AN AUGMENTED REALITY-BASED HYBRID APPROACH TO FACILITY LAYOUT PLANNING

JIANG SHUAI

(B. Eng., Wuhan University of Technology, China)

A THESIS SUBMITTED

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

NUS GRADUATE SCHOOL FOR INTEGRATIVE SCIENCES AND ENGINEERING

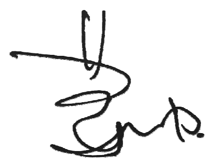
NATIONAL UNIVERSITY OF SINGAPORE

2013

Declaration

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in this thesis.

This thesis has also not been submitted for any degree in any university previously.



Jiang Shuai

11 July 2013

Acknowledgements

I would like to express my utmost gratitude to my supervisors, Professor Andrew Nee Yeh Ching and Associate Professor Ong Soh Khim, for their insightful guidance and the constant help and support for me during my PhD candidature. They gave me hope during the times of difficulties and they gave me encouragement during the times of frustration. I could not make it today without their effort. From the two supervisors, I have learned much more than I have expected.

I also would like to express my sincere appreciation to every member in the ARAT Lab, Dr. Zhang Jie, Dr. Shen Yan, Dr. Fang Hongchao, Dr. Wang Zhenbiao, Ng Laixing, Dr. Zhu Jiang, Andrew Yew, Yu Lu, Wang Xin, Yan Shijun, Yang Shanshan, Zhao Mengyu, Huang Jiming, Billy, and Zheng Xin. You have been great colleagues and best friends.

I would like to thank NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, for providing me with the research scholarship and the kind assistance and advice.

My deepest gratitude goes to those I've always been thinking of all the time. You will be there for always as you were.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
AC	Ant Colony Algorithm
AHP	Analytical Hierarchy Process
AR	Augmented Reality
ARHFLP	Augmented Reality-based Hybrid Facility Layout Planning
ARVIKA	Augmented Reality for Development, Production and Servicing
AFLOE	AR-based Facility Layout Optimization and Evaluation
CA	Construction Algorithm
CF	Constraint Function
CM	Criterion Model
CS	Coordinate System
ELECTRE	Elimination and Choice Expressing Reality
EKF	Extended Kalman Filter
FLP	Facility Layout Planning
FLPES	Facility Layout Planning for Existing Shopfloors
GA	Genetic Algorithm
GMCC	Genetic Method for Defining the Criteria and Constraints
GUI	Graphic User Interface
HMD	Head-mounted Display
IA	Improvement Algorithm
IAR	Industrial Augmented Reality
LP	Layout Planning

MADM	Multiple Attribute Decision Making
MIP	Mixed Integer Programming
PTAM	Parallel Tracking and Mapping
POI	Point of Interest
QAP	Quadratic Assignment Problem
ROIVIS	A Comprehensive System for AR-based Factory Planning
RRI	Real-time Reconstruction and Inpainting
SA	Simulated Annealing
SLAM	Simultaneous Localizing and Mapping
SLP	Systematic Layout Planning
TS	Tabu Search
TUI	Tangible User Interface
UI	User Interface
VR	Virtual Reality

Summary

Facility layout planning (FLP) has been a much pursued topic for decades. Due to the combinatorial complexity and the great impact it has on the modern industry, much research effort has been devoted to search for the effective solutions. Four types of approaches are currently available in FLP, namely, procedural, algorithmic, virtual reality (VR) -based, and augmented reality (AR) -based. Nowadays, the fast-growing industry has posed new challenges. Enterprises are often faced with the need to synchronize shopfloor layouts with the constantly changing production targets. Existing approaches are not efficient in addressing these FLP tasks.

In this research, an AR-based hybrid approach to FLP is proposed (ARHFLP). By integrating mathematical modeling techniques with AR technology, the ARHFLP approach is designed to address FLP for existing shopfloors (FLPES). The potentials of the AR technology are fully utilized to tailor the approach to address the characteristics of the FLPES problem, such as the constraints imposed by the presence of existing facilities, the wide variety of evaluation criteria and constraints, etc. In addition, mathematical models are used to define the quantitative criteria and constraints to provide real-time evaluation to facilitate decision-making. To support the ARHFLP approach, an AR-based fast modeling technique, a real-time reconstruction and inpainting method, and a generic method for formulating mathematical models for FLP are developed.

The AR-based real-time fast modeling technique makes use of the tracking results

of AR to facilitate the 3D point positioning process. A user-aided interactive modeling method is adopted, where the users can construct virtual models of the real objects using primitive models. In ARHFLP, this fast modeling technique is employed as a data collection method for building virtual models of the existing facilities. To facilitate the formulation of mathematical models for FLP, a generic method for formulating the criteria and constraints mathematically is proposed, namely, the GMCC (a generic method for defining criteria and constraints) method. GMCC provides an adaptable method for the users to define and customize the criteria and constraints in real-time so as to better meet the specific requirements of different FLP/FLPES tasks.

A system named AR-based facility layout optimization and evaluation (AFLOE) is developed to implement the ARHFLP approach. In AFLOE, the GMCC method is used to formulate the FLP problems as MADM (multiple attribute decision making) models. To solve the MADM models, two planning modes are provided, viz., information-aided on-site manual planning and AHP (analytical hierarchy process) – GA (genetic algorithm) based automatic planning. The two planning modes utilize human intelligence (manual planning) and the mathematical optimization techniques (automatic planning) to facilitate the layout planning and evaluation processes and provide feasible solutions to FLPES.

Chapter 1 Introduction

This chapter begins with a brief introduction to facility layout planning (FLP), such as the definition of FLP, its impact on industrial plants, the classification of FLP tasks in different scenarios, and the four existing approaches to FLP. Next, a short introduction to the augmented reality (AR) technology, which is the fundamental technology employed in this research, is presented. The research motivation and objectives of this research are presented next. The organization of this thesis is presented lastly.

1.1 Facility layout planning

1.1.1 Definition of FLP

Layout planning (LP) refers to the design of a layout plan or an assignment scheme for the proper distribution of existing facilities and resources for varied reasons. For decades, LP has drawn many studies and researches due to its significant impact on a wide range of applications, such as packaging design (Cagan, 1994), the printing layout planning (Yoshiyama *et al*., 1986), the furniture layout design (Fuji *et al*., 2012, Pfefferkorn, 1975), interior design (Ahlers *et al*., 1995), etc. In addressing different applications, LP has various formulations and distinct constraints. These variations add to the complexities of LP tasks. Researchers have been approaching LP from different aspects using various methods, such as simulation techniques, mathematical modeling, heuristic computing, virtual reality (VR), and more recently, AR.

