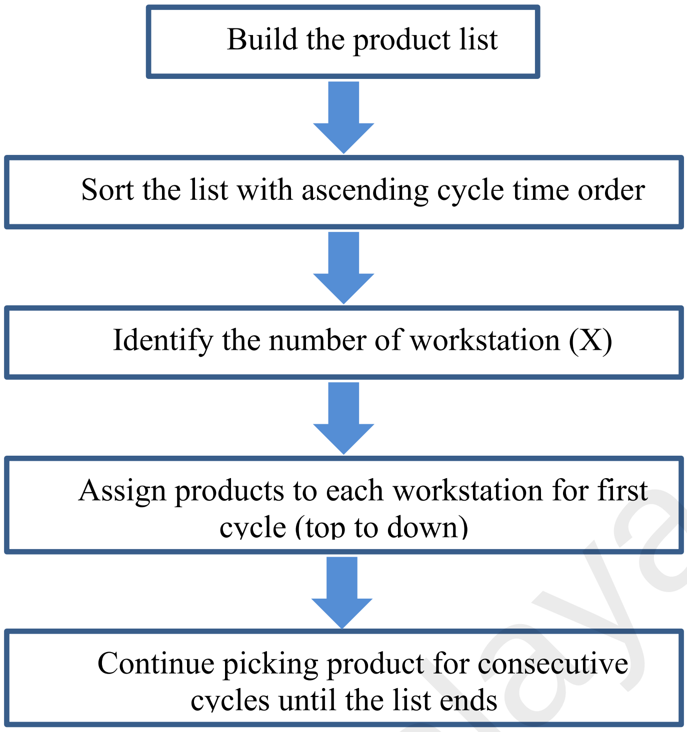



**Figure 3.9: SPT algorithm flowchart**

### 3.5.3 Cycle time optimization algorithm

First, a list of products is built by sorting the products in descending cycle time order. Next, the total time to complete all the product (T) is calculated and the number of the workstation (X) available is identified. The average cycle time for each workstation is calculated ($t_{ave}$=T/X). The products are arranged for Xth workstation (left to right), with the requirement of the total cycle time of workstation X, tx > t – 0.5%; tx < t + 0.5% until all the product in the list has been chosen. If the requirement (0.5%) is impossible to achieve, user may need to increase the percentage of the acceptance total cycle time (for example: tx > t – 1%; tx < t + 1%). By having a higher percentage, the cycle will be more imbalance. The perfect case is 0% difference but quite impossible to achieve in a real-world case. Figure 3.10 shows the flowchart of the cycle time optimization algorithm.

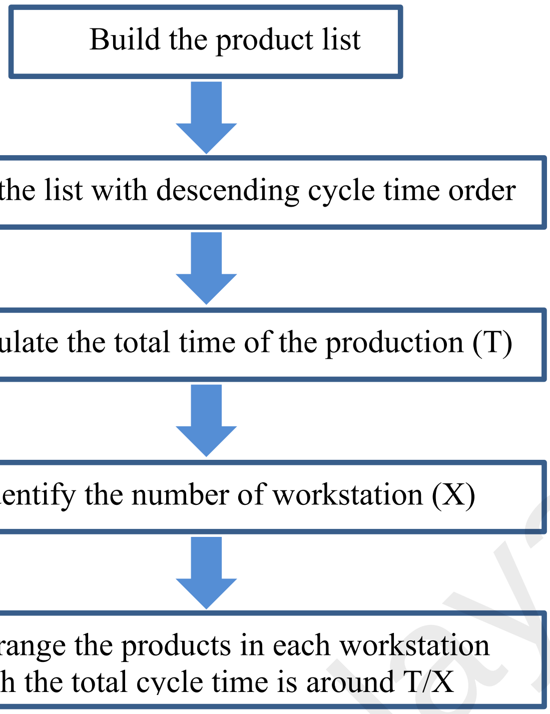



**Figure 3.10: Cycle time optimization algorithm flowchart**

## 3.6 Module-3: Shared facility in existing shopfloor

In the case of finding the best position of a shared facility specifically in an existing shopfloor, digitization method in Module 2a is applied. Module 3 uses the CoG method to locate a shared facility in an existing shopfloor. The workstations or machines in a shopfloor can be modelled into a rigid body with the weight assigned. The weightage represents the importance or the frequency of usage of the shared facility to a particular workstation in work. The CoG of the system represents the best position of the shared facility. For example, a material feeder robot's home position in a shopfloor is the best at the centre of gravity of the facility layout. CoG algorithm is explained step by step in the section below.

1. Identify the location ($x_i$, $y_i$) of each workstation.
2. Identify the weightage of each workstation ($w_i$).
3. The best location of the shared facility is calculated with the formula below:

$$\text{Best location, } (x_c,\ y_c) = \left(\frac{\sum_{i=1}^{n} x_i * w_i}{\sum_{i=1}^{n} w_i}, \frac{\sum_{i=1}^{n} y_i * w_i}{\sum_{i=1}^{n} w_i}\right)$$

4. The total distance between workstations:

$$d = \sum_{i=2}^{n} \sqrt{[(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2]} \tag{3.3}$$

where, n = total workstations in the layout

In this system, the user can move the facilities in the layout. Adding or removing machines or workstations are possible in this system as well. When the solutions provided by the program is not applicable, the user can amend or adjust the layout based on his judgement. Data of the proposed layout (distance between facilities, area occupied and production schedule) can be saved and exported as a text file while the floorplan can be saved and exported as a drawing. This last step of the data export is for reference and sharing purposes. Figure 3.11 shows the framework for the AR-based FLP shared facility locator program.

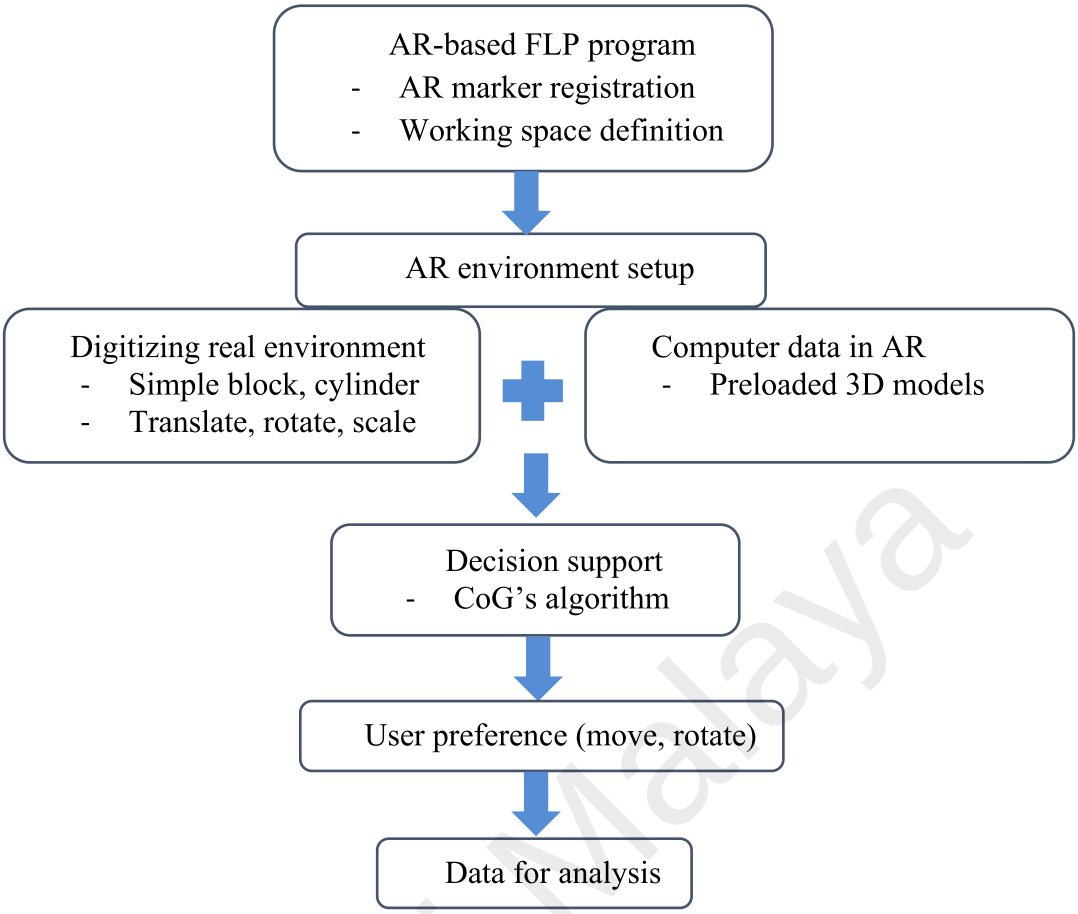



**Figure 3.11: Shared facility locator program structure**

## 3.7 Module-4: AR process planning for Loop-layout Robotic cell

Module 4 involves the digitization of an existing conveyor system. Stations for every process can be defined in the system, machines and robotic arm can be added in the digitized AR environment of the conveyor system. In the simulation, the robot's reachability and machines' clearance can be checked. Total material travel distance can be calculated once the station from the first to the last process is defined.

The distance calculation script algorithm is applied to calculate the total travel distance of part. The distance calculation script algorithm is illustrated in Figure 3.10. The part would enter the conveyor at the input station, go through processing machines and exit the work cell at the output station, the part's travelled distance on the conveyor belt would be calculated through the following procedures:

1. As the simulation started, the initial position of the part at the input station would be read and save as array data as

   $$p_i = [x_i, y_i]$$

   where $p_i$ is the initial position of the part, $x_i$, and $y_i$ is the geometry coordinate.

2. Then as the part arrives at the pickup point of the first machine for the first machining process, the position of part at that specific pickup point would be read and recorded in the array as

   $$p_{mi} = [x_{mi}, y_{mi}]$$

   where $p_{mi}$ is the position of the part at first machine pick up point, $x_{mi}$, and $y_{mi}$ is the geometry coordinate.

3. The distance travelled by the part from the input station to the first machine would be calculated by the equation below by using the information from above:

   $$d_1 = \sqrt{(x_{mi} - x_i)^2 + (y_{mi} - y_i)^2} \tag{3.4}$$

   where $d_1$ is the first calculated distance.

4. After completing the first machining process, the part would unload by the machine at the same pickup point, and the robotic arm would pick the part from the conveyor belt to the next station of the robotic cell. As the second machining process was completed, the part will be sent to the third machine for processing.

5. Then as the part completed the machining process of the third machine, it would unload to the drop-off point of the dummy machine at the conveyor, the position of that drop-off point would be read and recorded in the array as

$$p_{mi+1} = [x_{mi+1}, y_{mi+1}]$$

where $p_{mi+1}$ is the position of the part at first machine pick up point, $x_{mi+1}$, and $y_{mi+1}$ is the geometry coordinate.

6. As the part completed the processes, it would be sent to the output station through the conveyor, the final position of the part (output station) before leaving the robotic work cell would be recorded as

$$p_o = [x_o, y_o]$$

where $p_o$ is the final position of the part, $x_o$, and $y_o$ is the geometry coordinate

7. The distance of travel by the part from the third machine to output station would be calculated by equation (7) by using the information from equation (5) and (6):

$$d_2 = \sqrt{(x_o - x_{mi+1})^2 + (y_o - y_{mi+1})^2} \quad (3.5)$$

where $d_2$ is the second calculated distance.

8. The total travel distance of part obtained through equation (8) by using information from equation (4) and (7).

$$D = d_1 + d_2$$

where D = total travel distance.