Facility layout planning (FLP) focuses on the LP tasks in industrial plants or shopfloors. For FLP, according to Heragu (1997), the term facility can refer to a machine tool, a work centre, a manufacturing cell, a machine shop, a department, a warehouse, etc. It is defined as the subject to be laid out according to the task requirements. As shown in Figure 1.1.1, the facility can either refer to a department in a large-scale FLP task (block layout) or a machine in a small-scale FLP task (detailed layout).

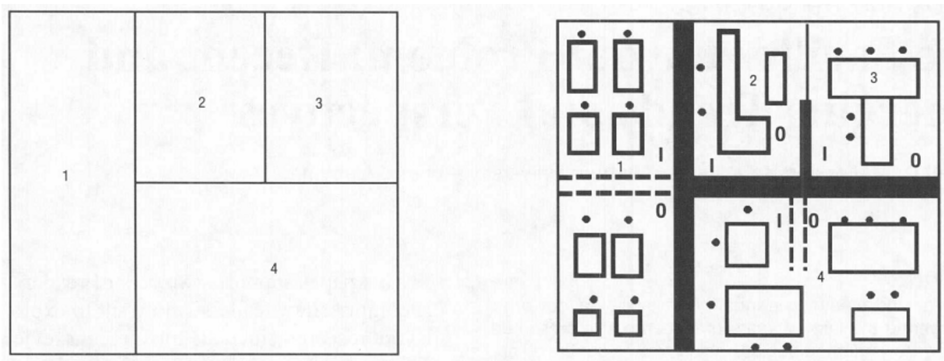


Figure 1.1.1: Department layout (left) and machine layout (right) (Meller and Gau, 1996)

FLP tasks can be found throughout the entire plant/shopfloor design and operating procedures. Figure 1.1.2 shows the FLP tasks at different stages, from the selection of the plant locations and the distribution of the departments within the plant, to the layout of the workstations within the department, the allocation of the machines within them, and the re-layout tasks of the workstations or the departments for improvement purposes.

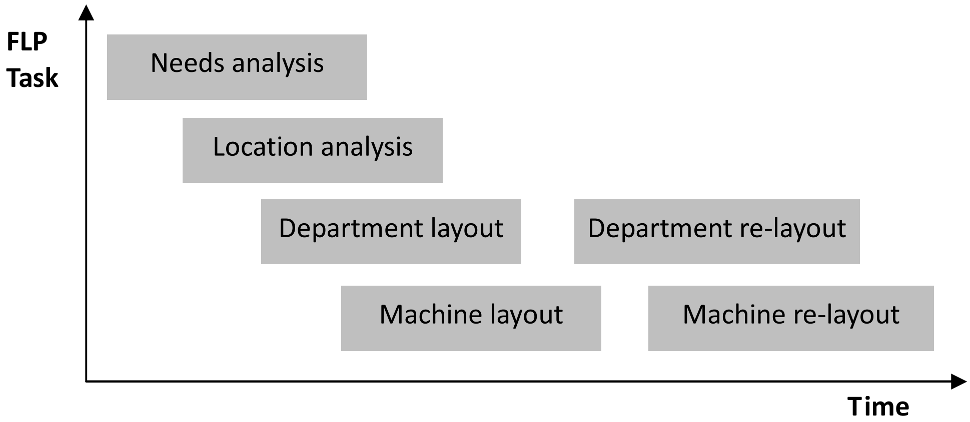


Figure 1.1.2: FLP tasks in different stages

Although there are a wide variety of FLP problems, the objective is the same, which is to increase the efficiency of the manufacturing systems. According to Xie and Sahinidis (2008), a well-designed layout plan can help reduce up to 50% of the operation costs. From the FLP viewpoint, the efficiency of a manufacturing system can be increased from several aspects, such as the material handling cost, the adjacency relationships (Wascher and Merker, 1997), the personnel flow, the aesthetic value, etc. Some of these issues are provided in Table 1.1.1.

Table 1.1.1: Commonly used criteria for FLP

Criterion	Definition
Material handling cost	The total cost for receiving and transporting the materials and goods within the plant.
Adjacency relationships	Ranks (from A to E) that indicate the preference for one facility to be placed adjacent to another.
Personnel flow	The total transportation volume of personnel between the facilities.
Space occupancy rate	The ratio between the volume occupied by the facilities and the volume of the open space.

For FLP, these issues are normally used as the criteria for evaluating the layout plans. In other words, FLP impacts on manufacturing systems from these aspects.

1.1.2 Existing approaches to FLP

Due to the intricate formulation and multifarious constraints, FLP has been a much studied topic for decades. Existing approaches to FLP generally fall into four categories, namely, procedural (Muther, 1984; Francis *et al*., 1991), algorithmic (Wascher and Merker, 1997; Erel *et al*., 2003; Drira *et al*., 2007; Hu *et al*., 2007; Mahdavi *et al*., 2008), VR-based (Iqbal and Hashmi, 2001; Zetu *et al*., 1998; Calderon *et al*., 2003), and AR-based approaches (Rauterberg *et al*., 1997; Gausemier *et al.*, 2002; Doil *et al.*, 2003; Poh *et al*., 2006; Lee *et al*., 2011). In this research, the procedural approach and the algorithmic procedural approach are regarded as the traditional approaches.

The procedural approach uses generalized implementation procedures to guide FLP. These procedures normally incorporate a wide range of criteria, where the FLP can be addressed from both the qualitative and the quantitative aspects. Figure 1.1.3 shows a procedural approach by Muther (1984). The drawback of the procedural approach lies in its heavy dependence on the layout designer's expertise and experience; the lack of quantitative reasoning deprives the credibility of the results that can be produced using this approach. Furthermore, the procedural approach normally uses generalized steps and instructions; the various characteristics of the FLP tasks under different scenarios cannot be incorporated properly. A comparison of different procedural approaches is provided in Section 2.1.

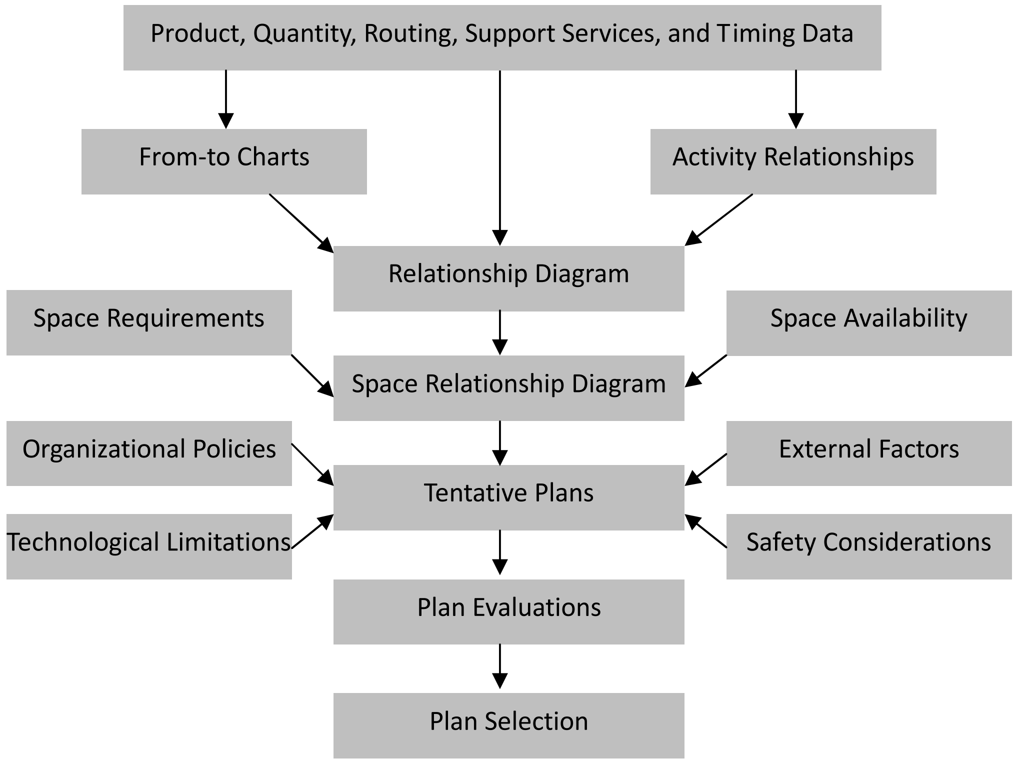
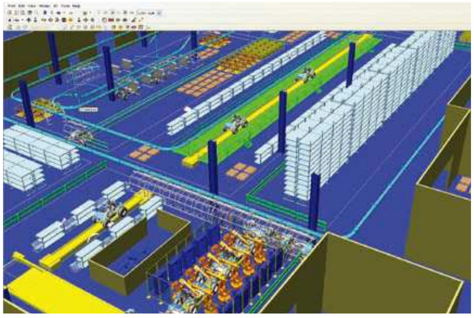
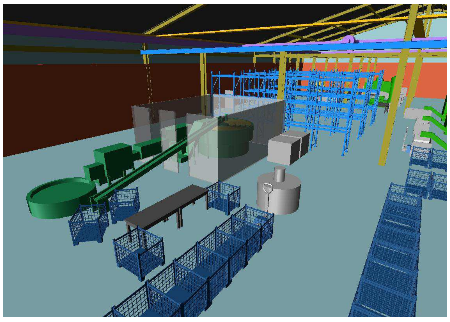


Figure 1.1.3: The systematic layout planning method (Muther, 1961)

The algorithmic approach (Singh *et al.*, 2006; Mahdavi *et al.*, 2008) focuses on the mathematical modeling of FLP, e.g., the QAP (quadratic assignment problem) model and the MIP (mixed integer programming) model. From the algorithmic point of view, it is extremely difficult to find the optimal solution of the FLP models. As a result, research on algorithmic approaches focuses on the development and adaptation of different heuristic algorithms to solve these models, such as, genetic algorithm (GA), simulated annealing algorithm (SA), Tabu search (TS), and ant colony algorithm (AC). However, as the algorithmic approach is essentially based on formulating FLP as mathematical models, due to the derivation of the models from the real FLP, the layout plans produced can be are empirical. It is widely accepted that the drawback of the algorithmic approach is the lack of adaptability (Benjaafar *et al*., 2002). The model designed for one FLP task may not be suitable for another. This drawback has greatly restricted the usability of the algorithmic approach. A comparison of different algorithmic approaches to FLP is provided in Section 2.2.

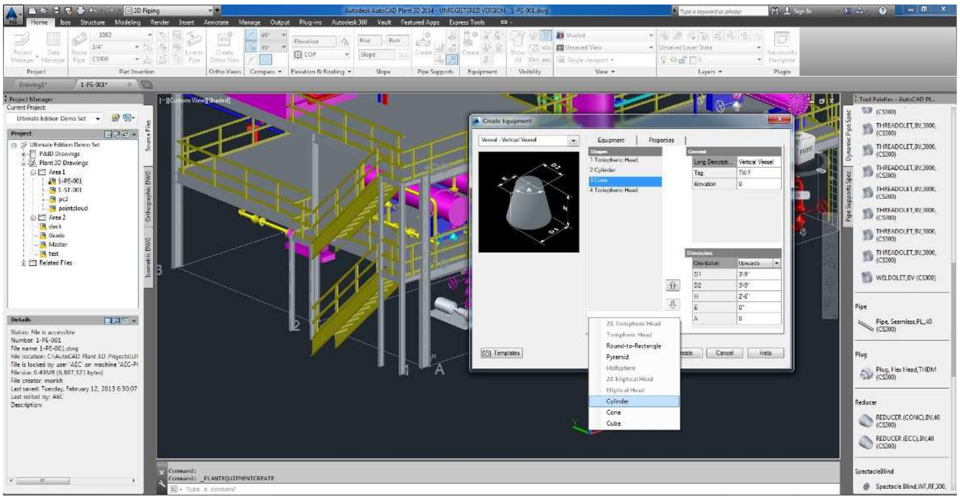
The development of VR technology has led to a new approach to FLP. By providing a virtual environment, where the users can manipulate the virtual facilities manually, the VR-based approach provides an interface for manual planning and facilitates FLP by providing visualization of the plans for the users. With an easy-to-use system interface, the VR-based FLP approach is playing an increasingly important role in factory layout design. Section 2.3 provides a comparison of different VR-based approaches to FLP. Many commercial products are available currently, such as the Tecnomatix Factory Layout Simulation by Siemens (Tecnomatix), Teamcenter Manufacturing Plant Simulation by UGS (Teamcenter), PDMS by AVEVA (PDMS), Plant 3D by Autodesk (Plant 3D), and MPDS4 Factory Layout by CAD Shroer (CAD Shroer). Snapshots of these systems are provided in Figure 1.1.4.