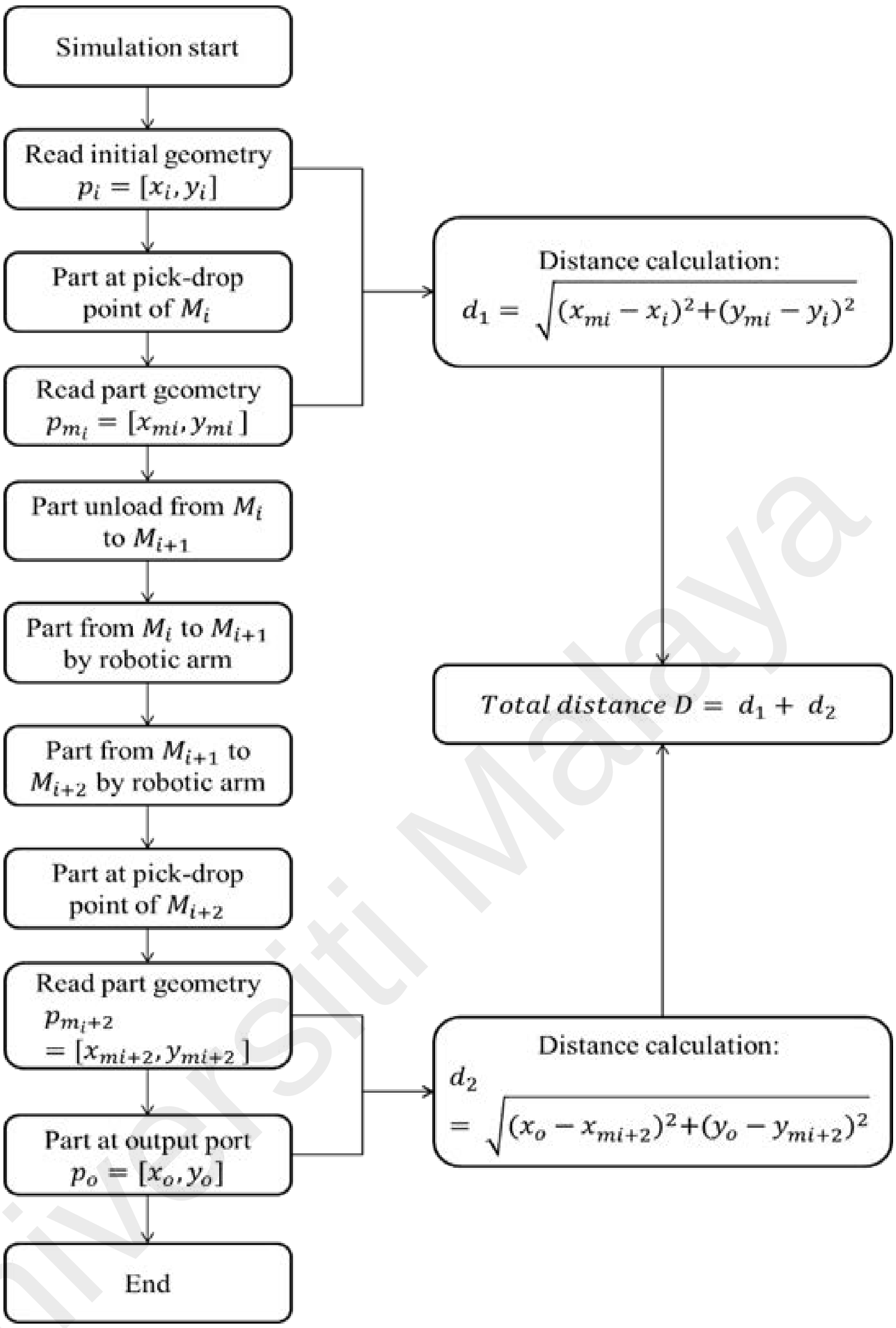



**Figure 3.12: Distance calculation script algorithm**

## 3.8 Summary

The marker-based AR system is proposed in this research study to solve the FLP issue specifically in an existing shopfloor. Few scenarios were considered including locating a new machine in an existing production floor, maximizing the space by putting as much as workstations as possible in an empty shopfloor, optimizing the production schedule, to locate a shared facility in an existing shopfloor and finally process planning of a conveyor system work cell. AR is found to have advantages as compared to the alternative FLP approaches when dealing with existing shopfloors. Some frameworks have been defined to make the AR system useful for example collision detection, space occupied calculator, material travel distance calculator, production scheduling algorithm, CoG calculator and process sequence simulator. 4 independent modules were created namely, space optimization of the existing shopfloor, space optimization of empty shopfloor with production schedule optimization, shared facility in existing shopfloor and process planning of conveyor system loop layout. Collision detection framework and existing objects digitization method are used in all the 4 modules where facilities are all defined with their safe working boundary well defined to avoid them clashing with other facilities. Module 1 has material travel distance calculator and space occupied calculator while Module 2 has the scheduling algorithm simulator. As for Module 3, it has the CoG algorithm simulator to locate the best location of a shared facility. Finally, in Module 4, all the workstation can be digitalized and their sequence in the production process can be defined. Material travel distance is an important function in Module 4.

# CHAPTER 4: RESULTS AND DISCUSSION

## 4.1 Introduction

Four case studies were conducted in this research. Case study-1 is where a production line of air conditioning unit metal casing was studied. As the drilling machine is identified as the bottleneck of the production, there is a need to add another drilling machine to increase productivity. AR is used to locate the best position of the new drilling machine in production where space occupied and the material travel distance are the judging criteria. Several production layouts were studied as well. Case study-2 is regarding the effort to maximize the productivity of a composite layup cleanroom. The cleanroom was digitalized and the free space of the cleanroom was calculated. By using the collision detection method, all the layup tooling table was loaded in the cleanroom. The minimum clearance between the tooling table and wall were taken care of. The production planning of the composite layup cleanroom was then optimized by loading industries commonly used algorithm. Case study-3 is about locating the share facility in a shopfloor where CoG algorithm is used. The user-defined mode is added in this case study in case the suggested location is not suitable. The case study-4 is the process planning of a closed-loop conveyor system. The existing conveyor system is having 3 independent stations where each station is handling only one machining process. The second station is fixed at the centre of the conveyor cell where a robotic arm, a CNC milling machine and a CNC lathe machine places. There are 3 options to locate the first and third station along the conveyor loop. The possible layouts were simulated in AR and part travel distance is recorded.

## 4.2 Case study-1

To test the capability of AR in FLP decision support in term of space occupied and total material travelled distance, production of the metal casing of air conditioning unit was chosen as a case study. There were 4 processes in the production cycle of that product (shear, punch, drill and bend). The raw material has to travel from the inventory to the shearing machine. Next, it has to move to the punching machine. Then, it will move to the drilling station and follows by the bending machine. Finally, the finished good will be sent back to the inventory. There were 5 facilities involved in this production. Figure 4.1 shows the production stations of the air conditioning unit metal casing production line.

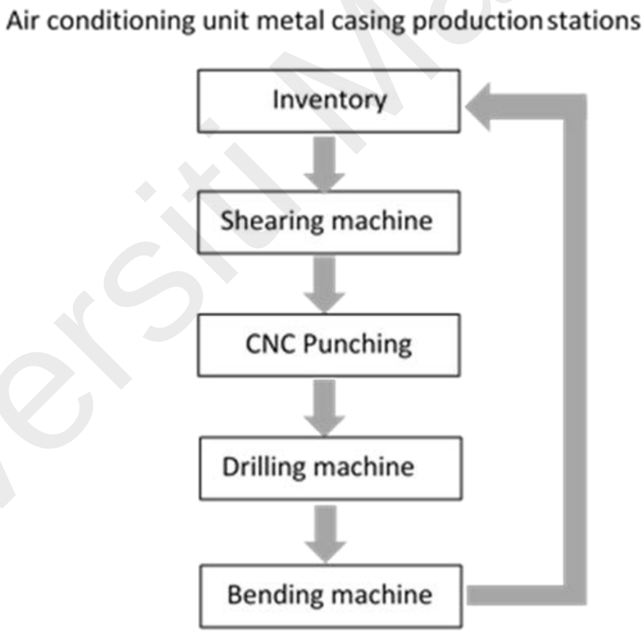


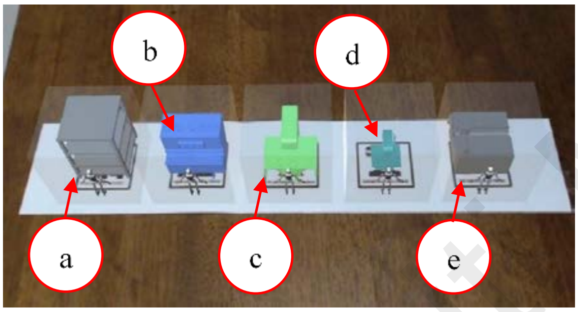

**Figure 4.1: Air conditioner unit metal casing production stations**

The bottleneck of the process is identified at the drilling process where the drilling takes longer time compared to the other processes. The proposed solution is to add a new drilling machine in the production line. To verify the ability of the AR program to suggest the best facility layout design, there were four common types of facility layout proposed in this study. The layouts are straight-line arrangement, W-shaped arrangement, U-shaped arrangement and V-shaped arrangement. The machines are placed as close as possible to each other in the layout with minimum clearance in between machines operation area. The straight-line layout is the layout where the facilities are arranged side by side in one straight line. This layout usually occupies the smallest area. The W-shaped arrangement is the layout where machines are arranged in W-shaped. From the top view, the first station and the last station are positioned on the same side. U-shaped layout is an arrangement where facilities formed U-shape with all the operators standing back to back. The V-shape layout has similar facilities arrangement with the u-shaped layout but the third machine is located slightly away from the layout, the first machine is located beside the second machine while the fourth and fifth machines are located side by side. The new drilling machine is added in the existing four layouts to form a new facility layouts. Assuming the original layout is fixed and cannot be modified. Material travel distance and area occupied were recorded. The new drilling machine was rotated and moved to check for other possible layout design. The results were tabulated and analyzed. The best facility layout should be the one which is having the shortest material travel distance and the minimum area occupied.

### 4.2.1 Straight-line layout study

The original straight-line layout of the 5 stations production line as shown in Figure 4.2, the total material travel distance is 6.48 m with the total area occupied 2.9 $m^2$. The new drilling machine can be added on the machines' side or the operators' side, beside the first machine or the last machine in the straight-line layout. The new drilling machine marker was added and checked for the best location. There is no space to add the new drilling machine without increasing the production floor area. From the data collected

(Table 4.1), the best new layout after added in the new drilling machine is layout LA, where the drilling machine is located at the operators' side of the straight-line layout, in between CNC punching machine and bending machine. But there is 0.09m longer material travel distance and about 2.6 $m^2$ (~97%) increase of total area if compared to the original layout area. If the total area occupied is the main consideration, layout LF and layout LG have smaller area compared to the layout LC which is 3.3 $m^2$. But, layout LF and LG have very long material travel distance. Layout LB, LC and LD are checked by rotating the new machine in layout LA by $90^{\circ}$ increment in rotation. These layouts have the same area occupied as layout LA but the material travel distance is longer.




| | |
|---|---|
| a | Inventory |
| b | Shearing machine |
| c | CNC punching machine |
| d | Drilling machine |
| e | Bending machine |

**Figure 4.2: Straight line layout**

**Table 4.1: Straight line layout study data**

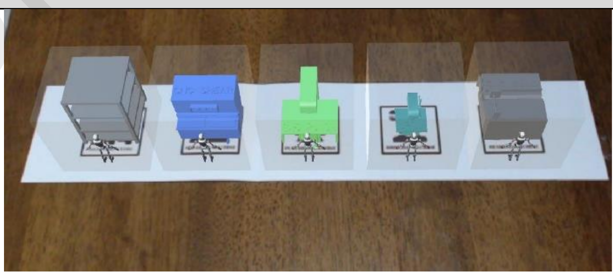
| No | AR Layout | Material Travel Distance (m) | Area ($m^2$) |
|---|---|---|---|
| 1 |  L0 (original Straight Line layout), no new machine | 6.48 | 2.9 |

**Table 4.1: Straight line layout study data (continued)**

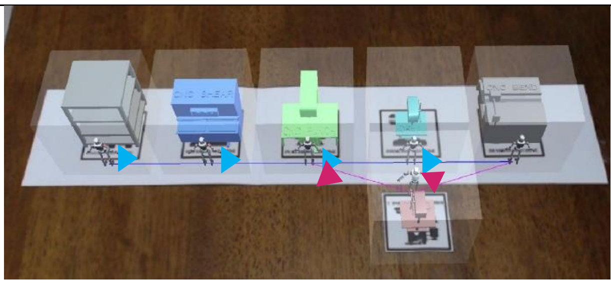
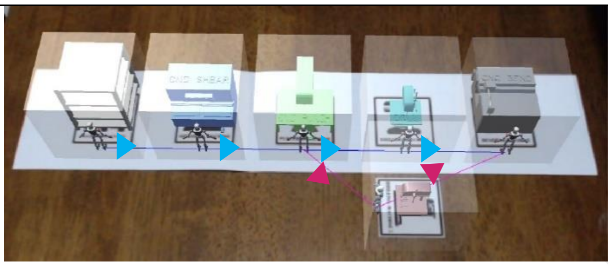
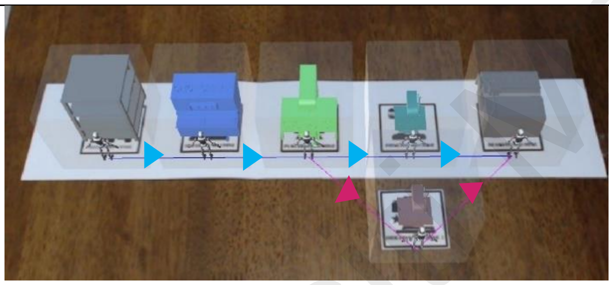
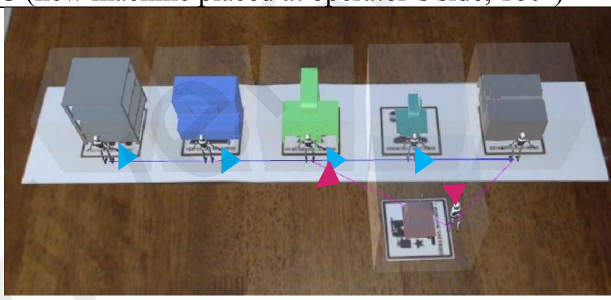
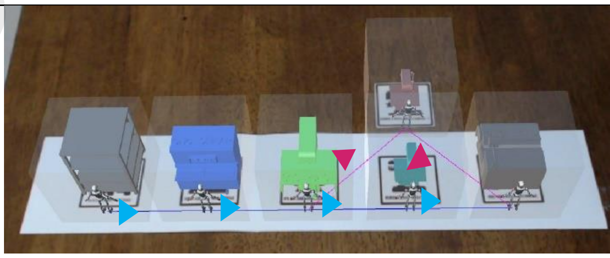
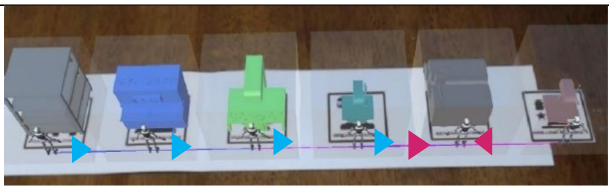
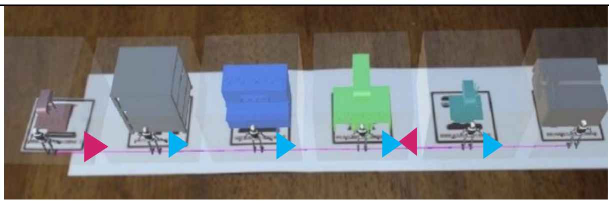
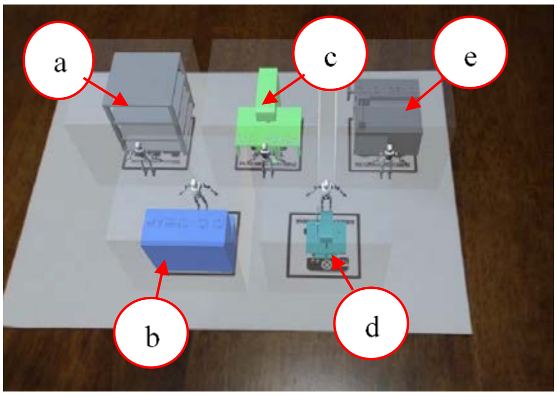
| | | | |
|---|---|---|---|
| 2 |  <u>**LA**</u> **(new machine placed at operator's side, 0°)** | **6.57** | **5.7** |
| 3 |  LB (new machine placed at operator's side, 90°) | 6.89 | 5.7 |
| 4 |  LC (new machine placed at operator's side, 180°) | 7.16 | 5.7 |
| 5 |  LD (new machine placed at operator's side, 270°) | 6.90 | 5.7 |
| 6 |  LE (new machine placed at machines' side) | 7.19 | 5.7 |