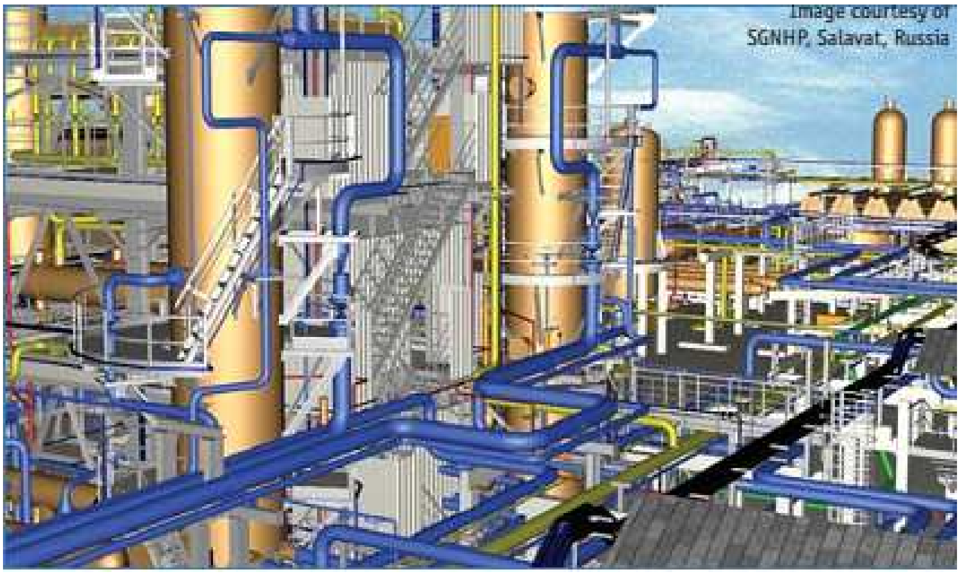


a. Tecnomatix Factory Layout Simulation

b. MPDS4 Factory Layout



c. Plant 3D



d. PDMS

Figure 1.1.4: VR-based FLP software

As tools designed to simulate the layout plans, these VR-based FLP systems are used to design the layout plans virtually before they are implemented. However, the design process is quite tedious as the users need to build the entire shopfloor virtually, which requires much time and expertise. Moreover, as the entire planning environment is simulated virtually, it is likely that this virtual environment may have some discrepancies from the real environment. These discrepancies will be accumulated throughout the design process and subsequently making the results deviate from practice (Benjaafar *et al.*, 2002). The usefulness of these approaches is thus reduced.

More recently, with the development of AR technology, AR-based approaches have been reported. When compared with the VR-based approach, the AR-based approach adopts a synthesized environment where virtual contents are integrated seamlessly into reality. As the layout plans can be rendered on the real shopfloor environment, it provides a feasible method to address the deviations of the results from reality. The enhanced sense of reality can help the users explore the human intuitiveness to facilitate decision-making. However, due to the limited development of the AR technology in the past, the earlier AR-based approaches reported did not fully utilize the advantages of AR and the applications of these approaches are greatly limited (a detailed survey of these approaches is provided in Section 2.4). Hence, an objective of this research is to improve the AR-based approach to FLP.

1.2 Augmented reality

The AR technology presents a synthesized environment to the users, where the virtual contents are well-merged into the real environment. In this synthesized environment, the virtual contents are registered spatially and temporally to the real scene so as to allow the users to perceive the virtual contents as objects that have been added to the real environment. Azuma (1997) states the three characteristics of AR as (1) combining virtual and real objects in a real environment, (2) running interactively in real-time, and (3) registering real and virtual objects with each other.

AR applications based on the use of web cameras have been the main stream of the research for many years. By using web cameras to capture the video streams of a real scene in real-time, research has been focused on the image processing techniques, e.g., template matching (Billinghurst *et al*., 2000) and feature point tracking (Klein and Murray, 2007), to calculate the location of the camera so as to obtain information of the real scene. This information is used to determine the locations and the poses of the virtual contents so that they can be rendered correctly. Both marker-based and marker-less AR techniques have been reported.

For marker-based AR techniques, markers are placed in the real environment and used as visual fiducials. By using computer vision techniques, e.g., template matching, information on the locations and the poses of the markers with regard to the real environment can be obtained. By using this information, the virtual contents that have been registered to the markers can be rendered properly, as shown in Figure 1.2.1. While the usage of markers facilitates the tracking process, it has drawbacks. In marker-based AR applications, markers need to be applied *a priori* to the proper locations. When the markers are outside the camera view, tracking is lost.

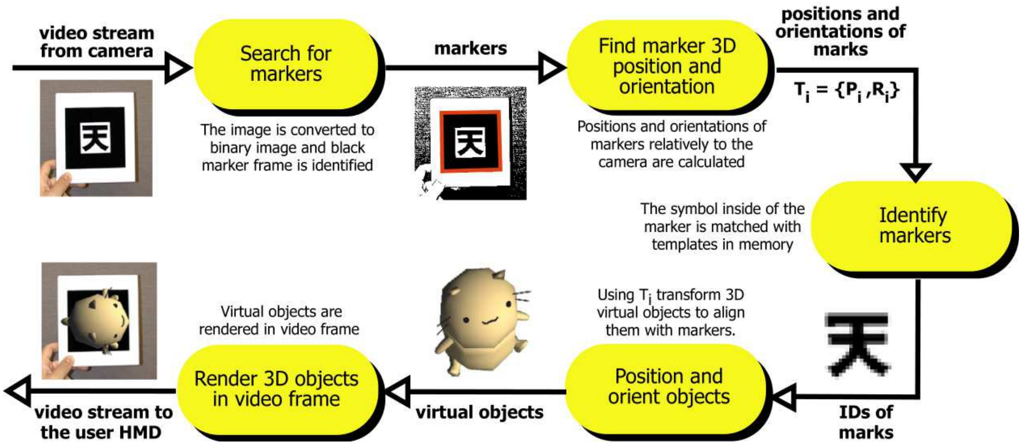
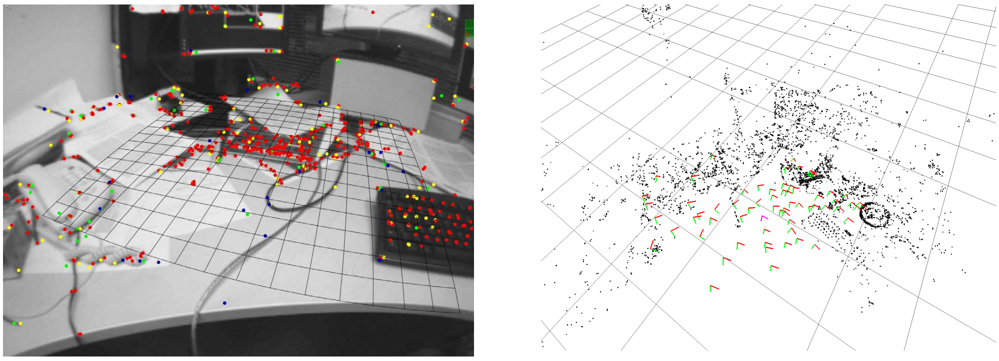


Figure 1.2.1: Marker-based AR (Billinghurst *et al*., 2000)

Marker-less AR techniques do not require markers to be placed in the real environment. Simultaneous localizing and mapping (SLAM) is a widely used technique. SLAM (Leonard and Durrant-Whyte, 1991) is normally applied in the field of robotics navigation. By processing the data received from the sensors, it can update the positions and poses of the robots in the real environment. Vision-based SLAM, either binocular or monocular, adopts varied tracking and mapping algorithms, e.g., EKF-SLAM (Davision *et al*., 2007), FastSLAM (Eade and Drummond, 2006), etc., to calculate the camera pose and construct a point cloud environment. A milestone was made by Klein and Murray (2007) for their PTAM (parallel tracking and mapping) system, as shown in Figure 1.2.2. In PTAM, the tracking and mapping procedures are separated into two parallel threads. Compared with EKF-SLAM and FastSLAM, PTAM is more robust and the tracking results are more stable. As the tracking and mapping procedures are separated into two parallel threads, a well-established 3D point map can be updated steadily whenever new feature points are tracked. PTAM is currently one of the most widely used techniques for marker-less AR.



(a) Tracking Thread (b) Mapping Thread

Figure 1.2.2: Marker-less AR (Klein and Murray, 2007)

1.3 Research motivations and objectives

1.3.1 Research motivations

Research on FLP has been focused on the design stage, i.e., prior to the construction of the new plants or shopfloors. Most of the procedural approaches, algorithmic approaches, and VR-based approaches are developed based on the assumption that the facilities are to be laid out in an empty shopfloor. For these FLP tasks, the criteria and constraints are formulated based on the production data of the manufacturing system, and layout the plans that are designed off-site can normally be implemented without modification. Although requiring some expertise and experience, the existing approaches are able to produce feasible solutions for these tasks.

However, the development of the modern industry has posed new challenges for FLP. To meet the fast-changing production targets, enterprises nowadays need to reconfigure the existing shopfloor layouts quite frequently, e.g., adding or removing the machines for updating the shopfloor operations. For these tasks, the presence of the existing facilities has imposed additional constraints. FLP for existing shopfloors (FLPES) have the following characteristics:

1) The presence of existing facilities and shopfloor structures poses critical constraints;
2) The FLP task normally tends to be on a smaller scale, e.g., removing and adding a number of machines; and
3) The criteria used tend to be wide-ranged in variety and often specific to different tasks. Sometimes the users may only determine the criteria to be used during the installation of the machines on-site.

Existing approaches are not efficient in addressing these issues. By using the procedural approaches, the conceptualized design steps for guiding the layout planning processes may be less usable because the constraints and criteria for FLPES are normally specific to the tasks, and routine procedures can seldom be used for all the FLPES tasks. The algorithmic approaches might be able to handle the FLPES tasks. However, the presence of the existing facilities introduces a large number of constraints. These constraints need to be formulated mathematically and incorporated properly. Moreover, the distinct criteria and constraints among different FLPES tasks would make the algorithmic approaches of lower adaptability, since the mathematical model developed for one FLPES task may not be suitable for another. VR-based approaches have the same problems and issues. In addition, with the presence of the existing facilities, the users have to collect the data of these facilities and build their virtual models, which could be time-consuming. The efficiency would thus be greatly reduced. All three approaches generate layout plans off-site, and hence there is a lack of a proper mechanism to implement immediate on-site evaluation for improvement purposes. On-site evaluation can provide an effective way to identify and address possible deviations of the layout plans from implementation and this is a useful technique for FLP. Moreover, for FLPES tasks, the requirement for the data to represent the existing facilities would exacerbate these problems and make these approaches inefficient. However, enterprises often have to choose a layout plan for implementation, which may be subjective and error-prone (Clough and Buck, 1993).

The AR-based approach is a promising alternative approach to this problem. In an AR environment, virtual contents are integrated into the real scene and a virtual planning space can be created in the real shopfloor such that an on-site planning and evaluation process can be implemented. In this research, an AR-based hybrid approach in addressing FLPES is proposed. The proposed approach adopts a real-time modeling technique to obtain information of the existing facilities, a real-time reconstruction and inpainting method to substitute existing facilities in the AR scene with their virtual replicas, and uses a generic method for the users to formulate the FLPES problems as mathematical models in real-time. By allowing the users to design and evaluate the layout plans on-site, it provides a feasible solution to the FLPES tasks.

1.3.2 Research objectives

The objectives of this research are summarized as follows.

1). Development of an AR-based technique to obtain information of the existing facilities effectively for FLPES tasks.

2). Development of a mechanism to define generic mathematical models that can incorporate various criteria and constraints. By using this model, requirements of different FLPES tasks can be considered.

3). Development of an AR-based hybrid approach for FLP/FLPES that fully utilizes the potentials of the AR technology and mathematical optimization techniques and implements a real-time information-aided interactive design and evaluation procedure to facilitate decision-making.