**Table 4.1: Straight line layout study data (continued)**

| | | | |
|---|---|---|---|
| 7 |  LF (new machine placed at beside the last machine) | 8.05 | 3.3 |
| 8 |  LG (new machine placed at beside the first machine) | 11.33 | 3.3 |

### 4.2.2 W-shaped layout study

The material in the 5 machines W-shaped layout (Figure 4.3) has to travel 3.62 m. This layout requires a total operation area of 3.5 $m^2$. The new drilling machine can be placed at the right, left, top and bottom side of the W-shaped layout. The total area occupied will increase when a new drilling machine is added. The best new drilling machine's location suggested is layout WE, where the new drilling machine is located at the right side of the layout and the operator is placed to face the right side of the layout. For the products that produced by new drilling machine in layout WE, the total material travel distance is 4.23 m, which is the shortest among the new layouts suggested. It has a total of 4.6 $m^2$ operation area. Layout WE have an increment of the material travel distance of 0.61 m and 14.3% of the area occupied compared to W0. WA, WC, WF and WG are having the same operation area as WE but longer material travel distance. Layout WB and WD have larger area occupied ($A_{WB}$ = 5.2 m & $A_{WD}$ = 5.4 m) and material travel distance compared to layout WE.




| | |
|---|---|
| a | Inventory |
| b | Shearing machine |
| c | CNC punching machine |
| d | Drilling machine |
| e | Bending machine |

**Figure 4.3: W-shaped layout**

**Table 4.2: W-shaped layout study data**

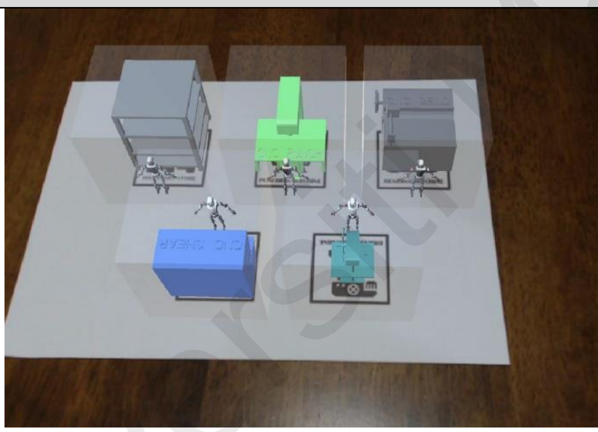
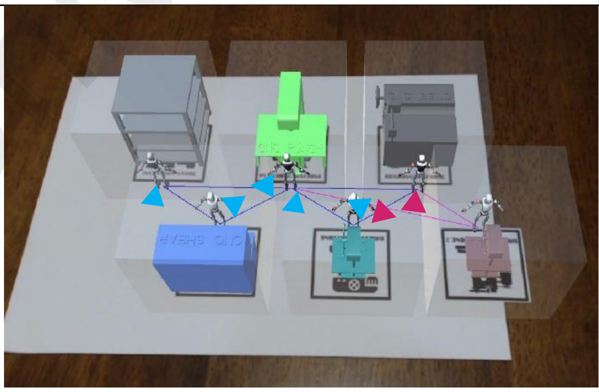
| No | AR Layout | Material Travel Distance (m) | Area ($m^2$) |
|---|---|---|---|
| 1 |  W0 (original W-shaped layout), no new machine | 3.62 | 3.5 |
| 2 |  WA (new machine placed at the right side of the layout) | 4.32 | 4.6 |

**Table 4.2: W-shaped layout study data (continued)**

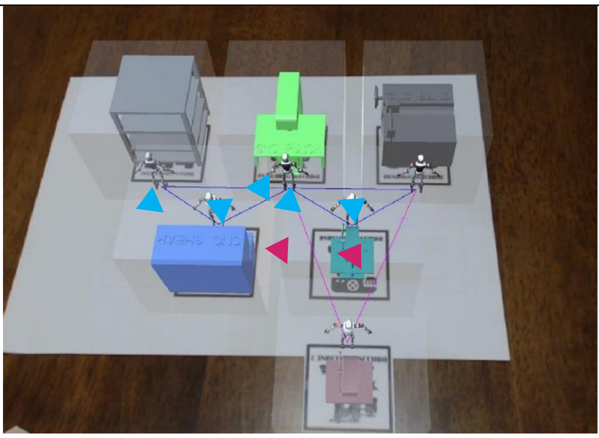
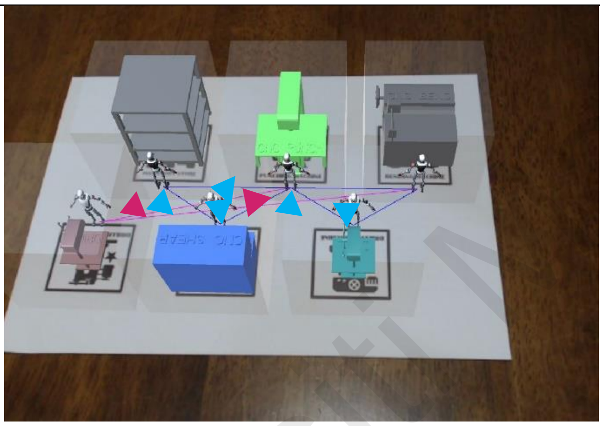
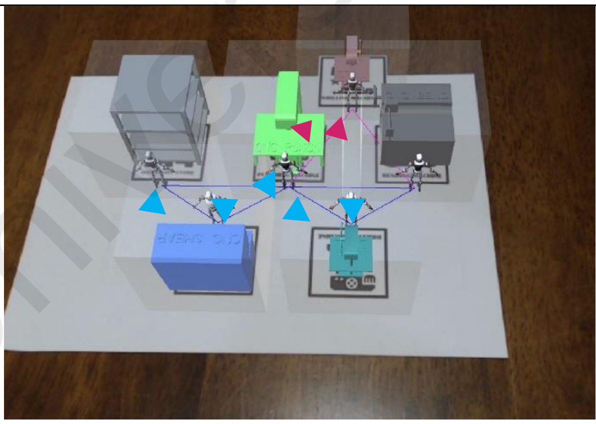
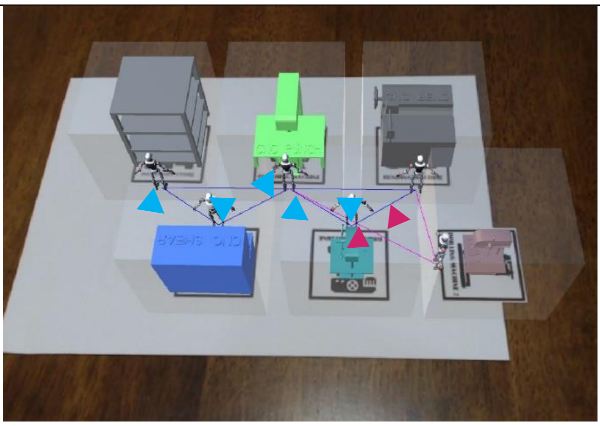
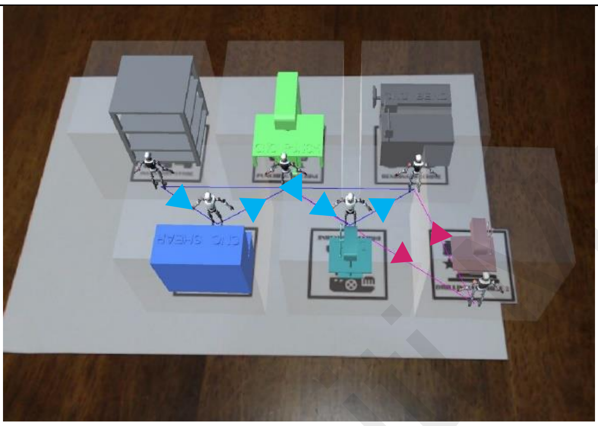
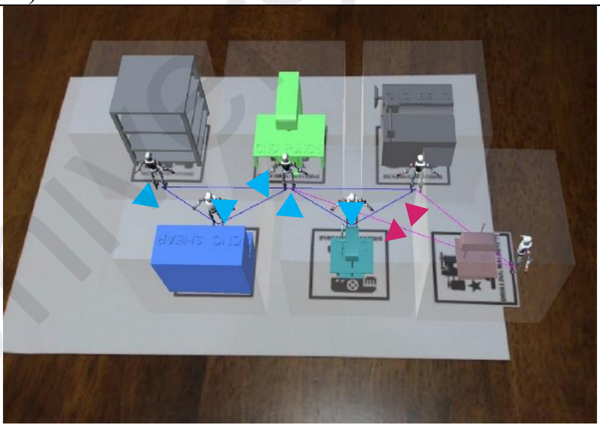
| | | | |
|---|---|---|---|
| 3 |  WB (new machine placed at the bottom side of the layout) | 4.82 | 5.4 |
| 4 |  WC (new machine placed at the left side of the layout) | 5.94 | 4.6 |
| 5 |  WD (new machine placed at the top side of the layout) | 4.60 | 5.4 |

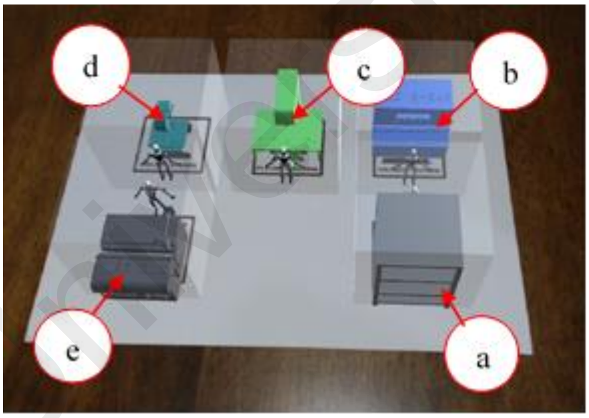
**Table 4.2: W-shaped layout study data (continued)**

| | | | |
|---|---|---|---|
| 6 |  **WE (new machine placed at the right side of the layout, 90°)** | **4.23** | **4.6** |
| 7 |  WF (new machine placed at the right side of the layout, 180°) | 4.85 | 4.6 |
| 8 |  WG (new machine placed at the right side of the layout, 270°) | 4.91 | 4.6 |

### 4.2.3 U-shaped layout study

U-shaped layout (U0) has total material travel distance 3.78 m and layout area 3.4 $m^2$. The best layout is achieved at layout UA, where the new drilling machine is placed in between inventory and bending machine (bottom side of the layout). Layout UA has total material travel distance 3.76 m, which is 0.02 m shorter compared to the original layout. The area occupied is the same as U0, since the new drilling machine is slotted in between the machines in the original layout. When the new drilling machine is placed at layout UB, UC and UD, the material travel distance is longer compared to UA. The area occupied is as well larger since the new drilling machine is placed out of the original layout. UE, UF and UG have the same area occupied as UA but somehow the material travel distance for UE, UF and UF are longer. Figure 4.4 shows the U-shaped layout production line pattern while Table 4.3 shows the distance and area data recorded for every possible arrangement.






| | |
|---|---|
| a | Inventory |
| b | Shearing machine |
| c | CNC punching machine |
| d | Drilling machine |
| e | Bending machine |

**Figure 4.4: U-shaped layout**

**Table 4.3: U-shaped layout study data**

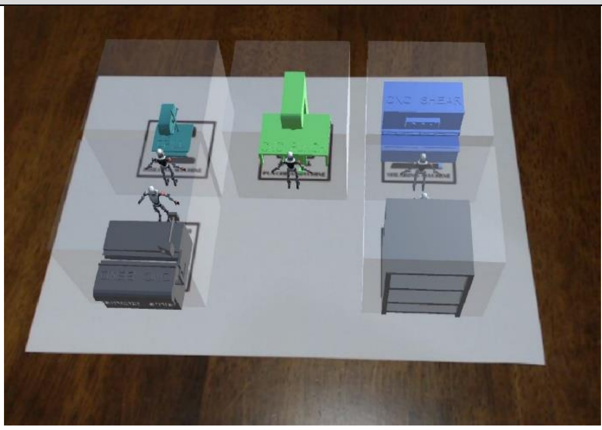
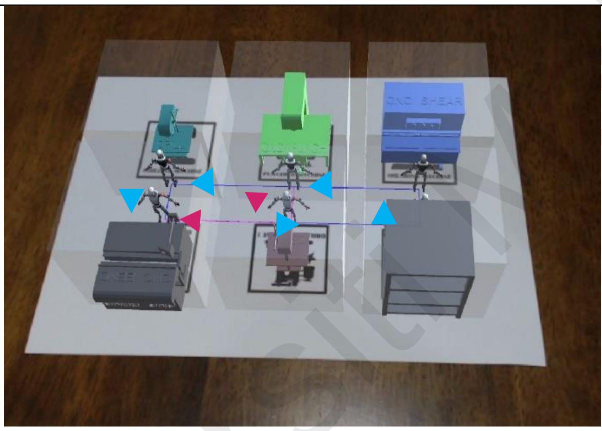
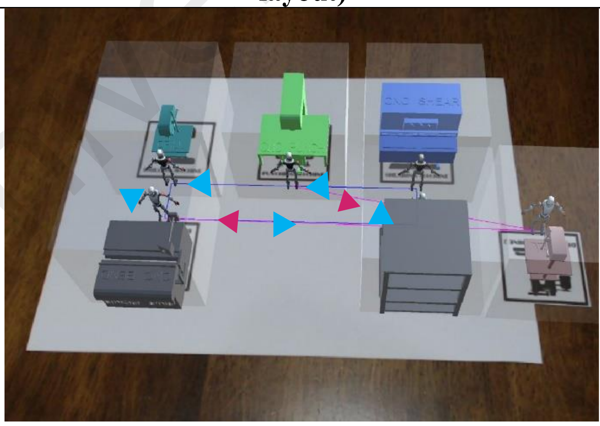
| No | AR Layout | Material Travel Distance (m) | Area ($m^2$) |
|---|---|---|---|
| 1 | <br>U0 (original U-shape layout), no new machine | 3.78 | 3.4 |
| 2 | <br>**UA (new machine placed at the bottom side of the layout)** | **3.76** | **3.4** |
| 3 | <br>UB (new machine placed at the right side of the layout) | 6.61 | 4.4 |

**Table 4.3: U-shaped layout study data (continued)**

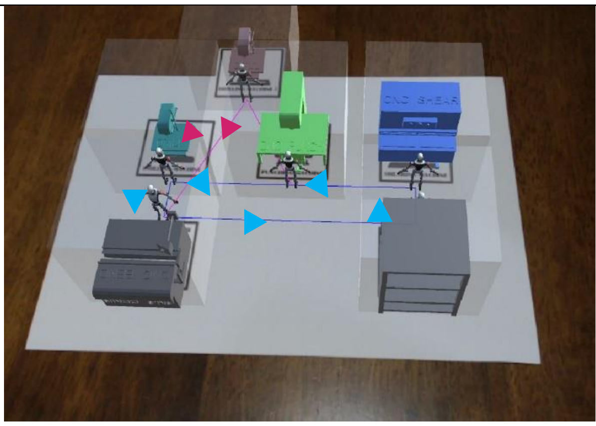
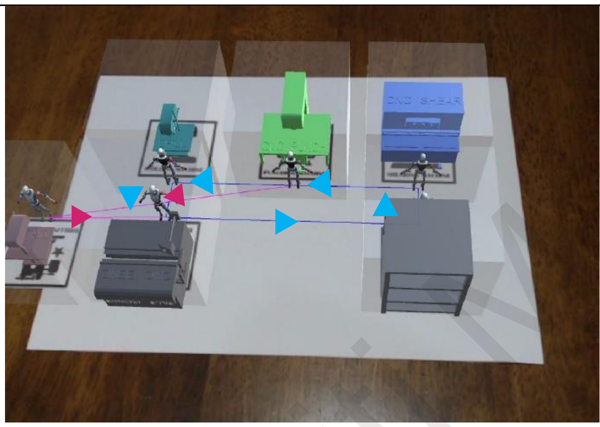
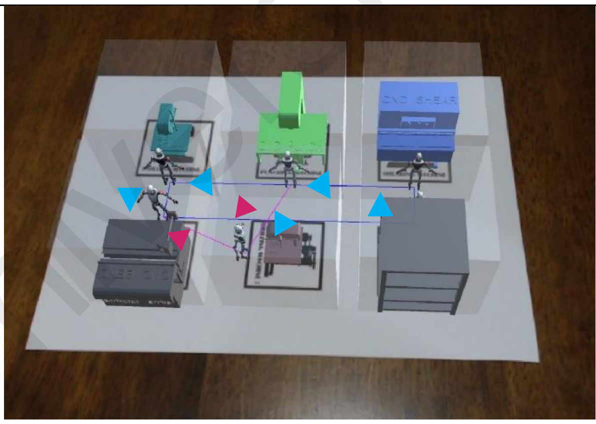
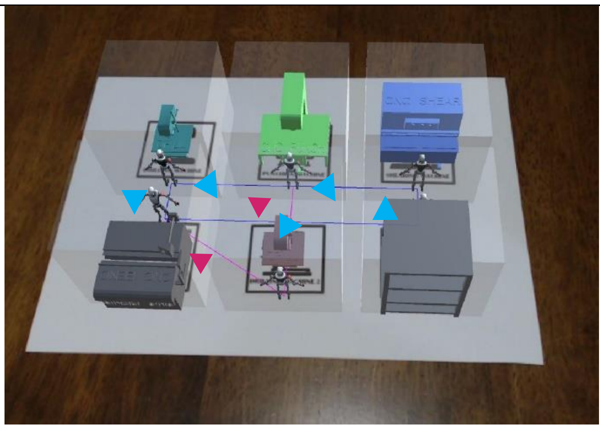
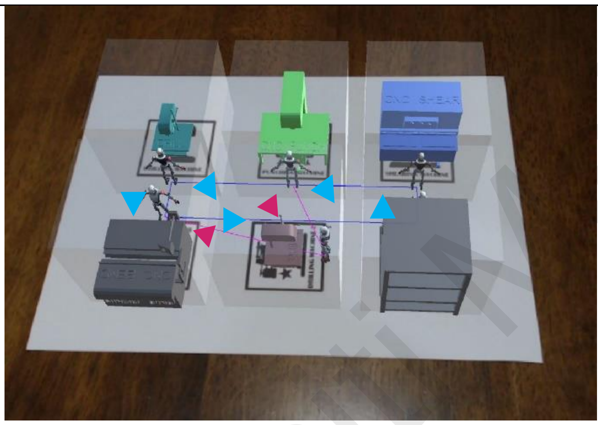
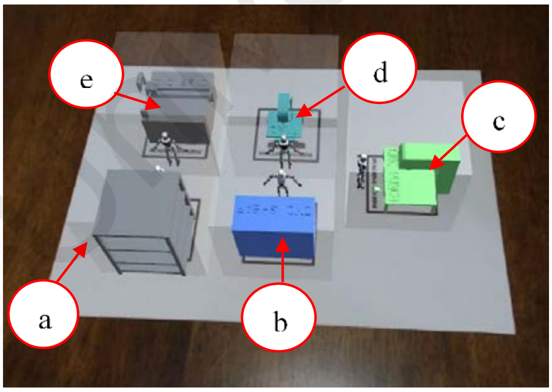
| | | | |
|---|---|---|---|
| 4 |  UC (new machine placed at the top side of the layout) | 5.07 | 5.3 |
| 5 |  UD (new machine placed at the left side of the layout) | 4.65 | 4.5 |
| 6 |  UE (new machine placed at the bottom side of the layout, 90°) | 3.86 | 3.4 |

**Table 4.3: U-shaped layout study data (continued)**

| | | | |
|---|---|---|---|
| 7 |  UF (new machine placed at the bottom side of the layout, 180°) | 4.41 | 3.4 |
| 8 |  UG (new machine placed at the bottom side of the layout, 270°) | 4.34 | 3.4 |

### 4.2.4 V-shaped layout study

Original V-shaped layout has total material travel distance 2.98 m and occupied 3.4 $m^2$ of the total layout area. The data shows the shortest material travel distance (3.82 m) is achieved at layout VC where the new drilling machine is placed at the top part of the existing drilling machine. But layout VC has occupied 5.3 $m^2$ area, which is 1.9 $m^2$ larger than original layout V0. Hence, VC is not the best new layout. Layout VG is the best new layouts, where the new drilling machine is placed at the left side of CNC punching machine. The operator of the new drilling machine is standing facing the same direction as the existing drilling machine operator for layout VG. Layout VG has a material travel distance of 3.91 m while layout VB's material travel distance is recorded at 3.92 m. Layout VA and VF, with the new drilling machine, are placed at the right side of the CNC punching machine are having longer material travel distance compared to layout VG. Layout VA, layout VB, layout VF and layout VG have occupied the same total area of 4.4 $m^2$. Layout VC, VD and VE have longer material travel distance and larger space as compared to layout VG. Figure 4.5 illustrates the V-shaped layout arrangement. Table 4.4 shows the V-shaped layout data on material travelled distance and area occupied.




| | |
|---|---|
| a | Inventory |
| b | Shearing machine |
| c | CNC punching machine |
| d | Drilling machine |
| e | Bending machine |

**Figure 4.5: V-shaped layout**

**Table 4.4: V-shaped layout study data**

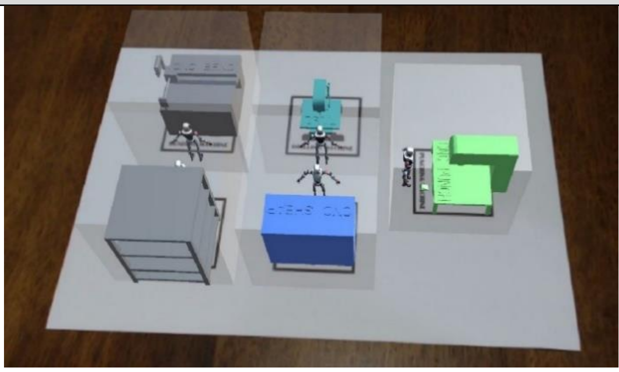
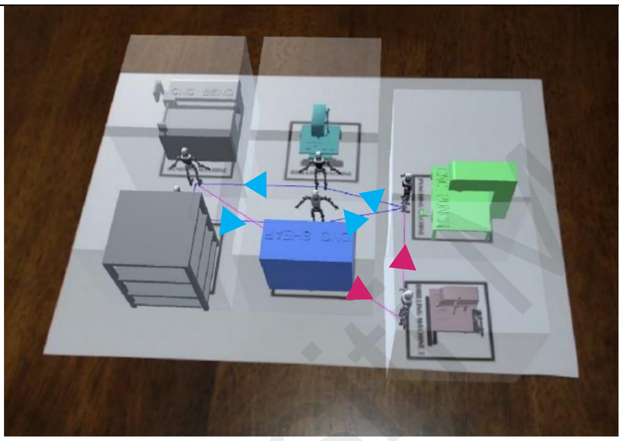
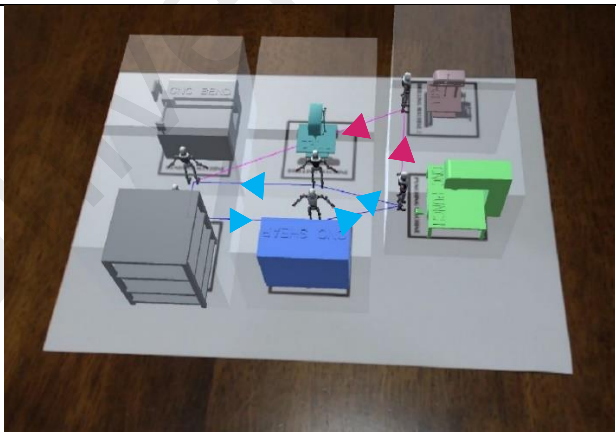
| No | AR Layout | Material Travel Distance (m) | Area ($m^2$) |
|---|---|---|---|
| 1 |  V0 (original V-shaped layout), no new machine | 2.98 | 3.4 |
| 2 |  VA (new machine placed at the right side of CNC punching machine, 90°) | 3.99 | 4.4 |
| **3** |  VB (new machine placed at the left side of CNC punching machine, 90°) | 3.92 | 4.4 |