1.3.3 Research scope

This research aims to develop a novel AR-based hybrid approach for FLP. The research issues to be addressed include the AR-based modeling techniques, mathematical formulations of the FLPES problems, and heuristic algorithms for mathematical optimization.

The type of the FLP considered in this research is FLP in a shopfloor scale for the layout of machines. For FLP on a larger scale, e.g., layout planning of different departments, AR is less applicable due to the difficulty in visualizing much larger elements. FLP on larger scales are thus not within the scope of this research. A multiple attribute decision making (MADM) model is adopted in this research. However, development of new algorithms to solve MADM models is not the focus of the present research and hence will not be explored. Lastly, the AR technique used in this research is the web camera-based AR; utilizations of other types of sensors, such as lasers, are not within the scope of this research.

1.4 Thesis organization

As shown in Figure 1.4.1, the rest of the thesis is organized as follows.

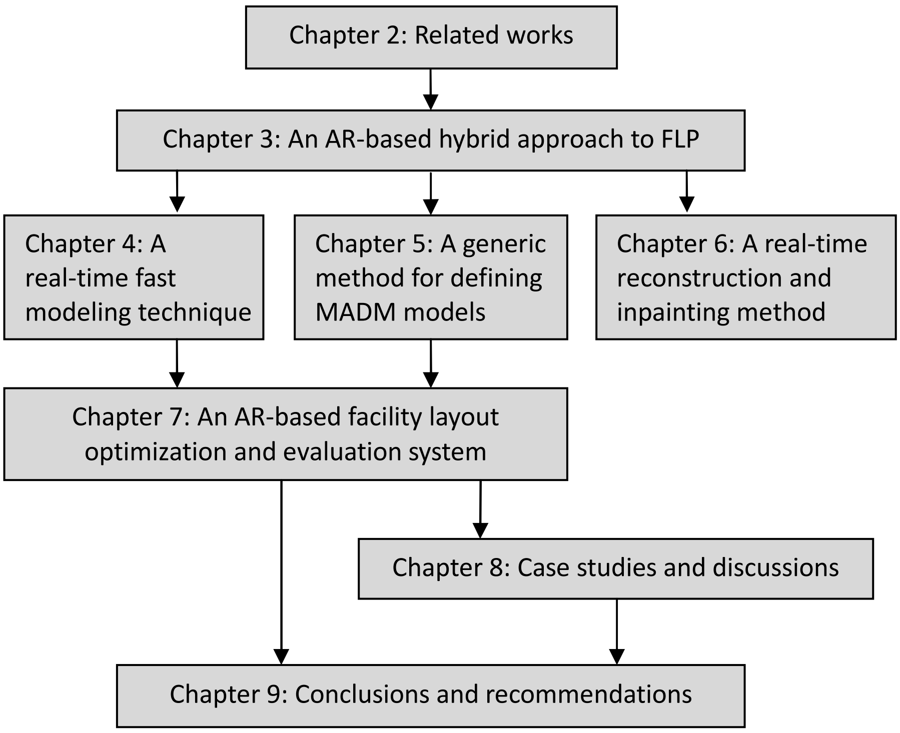


Figure 1.4.1: Thesis organization

In Chapter 2, reported research and studies on existing approaches to FLP and FLPES is reviewed. Analysis on the advantages and disadvantages of each reported method is provided to identify the motivations for the proposed research.

In Chapter 3, the architecture of the proposed AR-based hybrid approach to FLP (ARHFLP) is described. The four steps in ARHFLP, namely, data collection, problem formulation, layout planning, and results evaluation are presented. Development and implementation of the ARHFLP approach is the major research objective to be achieved.

In Chapter 4, the development of an AR-based real-time fast modeling technique is presented. A user-aided fast modeling procedure is implemented based on this technique to model the existing facilities.

In Chapter 5, the development of a generic method for formulating mathematical models for FLP, i.e., the GMCC (generic method for defining the criteria and constraints) method, is presented to address the criteria and the constraints in FLPES tasks. By using this method, the users can define and customize the criteria and the constraints so as to design the mathematical models according to the requirements.

In Chapter 6, a real-time reconstruction and inpainting method is presented. By constructing virtual models for the real objects and simultaneously inpainting the real objects in real-time, this method is developed to create virtual replicas that can be used to substitute the corresponding real objects. By using these virtual replicas, the users can design and evaluate the re-layout of the real objects.

In Chapter 7, an AR-based facility layout optimization and evaluation system (AFLOE) is presented. The AFLOE implements the ARHFLP approach and provides two planning modes, viz., manual planning and automatic planning. The use of GMCC provides real-time information to facilitate the manual planning process. An AHP (analytic hierarchy process) -GA (genetic algorithm) –based optimization scheme is applied for automatic planning.

In Chapter 8, two case studies are presented. The AFLOE system is tested under two different FLPES scenarios. The effectiveness of the system is validated. User studies have been conducted to evaluate the usability of the AFLOE system as well as the effectiveness of the ARHFLP approach.

Finally, Chapter 9 summarizes the thesis by presenting the key contributions of the research and future research opportunities.

Chapter 2 Related studies

In this chapter, a brief review on the related studies is presented. Researchers (Yang and Kuo, 2003; Ertay *et al*., 2006; Yang and Hung, 2007; Shahin, 2010) have grouped the existing approaches to FLP into four categories, viz., procedural, algorithmic, VR-based, and more recently AR-based approaches. A literature review on these four existing approaches is provided in this chapter.

Although each of these four approaches is equally capable in providing standalone solutions in addressing FLP, there are often some particular planning stages for which one approach has advantage over the others. For example, the algorithmic approach is more suitable in problem formulating and produces layout plans by using mathematical optimizations, whereas VR– and AR– based approaches are efficient for result visualization and thus they facilitate manual planning. In other words, these approaches employ different technologies to solve FLP from different perspectives. Consequently, a hybrid approach is developed to incorporate the advantages of the different approaches. In this chapter, reported studies on hybrid approaches related to each of the four approaches are provided. The ARHFLP approach presented in this research is a hybrid approach that integrates mathematical modeling techniques with AR technology.

Since the development of the AR technology, research on its applications in the industry has been much pursued. With the ability to provide a synthesized environment where reality can be augmented with additional information, the AR technology has manifested great potential for simulation visualization, guidance for training purposes, on-site information servicing, and particularly in the context of this research, FLP. This chapter starts with literature reviews on procedural, algorithmic, and VR-based approaches. Next, reported studies on industrial AR applications and the AR-based approach to FLP are presented.