**Table 4.4: V-shaped layout study data (continued)**

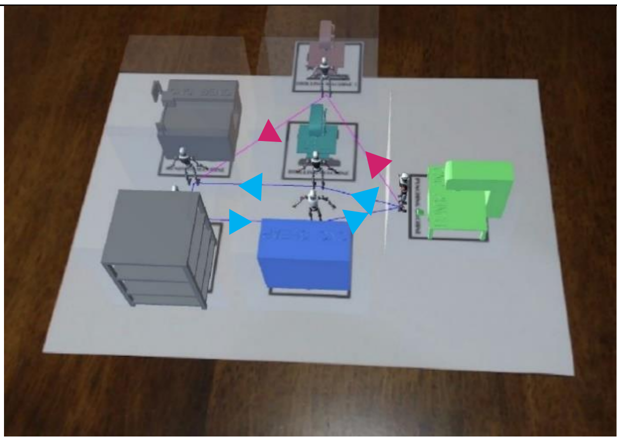
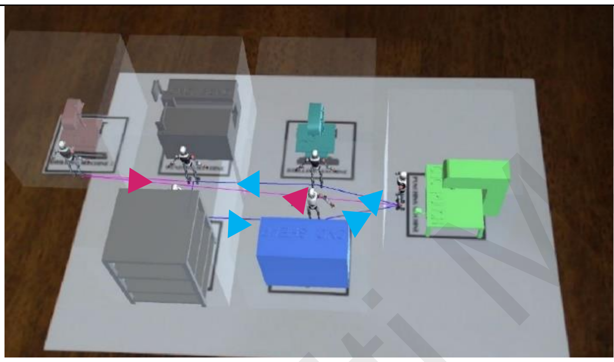
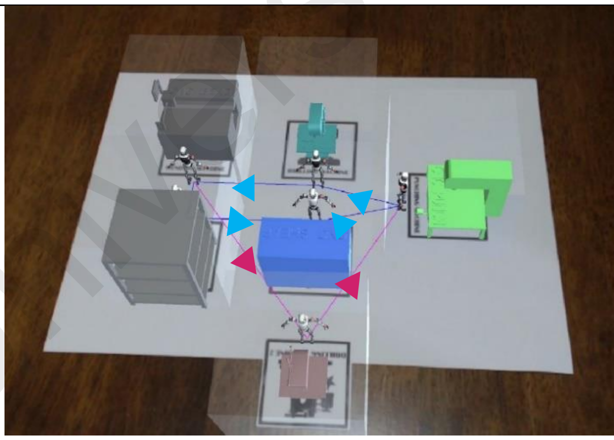
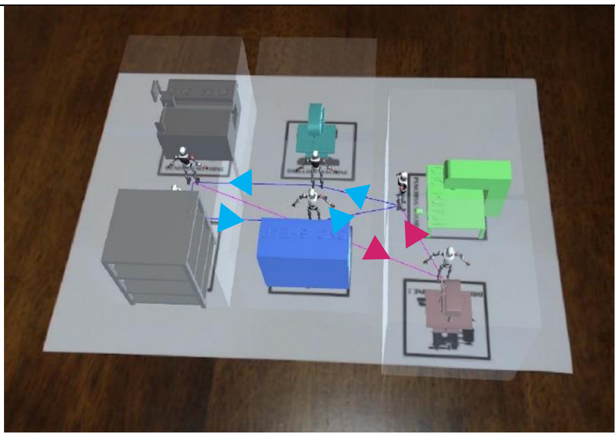
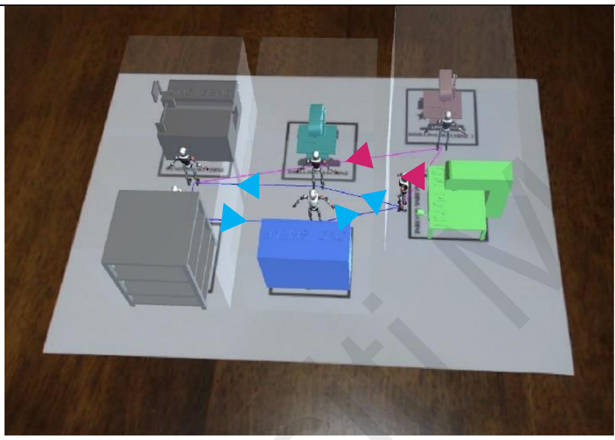
| | | | |
|---|---|---|---|
| 4 |  VC (new machine placed at the top side of the layout) | **3.82** | 5.3 |
| 5 |  VD (new machine placed at the left side of the layout) | 4.54 | 4.7 |
| 6 |  VE (new machine placed at the bottom side of the layout) | 3.98 | 5.3 |

**Table 4.4: V-shaped layout study data (continued)**

| | | | |
|---|---|---|---|
| 7 |  VF (new machine placed at the right side of CNC punching machine, 180°) | 3.98 | 4.4 |
| 8 |  **VG (new machine placed at the left side of CNC punching machine, 0°)** | 3.91 | **4.4** |

## 4.3 Case study-2

Case study-2 was conducted to prove the concept used in Module 2. A composite layup cleanroom was chosen as the FLP study. The tooling tables in the cleanroom are independent of the other facilities. All the tooling tables are doing the same process which is a composite layup. The tools must be nicely arranged in the cleanroom with sufficient clearance for machines or operators to move in that area. To digitize the environment, a green wireframe plane to represent the floor needs to be initiated. Four invisible walls of the layout are defined on the edge of the floor plane. All the obstacles in the environment, for example, machines or storage shelves in the shopfloor have to be represented with blue wireframe cube or cylinder. This is to allow the program to recognize the facilities. Figure 4.6 shows the AR environment setup of the composite layup cleanroom. The cleanroom is located on the white square area with 3 obstacles in the space (1 cylinder and 2 rectangle boxes). Area available were digitized with green wireframe plane overlaid on top while cylinder and boxes were used to represent the obstacles. Once the AR environment is ready, space optimization algorithm was executed to load the working table in the workspace available. The collision detection method was used to check if there is a collision when the new table is placed in a certain position. Collider that is larger (90cm each side) was placed on the tables for sufficient clearance in between workstation. By taking all the constraint into consideration, Figure 4.7 shows a maximum of 8 tooling tables can be loaded in the cleanroom. User may add or remove the tooling table in the cleanroom as well as to relocate them.

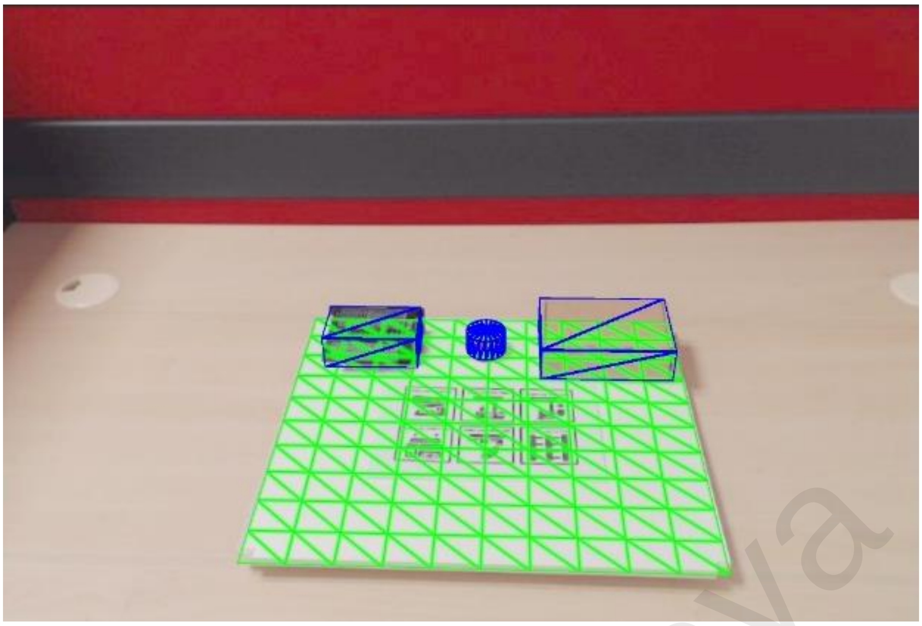


**Figure 4.6: AR Environment setup**

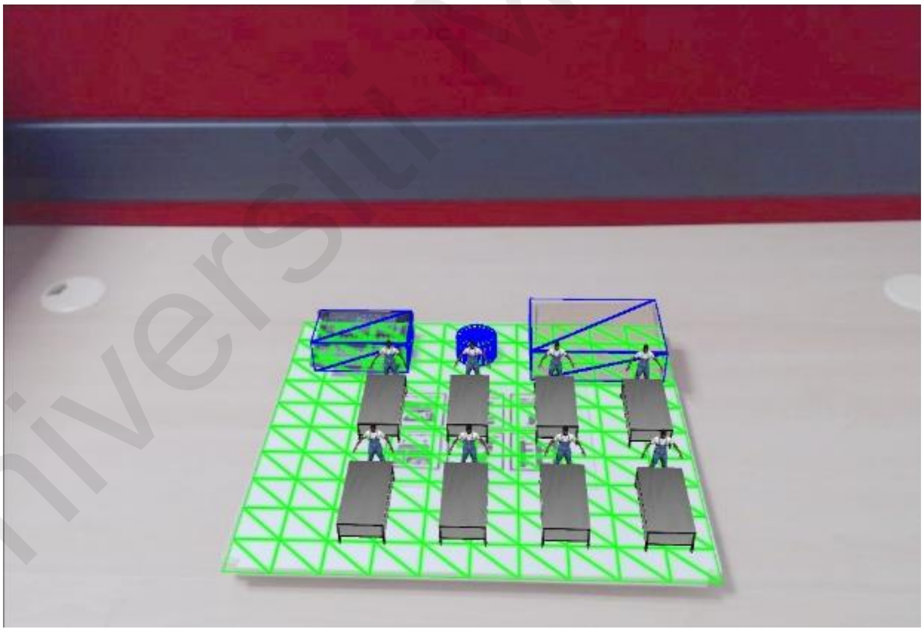


**Figure 4.7: Tooling tables are loaded in the AR environment**

To simulate production schedule using algorithms on the layout plan in the AR environment, LPT, SPT and total cycle time algorithm were used to suggest the production schedule. In real production floor, there were a total of 36 parts produced in this cleanroom. Table 4.5 shows a list of parts and the corresponding process time.

The process was simulated by arranging the production based on the LPT, SPT and total cycle time optimization algorithm. Table 4.6 shows the simulated production schedule based on LPT, Table 4.7 shows the simulation of the SPT production schedule while the total cycle time optimization's simulation is shown in Table 4.8. The simulation results can be shown in real-time in the AR FLP program as shown in Figure 4.8.

In this case, the maximum number of the table that can be fitted in is 8. To produce Product A (part A01 – A20) and Product B (part B01 – B16) with these 8 working tables, minimum 5 cycles of production is required to complete the production.

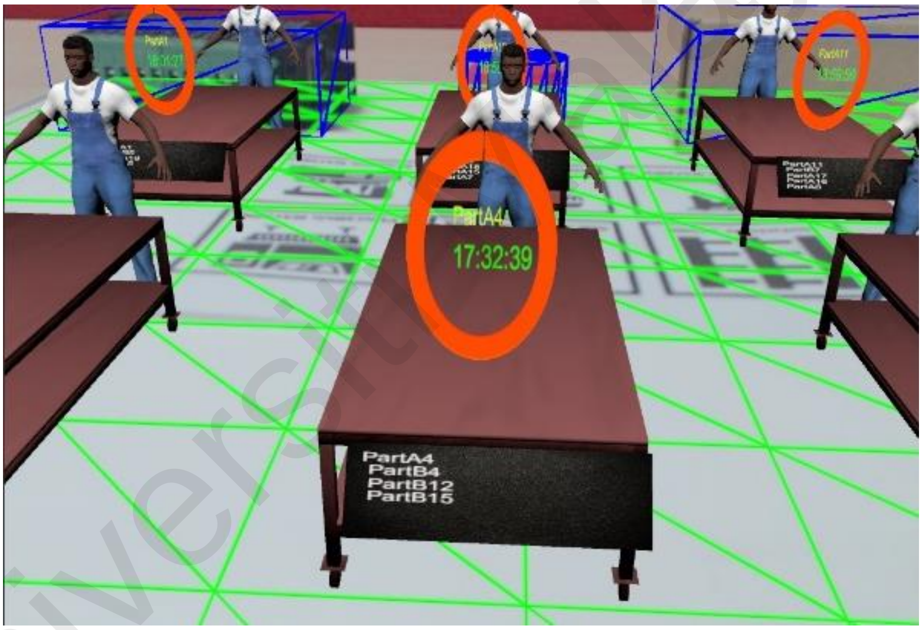



**Figure 4.8: Production schedule simulation result**

**Table 4.5: List of parts with the cycle time**

| Product A | | Product B | |
|---|---|---|---|
| Part | Process time, (h) | Part | Process time, (h) |
| A01 | 18.08 | B01 | 12.43 |
| A02 | 18.08 | B02 | 12.43 |
| A03 | 17.6 | B03 | 12.43 |
| A04 | 17.6 | B04 | 12.43 |
| A05 | 8.38 | B05 | 12.43 |
| A06 | 8.38 | B06 | 12.43 |
| A07 | 7.81 | B07 | 12.43 |
| A08 | 7.81 | B08 | 12.43 |
| A09 | 17.28 | B09 | 12.43 |
| A10 | 17.28 | B10 | 12.43 |
| A11 | 19.05 | B11 | 12.43 |
| A12 | 19.05 | B12 | 12.43 |
| A13 | 7.01 | B13 | 8.72 |
| A14 | 7.01 | B14 | 8.72 |
| A15 | 9.19 | B15 | 8.72 |
| A16 | 9.19 | B16 | 8.72 |
| A17 | 9.36 | | |
| A18 | 9.36 | | |
| A19 | 12.23 | | |
| A20 | 12.23 | | |