2.1 Procedural approach

The procedural approach refers to the development of the procedures designed to guide FLP (Francis *et al*., 1991), such as the systematic layout planning (Muther, 1961). These procedures define sequential steps for producing layout plans. Table 2.1.1 provides a comparison of the five best-known procedural approaches. In SLP, for example, the first step is to collect and analyse production data, including products, quantify, routing, supporting and time. Based on the material flow analysis, the activity relationships can be created. The spatial locations of the facilities are determined manually based on the activity relationships (Shahin, 2010).

Procedural approach can generally incorporate a large variety of design objectives. However, as it lacks theoretical foundation, the success of a procedural approach implementation is dependent on the generation of quality design alternatives, which often requires expertise and experience (Yang and Kuo, 2003).

Table 2.1.1: Comparison of different procedural approaches

Method	Objective/aim	Methodology/feature	Mathematical analysis method	Application for FLPES
Immer's basic steps (1950)	1. Equipment layout design 2. Low-cost production	1. Lines of flow 2. Lines of machines	N.A.	No
Naddle's ideal system approach (1961)	1. Design the "workable ideal system" (A philosophical approach for designing work systems)	1. Aim for the "theoretical ideal system" 2. Conceptualize the "ultimate ideal system" 3. Design the "workable ideal system" 4. Install the "recommended system"	N.A.	Yes
Reed's plant layout procedure (1961)	Meet varied manufacturing requirements	1. Determine the required process 2. Prepare layout planning charts 3. Determine work stations 4. Establish storage area requirements, office requirements, etc.	Layout planning charts	No
Muther's Systematic Layout Planning (1961)	1. Meet space requirement 2. Reduce material handling cost	1. Information gathering 2. Develop activity relationship 3. Develop space relationship 4. Develop alternative layout plans	1. Activity relationship diagram 2. Space relationship diagram	No
Apple's Plant Layout Procedure (1977)	1. Meet space requirement 2. Reduce material handling cost	1. Plan the material flow pattern 2. Plan individual work stations 3. Plan service and auxiliary activities 4. Construct master layouts	Activity relationship diagram	No

2.2 Algorithmic approach

The algorithmic approach focuses on the development of efficient algorithms for solving FLP as mathematical optimization problems. Due to the complex criteria and constraints, FLP tasks seldom have an exact solution. Research efforts have been devoted to the development of various heuristic algorithms for producing optimal solutions. In this context, for the purpose of classifying different algorithms, many researchers (Singh and Sharma, 2006; Drira *et al.*, 2007) use the term "heuristic algorithm" for the heuristic algorithms reported earlier, e.g., construction algorithm and improvement algorithm, and use the term "meta-heuristic algorithm" for the stochastic search algorithms, such as genetic algorithm, Tabu search, simulated annealing algorithm, and ant colony algorithm. For the same purpose, this terminology is used in this section of the thesis.

For FLP, reported heuristic algorithms can be classified as two types, namely, the construction algorithms (CA) and the improvement algorithms (IA). Addressing FLP as QAP models, CA adopt the trial-and-error method to build the layout plans from scratch. In contrast, IA starts with a random initial solution and refines it gradually by interchanging the facilities pair wise. Heuristic algorithms were the focus of the early studies in algorithmic approaches for FLP and many methods had been reported (Armour and Buffa, 1963; Lee and Moore, 1967; Seehof and Evans, 1967; Drira *et al.*, 2007). However, as the mathematical models highly abstract the FLP tasks, the layout plans obtained by solving these models are normally 2D layouts. For this reason, algorithmic approaches are normally applied during the conceptual layout design stage.

Meta-heuristic algorithms are developed to address more complex FLP tasks, where varied constraints are incorporated. There are reported studies on Tabu search algorithms (TS) (Chiang and Kouvelis, 1996), simulated annealing algorithms (SA) (Chwif *et al*., 1998), ant colony algorithms (AC) (Baykasoglu *et al*., 2006), and genetic algorithms (GA) (Aiello *et al*., 2006). Hybrid approaches have been reported as well (Chwif *et al*., 1998; Azadivar and Wang, 2000; Aiello *et al*., 2006). Most algorithmic approaches adopt the minimization of the material handling cost (Chwif *et al*., 1998) or the maximization of the adjacency score (Wang *et al*., 2005) as the target to achieve. Some works (Chen and Sha, 2005) integrate with prioritization techniques to address multi-criteria FLP tasks while others utilize future production data to solve dynamic layout planning problems, such as robust layout (Aiello and Enea, 2001), dynamic layout (Baykasoglu *et al*., 2006), and reconfigurable layout (Meng, *et al*., 2004). Table 2.2.1 provides a comparison between different algorithmic approaches to FLP.

Algorithmic approach provides an efficient solution for addressing FLP mathematically. However, it is widely acknowledged that the results deviate from reality because of the simplification of both the design constraints and objectives (Yang and Kuo, 2003). Moreover, it lacks an effective mechanism for implementation evaluation, which plays an important role in FLP.

Table 2.2.1: Comparison of different algorithmic approaches

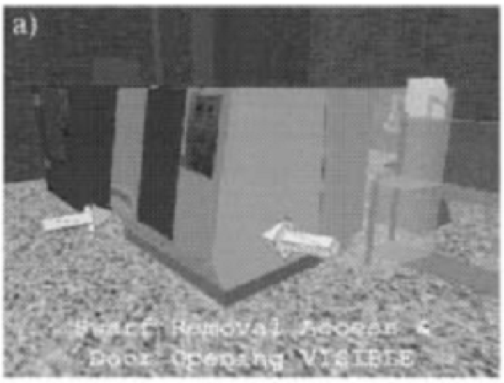
Method/group	Algorithm	MADM	Objective function	Hybrid	Methods/features	Application for FLPES
CRAFT (Armour and Buffa, 1963)	IA	No	Minimize material handling cost	No	1. Starting with a random layout pan 2. Exchange two facilities if it reduces material handling cost	No
CORELAP (Lee and Moore, 1967)	CA	No	Maximize adjacency score	No	1. Define activity relationship 2. Allocate facilities in the sequence of adjacency rates	No
ALDEP (Seehof and Evans, 1967)	CA	No	Maximize adjacency score	No	1. First facility is placed randomly 2. Virtual scanning pattern for allocating facilities 3. Allocate facilities in the sequence of adjacency rates	No
Chiang and Kouvelis (1996)	TS	No	Maximize adjacency score	No	1. A long term memory structure 2. Dynamic Tabu list size 3. An intensification criteria 4. Diversification strategies	No
Dweiri and Meier (1996)	CA	Yes	1. Minimize material handling flow 2. Minimize equipment flow 3. Minimize information flow	No	1. Incorporate fuzzy set theory 2. AHP for prioritization	No
Chwif *et al.* (1998)	SA	No	Minimize material handling cost	SA and IA	1. Equal size facilities 2. Dynamic layout problem 3. Combines SA and IA	Yes