**Table 4.6: Simulation result of LPT product prioritized**

| Workstation no: | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | | Cycle 5 | | Total Cycle Time (h) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Part | Time (h) | Part | Time (h) | Part | Time (h) | Part | Time (h) | Part | Time (h) | |
| Workstation 1 | A11 | 19.05 | B07 | 12.43 | A17 | 9.36 | A16 | 9.19 | A08 | 7.81 | 57.84 |
| Workstation 2 | A12 | 19.05 | B08 | 12.43 | A18 | 9.36 | A15 | 9.19 | A07 | 7.81 | 57.84 |
| Workstation 3 | A01 | 18.08 | B05 | 12.43 | A19 | 12.23 | A05 | 8.38 | - | - | 51.12 |
| Workstation 4 | A02 | 18.08 | B06 | 12.43 | A20 | 12.23 | A06 | 8.38 | - | - | 51.12 |
| Workstation 5 | A03 | 17.6 | B03 | 12.43 | B11 | 12.43 | B16 | 8.72 | - | - | 51.18 |
| Workstation 6 | A04 | 17.6 | B04 | 12.43 | B12 | 12.43 | B15 | 8.72 | - | - | 51.18 |
| Workstation 7 | A09 | 17.28 | B01 | 12.43 | B09 | 12.43 | B13 | 8.72 | A13 | 7.01 | 57.87 |
| Workstation 8 | A10 | 17.28 | B02 | 12.43 | B10 | 12.43 | B14 | 8.72 | A14 | 7.01 | 57.87 |
| | | | | | | | Max - Min (cycle time) | | | | 6.75 |

**Table 4.7: Simulation result with SPT product prioritized**

| Workstation no: | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | | Cycle 5 | | Total Cycle Time (h) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Part | Time (h) | Part | Time (h) | Part | Time (h) | Part | Time (h) | Part | Time (h) | |
| Workstation 1 | A13 | 7.01 | B16 | 8.72 | B02 | 12.43 | B10 | 12.43 | A02 | 18.08 | 58.67 |
| Workstation 2 | A14 | 7.01 | B15 | 8.72 | B01 | 12.43 | B09 | 12.43 | A01 | 18.08 | 58.67 |
| Workstation 3 | A07 | 7.81 | A16 | 9.19 | B04 | 12.43 | B12 | 12.43 | A12 | 19.05 | 60.91 |
| Workstation 4 | A08 | 7.81 | A15 | 9.19 | B03 | 12.43 | B11 | 12.43 | A11 | 19.05 | 60.91 |
| Workstation 5 | A05 | 8.38 | A18 | 9.36 | B06 | 12.43 | A10 | 17.28 | - | - | 47.45 |
| Workstation 6 | A06 | 8.38 | A17 | 9.36 | B05 | 12.43 | A09 | 17.28 | - | - | 47.45 |
| Workstation 7 | B13 | 8.72 | A20 | 12.23 | B08 | 12.43 | A04 | 17.6 | - | - | 50.98 |
| Workstation 8 | B14 | 8.72 | A19 | 12.23 | B07 | 12.43 | A03 | 17.6 | - | - | 50.98 |
| | | | | | | | Max - Min (cycle time) | | | | 13.46 |

**Table 4.8: Simulation result with workstations' total cycle time optimized**

| Workstation no: | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | | Cycle 5 | | Cycle 6 | | Total Cycle Time (h) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Part | Time (h) | Part | Time (h) | Part | Time (h) | Part | Time (h) | Part | Time (h) | Part | Time (h) | |
| Workstation 1 | A11 | 19.05 | A01 | 18.08 | A17 | 9.36 | A08 | 7.81 | - | - | - | - | 54.3 |
| Workstation 2 | A12 | 19.05 | A02 | 18.08 | A18 | 9.36 | A07 | 7.81 | - | - | - | - | 54.3 |
| Workstation 3 | A09 | 17.28 | B05 | 12.43 | B09 | 12.43 | B07 | 12.43 | - | - | - | - | 54.57 |
| Workstation 4 | A10 | 17.28 | B06 | 12.43 | B10 | 12.43 | B08 | 12.43 | - | - | - | - | 54.57 |
| Workstation 5 | A03 | 17.6 | B03 | 12.43 | B11 | 12.43 | A19 | 12.23 | - | - | - | - | 54.69 |
| Workstation 6 | A04 | 17.6 | B04 | 12.43 | B12 | 12.43 | A20 | 12.23 | - | - | - | - | 54.69 |
| Workstation 7 | B01 | 12.43 | A16 | 9.19 | B13 | 8.72 | B16 | 8.72 | A05 | 8.38 | A13 | 7.01 | 54.45 |
| Workstation 8 | B02 | 12.43 | A15 | 9.19 | B14 | 8.72 | B15 | 8.72 | A06 | 8.38 | A14 | 7.01 | 54.45 |
| | | | | | | | | | Max - Min (cycle time) | | | | 0.39 |

In this particular case, it is clear that by arranging the production schedule with an optimized total cycle time has a better result, where the shortest total production time (54.69 hours) is achieved. The difference between workstation with maximum cycle time and workstation with minimum cycle time is the least (0.39 hours or 23.4 minutes). When we arrange the production order with LPT product prioritized, the total production time is 57.87 hours while the fastest workstations have 6.75 hours earlier to complete the production. If we arrange the production schedule with SPT as priority consideration, the total production time is the longest among these 3 methods. It requires 60.91 hours to complete the production. The production time difference between fastest and slowest workstations is 13.46 hours.

## 4.4 Case study-3

An office with 5 workstations was chosen for the case study for Module-3's verification. The best location for the printer which is shared among all the workstations is identified using the CoG algorithm. Cubes are used to digitize the office environment with assigned weightage to present the usage of the printer of a particular workstation. High weightage's workstation has used the printer more than the low weightage workstation. CoG of the workstations distributed is the best location for the printer. The total distance between the shared printer and the workstations can be calculated in this AR facility planning system. Figure 4.9 shows the AR environment of an office with 5 workstations. The black dot is the origin of the AR environment where the red arrow represents the x-axis and the green axis is the y-axis. Green wireframe plane represents the available space for the office layout design while blue wireframe cubes were built to overlap on top of the workstation for representation.

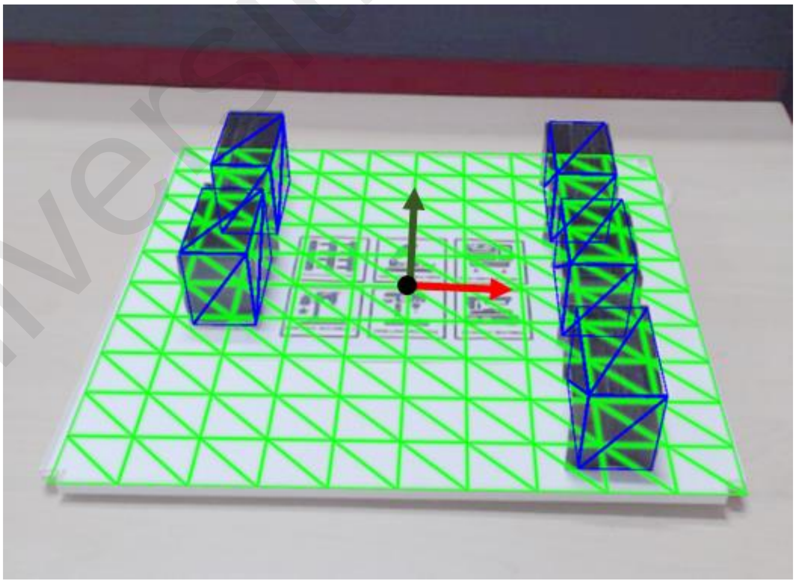


**Figure 4.9: AR environment of an office with 5 workstations**

For case 1, the system is tested with all the workstation is assumed to have equal usage of the printer (weightage = 1 for all workstation). The best location for the printer is found at x = 0.212 m, y = 0.068 m from the origin of the layout, the centre of the floor plan. Figure 4.10 shows the yellow printer located on the centre of gravity of the 5 workstations, labelled as Location-A. The printer is located nearest to W2 (0.825 m), followed by W1 (1.057 m), W4 (1.219 m), W3 (1.363 m) and finally W5 (1.406 m). The centre of gravity of the facilities is located near to the area where workstation W1, W2 and W3 is located. Table 4.9 lists out the location of workstations and printer for case 1 as well as the distance from printer to each workstation.

**Table 4.9: Location of workstations and printer for case 1**

| Workstation | X position | Y position | weightage |
|---|---|---|---|
| W1 | 1.02 | 0.75 | 1 |
| W2 | 1.02 | -0.10 | 1 |
| W3 | 1.02 | -1.03 | 1 |
| W4 | -1.00 | -0.06 | 1 |
| W5 | -1.00 | 0.78 | 1 |
| Printer | 0.212 | 0.068 | - |

| | Distance (m) |
|---|---|
| Printer to W1 | 1.057 |
| Printer to W2 | 0.825 |
| Printer to W3 | 1.363 |
| Printer to W4 | 1.219 |
| Printer to W5 | 1.406 |

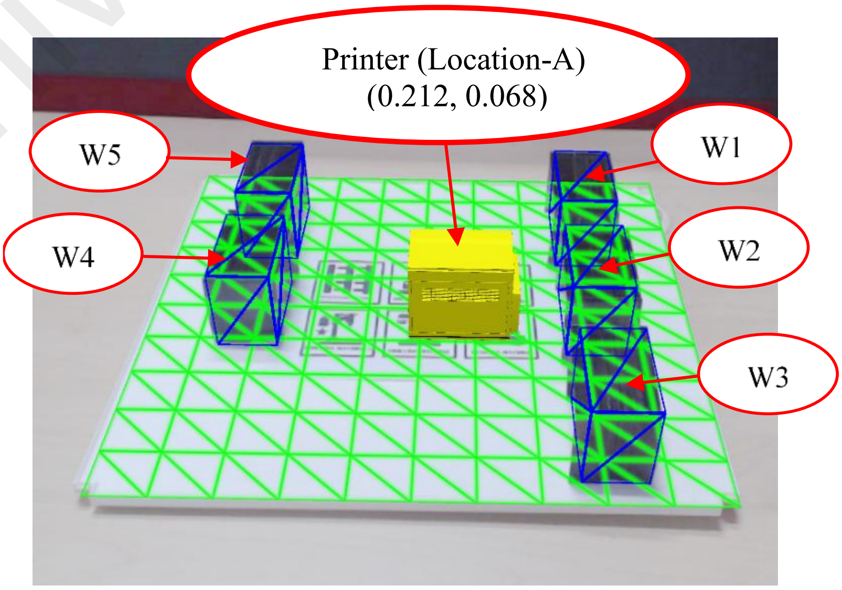



**Figure 4.10: Suggested location of the printer in case 1**

In the case 2, to consider cases where the printer is not allowed to locate at the suggested place, for instant electrical power point cannot be added at the suggested place or safety concern where space should be cleared in order to fulfil safety regulations. The users can move the printer to other places. For example (see figure 4.11), the printer is moved to the Location-B (x = -0.877, y = -0.853). Table 4.10 shows the distance between each workstation to the printer at Location-B. The maximum distance is 2.484m (Printer to W1) and the shortest distance is 0.802m (Printer to W4).

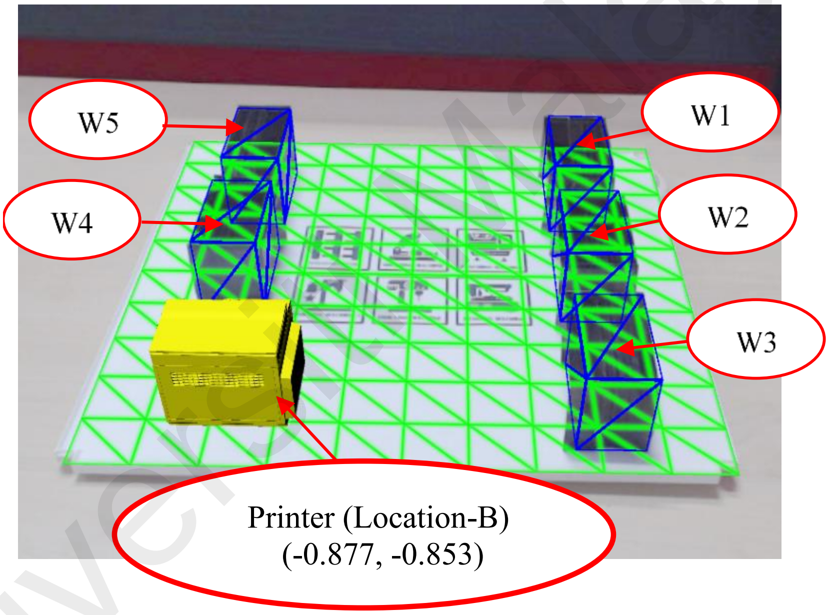



**Figure 4.11: User defined mode to locate the printer**

**Table 4.10: Location of workstations and printer for case 2**

| Workstation | X position | Y position | weightage |
|---|---|---|---|
| W1 | 1.02 | 0.75 | 1 |
| W2 | 1.02 | -0.10 | 1 |
| W3 | 1.02 | -1.03 | 1 |
| W4 | -1.00 | -0.06 | 1 |
| W5 | -1.00 | 0.78 | 1 |
| Printer | -0.877 | -0.853 | - |

| | Distance (m) |
|---|---|
| Printer to W1 | 2.484 |
| Printer to W2 | 2.041 |
| Printer to W3 | 1.905 |
| Printer to W4 | 0.802 |
| Printer to W5 | 1.638 |



Case 3 is to consider the weightage of the workstation 5 which has more usage of the printer (weightage = 5). This is the case where workstation 5's owner is a clerk, who uses the printer more frequently (5 times more than the rest of the staffs in the office). The best location is suggested at Location-C, x = -0.327 m and y = 0.384 m from the origin of the layout, the centre of the floor plan. Figure 4.12 shows the location of the shared printer on the centre of gravity of the 5 workstations. The distance between workstation 5 and printer is shorter compared to case 1. Workstation W5 is the nearest to the printer in this case, which is 0.781 m. The next nearest workstation to the printer is W4 (0.806 m), followed by W1 (1.396 m), W2 (1.431 m) and finally W1 (1.953 m). The centre of gravity of facilities in case 3 falls nearer to workstation W4 and W5, where W5 uses printer most among the colleagues. Table 4.11 lists out the location of workstations and printer as well as the distance of printer to each workstation.

**Table 4.11: Location of workstations and printer for case 3**

| Workstation | X position | Y position | weightage |
|---|---|---|---|
| W1 | 1.02 | 0.75 | 1 |
| W2 | 1.02 | -0.10 | 1 |
| W3 | 1.02 | -1.03 | 1 |
| W4 | -1.00 | -0.06 | 1 |
| W5 | -1.00 | 0.78 | 5 |
| Printer | -0.327 | 0.384 | - |

| | Distance (m) |
|---|---|
| Printer to W1 | 1.396 |
| Printer to W2 | 1.431 |
| Printer to W3 | 1.953 |
| Printer to W4 | 0.806 |
| Printer to W5 | 0.781 |

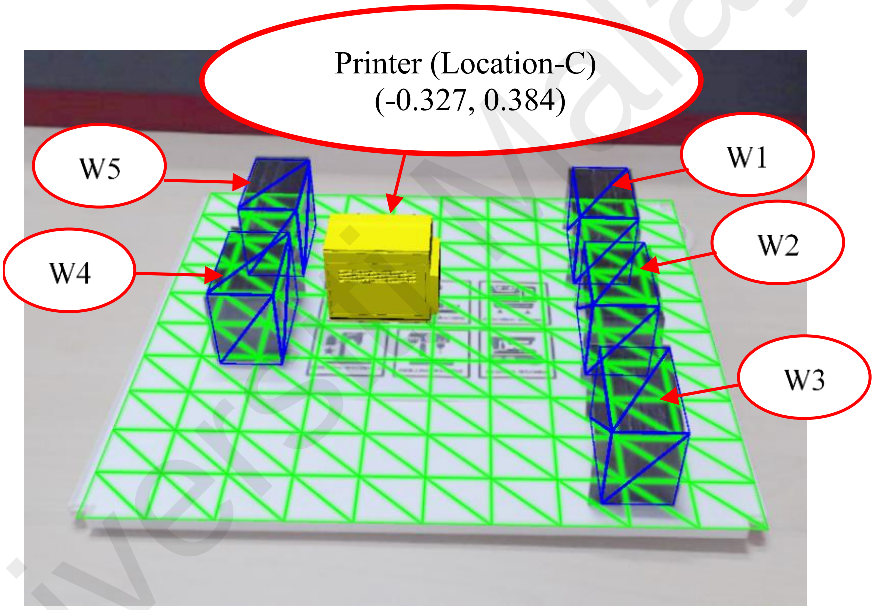



**Figure 4.12: The suggested location of the printer in case 3**

By enabling the collision detection method, the suggested shared facility location will be shifted to the nearest possible place next to the centre of gravity of the facility layout system if the suggested location is occupied. By enabling user-defined mode, the user is allowed to move the virtual objects according to their judgement. Data like the distance between facilities, area occupied will be used to judge if the layout is good or bad.

## 4.5 Case study-4

A loop-layout robotic cell placed in Computer Integrated Manufacturing (CIM) Lab, University of Malaya is chosen for the demonstration of Module 4. The original setting of the robotic cell is as shown in Figure 4.13, which the system has two CNC machines and a robotic arm placed at the centre of the robotic cell. The CNC milling machine is denoted as M1, the CNC lathe machine is denoted as M2 and the robotic arm is denoted as R. The layout has flexibility arrangement three dummy machines (denoted as M3, M4 and M5) can be placed around the conveyor for the additional process done by workers. For production, the goods will feed in from the input station, go through three machining process. First and third machining process must be done by either M3, M4 or M5 while the second process can be done by either M1 or M2 only. The goods will finally leave the layout at the output station after gone through the three processes. The robotic arm serves as the feeder of the system to bring goods from one station to another station. There were few assumptions made in this closed loop-layout robotic work cell.

1. The robot can hold only one part per time
2. One machine is involved in the single manufacturing process
3. One machine can handle only one part at a time
4. Parts produced must go through three processes (first and third processes must be done by M3, M4 or M5, the second process can only be done by M1 or M2)
5. No buffer for intermediate storage between processes within the cell
6. Only one input station and one output station, parts cannot enter or leave the loop-layout from anywhere other than input or output station.

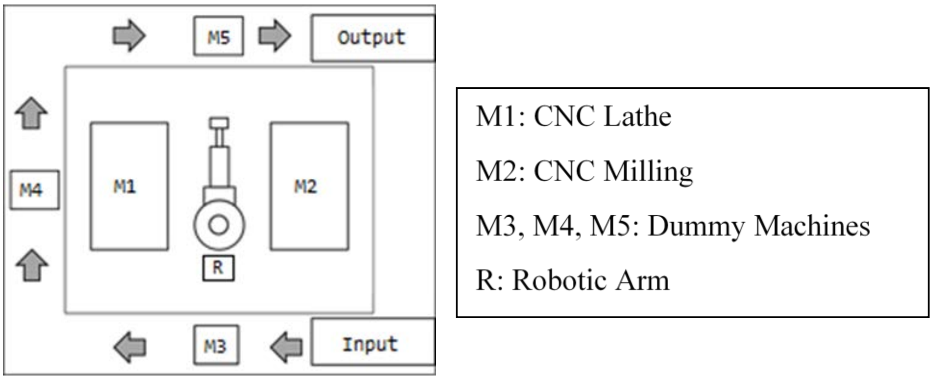



**Figure 4.13: Robotic cell layout (top view)**

To conclude the above-mentioned constraints and limitations, the AR-based FLP system should be able to capture the full scene of the conveyor system (real world) and a marker should be placed on top of the conveyor system as the reference point of the system. The system should have pre-saved 1:1 scaled 3D model on the CNC milling machine (M1), CNC lathe machine (M2) and the robotic arm. Cubes will be used to represent the dummy machines (M3, M4 and M5) as well as the input and output stations. On the programming side, the formula in Section 3.7 was programmed and show on the Unity program in real-time, where the centre of the AR 3D models are recorded and used to calculate the distance between machines and stations. The program is designed in a way where the first, second and third machine can be changed according to the plan. In this case, the possible options for the first machine are three and there will be two options for the third machine (since the first machine has been used). As for the second machine, since the robotic arm is used to handle the parts, the distance for part travelled in case M1 or M2 makes a less significant impact. Thus, it is assumed to be same. Possible solutions for the process planning are six solutions as listed in Table 4.12.

$$P(Process\ Sequence) = P(1st\ machine) \times P(2nd\ machine) \times P(3rd\ machine)$$

where,

P(1st machine) = 3, three dummy machines can be selected

P(2nd machine) = 1, two possible options, but since the robotic arm is used to handle the part. The difference can be neglected. Thus, the possibility would be 1.

P(3rd machine) = 2, there are two possibilities as the part would not undergo the same process twice. Since one machine has been used in the first process, remain only two options for the third machining process.

$$P(Process\ Sequence) = 3 \times 1 \times 2 = 6$$

**Table 4.12: Possible process sequences**

| No | List of possible part sequences |
|---|---|
| 1 | M3 – M1 – M4 |
| 2 | M4 – M1 – M3 |
| 3 | M3 – M1 – M5 |
| 4 | M5 – M1 – M3 |
| 5 | M4 – M1 – M5 |
| 6 | M5 – M1 – M4 |

Figure 4.14 shows the physical environment of the robotic conveyor cell captured by a camera while Figure 4.15 shows the AR-based FLP environment setup where virtual models are blended into the physical environment. The conveyor system and the working area are real-world objects. While the blue transparent boxes are the digitized version of the conveyor system and green wireframe plane is the digitized version of the floor. The 3D models of the Kuka robotic arm, CNC milling machine (M1), CNC lathe machine (M2) and machines M3, M4 and M5 are added in the AR environment. Red boxes are added to represent the input and output station. AR marker is highlighted in the yellow colour plane in Figure 4.15. The machines' sequences can be set in the inspector window by dragging the machines or stations into the respective sequence column.


**Figure 4.14: Physical laboratory setup**

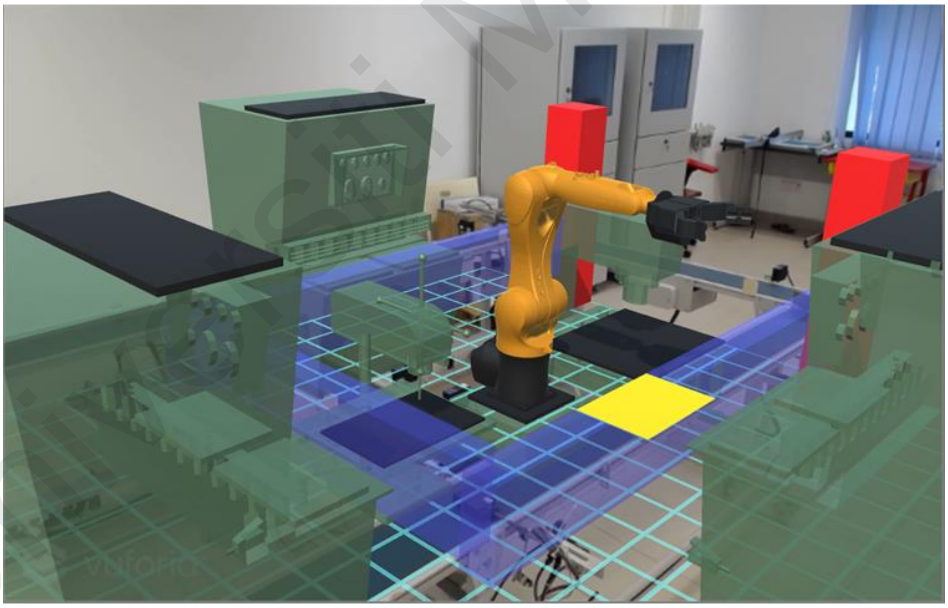


**Figure 4.15: AR-based FLP (physical laboratory setup with virtual models)**

Figure 4.16 shows the AR-based FLP program screenshot. The left panel of the window shows the 3d models library prepared for the AR program, the centre panel is the view captured from the camera with AR features enabled, while the right panel shows the properties of the 3d models as well as the programming scripts. This screenshot shows the distance calculator script written to record distance travelled by the product in the robotic cell where the sequence can be changed.

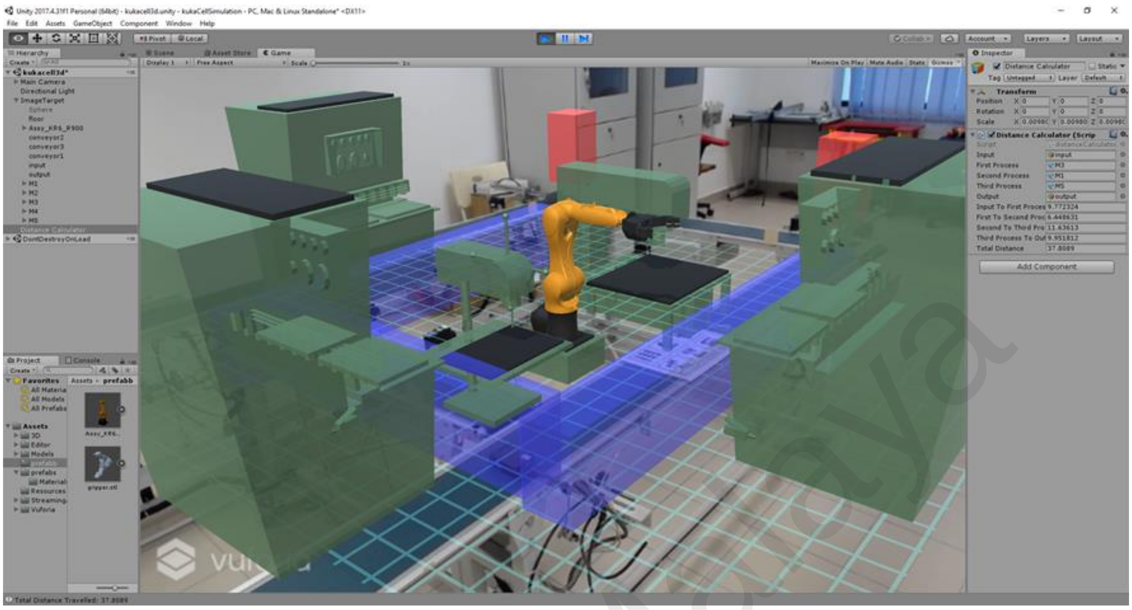
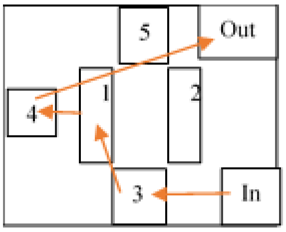
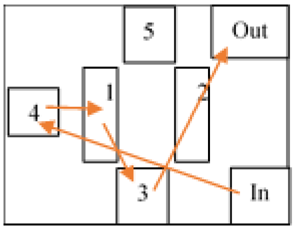
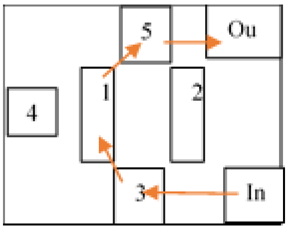
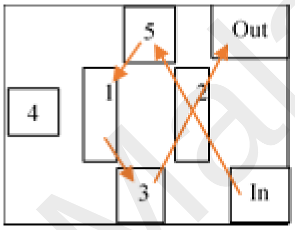
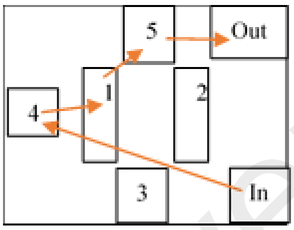
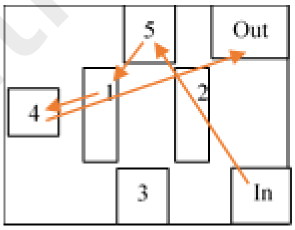


**Figure 4.16: AR-based FLP program interface**

Table 4.13 lists all the possible process to run the production, as well as the total distance, travelled of the part and the comparison. The process of M3-M1-M4 has achieved the shortest material travelled distance (37.5515 virtual unit), followed by M3-M1-M5 (37.8089 virtual unit). While M4-M1-M5 is the third shortest (recorded as 43.0927 virtual unit). The process of M5-M1-M3 has the longest material travelled distance with 51.5880 virtual unit. While M5-M1-M4 is the second-longest (50.3164 virtual unit) and M4-M1-M3 is the third-longest (44.1070 virtual unit). In this case, the virtual unit is equal to 270 mm SI unit.

**Table 4.13: Possible production processes list**

| Part sequence | Distance (virtual unit) | Part sequence | Distance (virtual unit) | Percentage of difference (%) |
|---|---|---|---|---|
| M3 – M1 – M4<br> | 37.5515 | M4 - M1 – M3<br> | 44.1070 | 17.46% |
| M3 – M1 – M5<br> | 37.8089 | M5 – M1 – M3<br> | 51.5880 | 36.44% |
| M4 - M1 – M5<br> | 43.0927 | M5 - M1 – M4<br> | 50.3164 | 16.76% |

## 4.6 Discussion

### 4.6.1 Case study-1

Case study-1 is to locate the new facility to be added in the existing production line. Table 5.1 shows the summary of the 4 types of the layout before and after adding in a new machine at the bottleneck of the air conditioning unit metal casing production line. It shows that the original V-shaped layout has the shortest material travel distance while the original straight-line layout has the smallest working area. When a new drilling machine is added to the existing layout, U-shaped has the shortest material travel distance and smallest working area. The proposed layout UA even has shorter material travel distance compared to the original U-shaped layout (U0). This is because the new drilling machine is able to place in the empty space in the original U-shaped layout. The shorter material travel distance for line 2 in the U-shaped layout shows that original U-shaped is not optimized. To add a new machine in a straight line layout, the area has to increase by almost 100%. There is a large empty space in layout LA. There is the increment of the area occupied in W-shaped and V-shaped layout when a new machine is added. VG layout has the shortest total material travel distance, 6.89 m among the proposed new layouts (LA: 13.05 m, WE: 7.85 m, UA: 7.54 m). If a new drilling machine needs to be added to the 5 stations air-conditioning unit metal casing production, the layout UA is the best layout in term of the smallest area occupied while the layout VG is the best layout in term of shortest material travel distance. The orientation of the machines does affect the performance of the layout. The new machine added should be placed in a way where the location of the operator standing is as close as possible to the other machine. As this will determine the material travelled distance. Since the machine may not be square in shape, the machine orientation will affect the space occupied as well.

**Table 4.14 Summary result of Case study-1**

| | Distance (m) | | | Area ($m^2$) | | |
|---|---|---|---|---|---|---|
| Layout | Original | Proposed | % | Original | Proposed | % |
| Straight line | 6.48 | LA Line 1: 6.48 | + 1.39 | 2.9 | 5.7 | + 96.55 |
| | | LA Line 2: 6.57 | | | | |
| W-shaped | 3.62 | WE Line 1: 3.62 | + 16.85 | 3.5 | 4.6 | + 31.43 |
| | | WE Line 2: 4.23 | | | | |
| U-shaped | 3.78 | UA Line 1: 3.78 | - 0.53 | 3.4 | 3.4 | 0 |
| | | UA Line 2: 3.76 | | | | |
| V-shaped | 2.98 | VG Line 1: 2.98 | + 23.79 | 3.4 | 4.4 | + 29.41 |
| | | VG Line 2: 3.91 | | | | |

### 4.6.2 Case study-2

Case Study-2 uses collision detection method to plan the layout area where machines can be put in place. Floor layout and existing obstacles must be defined at the beginning of simulation with reference to an AR marker on the floor. Planes and simple shapes (eg.: box, sphere, cylinder) are available in the simulation library to define the location and the shape of the existing obstacles. The simulation environment setup is manually by the users. It can be further improved by having a 3D scanner implant in the system instead, to make the system more intelligent. However, it is not necessary if the shopfloor is not so complicated, especially for a new factory layout planning.

The simulation result can be shown in real-time in the AR FLP system. Necessary changes can be done if users would like to modify the facility layout design. Although the result in this case study shows that by arranging the production order based on total cycle time optimization is the best to achieve shortest total production cycle time and shortest time different between slowest and fastest workstations, there is some special case where this method is not applicable. For example, when the production requirement is the longest cycle time product must be delivered to customer-first or when the requirement is to complete the shortest cycle time product first. Therefore, these 3 methods are proposed as optimization options in this research.

### 4.6.3 Case study-3

It is very common to plan the location of shared machines in a layout. For example, to locate a shared printer in an office, to place a packaging machine in a production floor with several production lines, to decide the location of an Automated Ground Vehicle (AGV) charging dock where the AGV moves around dynamically, to locate a shared tooling cabinet in a workshop where foremen keep their tools and etc.

Case Study-3 has demonstrated to suggest the best location of a printer in an office by using CoG algorithm. The printer (shared facility) will be placed nearer to a workstation when the owner of that workstation has more privilege or uses the printer more frequently. Sometimes, the suggested location is not practical. For instance, the location has something that is blocking. The system will be able to notice and suggest the next nearer location. While for the case where that location has no power supply, and the printer has to place at the place where the power supply is located, this system can be used to check the difference of real setup versus the ideal case. The decision can be made easily if the difference is a lot, re-layout should be conducted. While the setup can be maintained if the difference is ignorable.

### 4.6.4 Case study-4

In the case of robotic work cell design, the developed AR-based FLP program can be used to plan the machine process sequence. Similar concept as case study-2 and 3, we need to digitize the shopfloor by placing an AR marker as a reference point of the AR environment. Next, we need to place in the plane to represent the floor as well as boxes or any other shapes to turn the real object into digital data. Any items we would like to add in the shopfloor can be imported into the AR-based FLP program. Similar to case study-2 and 3, the distance calculator script can be used to measure the distance between the machines to check the material travelled distance. The sequence can be changed easily by drag and drop the 3d model from the AR environment into the calculator windows. Do take note that the distance calculated from the x, y and z position of the 3d models. The height of the material handling area of the machine does play a role in this distance measurement. For example, materials will travel a longer distance when a machine is placed at a higher position.

From the Case Study-4, the material travelled distance is shortest when the machines are placed in sequence (M3-M1-M4). If we are judging the layout only from the top view, M3-M1-M5 seems to have a shorter distance. In fact, the height of the machine will affect the material travelled distance. This shows the importance and feasibility of this AR-based FLP system. For comparison purpose, the virtual unit can be used. If the user would like to know the exact distance, it can be calculated easily as well. 1 virtual unit is equal to the width or the height of the marker (unit is mm), whichever longer.

## 4.7 Summary

Case study-1, 2, 3 and 4 have shown how AR can be used to assist in FLP. Case study-1 used AR technology to figure out the best location of a newly added machine in the existing production line. Four common layouts, namely W-shape, U-shaped, V-shaped and Straight-line layouts were studied. AR is applied in case study-2 to maximize the space in the production floor and visualize the production planning. Real-world objects were digitalized by overlay plane, cylinder or boxes on top as representation. The collision detection method was used to load as much as workstations possible on the shopfloor. Finally, the production schedule was optimized with LPT, SPT and cycle time optimization algorithm. While case study-3 locates the best location of a shared facility using CoG algorithm. The final case study-4 used AR to design production machine planning in a conveyor robotic work cell which material travel distance was concerned. Main considerations to aid FLP designer in decision making are the area occupied, products distance travelled and the production time in these case studies.

# CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

The main objective of this research is to apply AR technology together with the algorithm to assist the designer in FLP. In order to ensure the objectives were achieved, literature review on FLP design and considerations, FLP optimization approaches as well as AR technology and its applications are done. Issues on FLP are addressed and a working AR-based FLP simulation system has been successfully developed from this study as to achieve Objective 1. Four (4) modules were developed to solve FLP issues, listed as below:

1. New facility location searching module
2. Shopfloor space and process optimization module
3. Shared facility location searching module
4. Loop conveyor system space and process sequence optimizing module

The 4 modules above have covered the research Objective 2 where the AR technology is applied in FLP with space occupied, material travelled distance and time taken in production are used as consideration criteria to assist FLP designer in decision making. The AR-based FLP simulation developed supports real-time virtual objects manipulation where FLP designer can move and re-locate the facilities despite the suggested location as well as the original position of physical objects. This makes the FLP solution to be more realistic and flexible and Objective 3 was achieved. AR technology makes the FLP possible to visualize in 3D which is for certainly better than the 2D design method.

This system is especially useful when the modification of the existing facilities' arrangement is needed. The FLP design can be done without interrupting current production, hence it is safe to use and the study can be conducted in as many ways as the designer wishes to.

## 5.2 Recommendations

Despite the achievements mentioned in section 6.1, this study can be further improved in several ways. Graphical User Interface (GUI) can be included in the AR system to guide the user to operate the AR system. A step-by-step on-screen instruction would be great to assist users to learn how to use the AR system. If the voice clip can be added, it would be another great feature to make it user-friendly. Touch screen feature as well as gesture control feature can be considered to implement in the system as it would be more intuitive if compared to keyboard and mouse control.

A common problem of marker-based AR system is the errors that cause the virtual objects to appear shaking in the AR environment. Since the FLP are generally deal with large scale objects, the errors are acceptable. However, it would be great if the errors can be reduced. Controlled lighting environment is a must to reduce the errors. Make sure a good lighting environment when we used the AR system. A good quality camera would reduce errors as well.

There is a limitation where the system develops cannot apply for a very huge scale FLP, for example, several departments are involved. A movable 360° camera can be considered to tackle this limitation. Location-based AR or 3D object-based AR may be able to solve this issue as well. The combination of the above-mentioned solutions maybe could bring a good result.

The algorithm applied in this study is simple. The more complicated algorithm can be implemented if better computing power's computer is used. The graphic presentation can be more realistic as well. Good graphic rendering requires a good graphic card and processor.

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# LIST OF PUBLICATIONS AND PAPERS PRESENTED

ISI/WOS Journal (Published)

1. Yap, H. J., Tan, C. H., Phoon, S. Y., Liew, K. E., & Sekaran, S. C. (2019). Process planning and scheduling for loop layout robotic workcell using virtual reality technology. *Advances in Mechanical Engineering, 11*, 168781401987832. doi:10.1177/1687814019878326