Azadivar and Wang (2000)	GA	No	Minimize material handling cost	GA and simulation technique	1. Incorporate operational constraints 2. Dynamic layout problem 3. Simulation for evaluation	Yes
Balakrishnan *et al*. (2003)	SA	No	Minimize material handling cost	No	1. Combine SA and GA 2. Unequal size facilities 3. A user-friendly interface	No
Shayan and Chittilappilly (2004)	GA	No	Minimize material handling cost	No	1. Slicing tree representation of the layout plan 2. Avoid reparation procedures	No
Wang *et al*. (2005)	GA	No	Maximize adjacency score	No	1. Space filling curves for encoding 2. Unequal size facilities	No
Chen and Sha (2005)	IA	Yes	1. Minimize workflow 2. Maximize adjacency score 3. Minimize material handling time 4. Minimize hazardous movement	No	1. Linear combination of different objectives 2. A multi-pass and doubling procedure based comparison method 3. A method for correcting inconsistent matrix.	No
Baykasoglu *et al*. (2006)	AC	No	Minimize material handling cost	No	1. Budget constraints 2. Dynamic layout problem	Yes
Aiello *et al*. (2006)	GA	Yes	1. Minimize material handling cost 2. Maximize adjacency score	GA and ELECTRE method	1. Produce the entire Pareto solutions 2. ELECTRE method (ELECTRE) for selecting the optimal solution	No

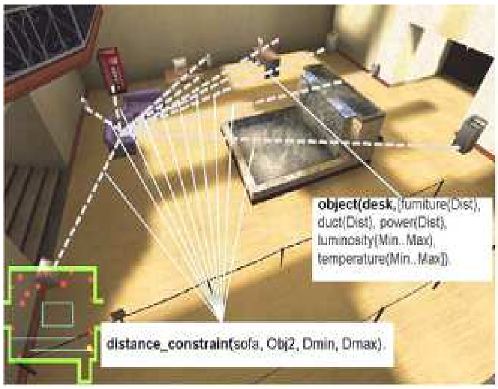
2.3 VR-based approach

By immersing the user in a virtual environment, VR technology has been applied to facilitate FLP. When compared with the procedural approach and algorithmic approach, VR-based approach adopts an interactive design process. Travelling through and manipulating objects within the virtual shopfloor offers a more natural and direct layout planning agent (Smith and Heim, 1998). Figure 2.3.1 shows some VR-based systems for FLP.

Since Banerjee *et al.* (1996) reported a viewing platform for a virtual shopfloor running on a CAVE (cave automatic virtual environment) system, there has been a number of reported VR-based FLP systems. Many of them provide an immersive virtual environment where the users can build the virtual models of the facilities and design the layout plans by manipulating the facility models. Korves and Loftus (1999) reported an immersive VR-based approach to the planning and implementation of manufacturing cells. In this approach, equipment can be moved on the shopfloor with realistic behavior and feedback is given when predefined constraints are violated. A similar framework has been reported by Calderon *et al.* (2003), where the users design the layout plans by refining a master layout plan. Kuhn (2006) reported a hybrid VR-based framework for FLP where simulation schemes are integrated to enhance the production engineering process. In this framework, the digital factory concept is applied and simulation schemes are integrated on different planning stages to optimize the production planning, the factory flow, and the plant design. Integration of simulation techniques with VR technology marks the current development of the VR-based approaches and many commercial software are currently available (PDMS; Plant 3D; Plant Simulation; FlexSim). Table 2.3.1 provides a comparison of different VR-based approaches.



Korves and Loftus (1999)



Calderon *et al.* (2003)

Yang *et al*. (2008)

Back *et al*. (2010)

Figure 2.3.1: VR-based approach for FLP

Table 2.3.1: Comparison of different VR-based approaches

Method/group	Objective/aim	Functions/feature	Hybrid	Application for FLPES
Chung *et al* (1998)	1. A user-friendly VR environment for FLP 2. Multi-story layout planning 3. Real-time virtual "walk-through"	1. Four views interface (plan, side, front, and perspective) 2. Pre-drawn facility modules 3. Multi-layered design	N.A.	Yes
Korves and Loftus (1999)	1. Quick visual assessment of layout alternatives 2. Reduce the required skill level for the users	1. Provide standard shopfloor equipment 2. Animated facility features 3. Feedback from predefined constraints	N.A.	Yes
Calderon *et al.* (2003)	Exploring alternative solutions based on domain knowledge for improvements	1. Integrate constraint logic programming with 3D environment 3. Real-time constraint propagation 2. Produce new solution by modifying old one	VR and constraint logic programming	Yes
Kuhn (2006)	1. Digital factory 2. Integrating simulation processes with planning stages	1. Plant, line and process simulation 2. Dynamic line balance and machine planning 3. Human resources simulation	VR and simulation technique	Yes
Yang *et al*. (2008)	1. Digital factory 2. Simulation and optimization of product design, manufacturing process, production planning.	1. Object-oriented technology 2. Construct manufacturing resource library 3. Dynamic production process simulation	VR and simulation technique	Yes

Back *et al*. (2010)	1. VR-based collaboration, control, and display system 2. Enhanced collaboration between remote parties	1. Multiverse client customizations 2. Import contents in multiple formats 3. Remote factory observation, machine monitoring	VR and simulation techniques	Yes
Commercial software (PDMS; Plant 3D; Plant Simulation; FlexSim)	1. 3D plant design and planning 2. Real-time production simulation 3. Construtting documents and reports	1. Collaborative multi-user platform 2. Standard equipment library 3. Integrating ANSI/ASME and DIN/ISO catalogue 4. Automatic simulation and analysis 5. P&ID planning	VR, simulation techniques, and genetic algorithm	Yes

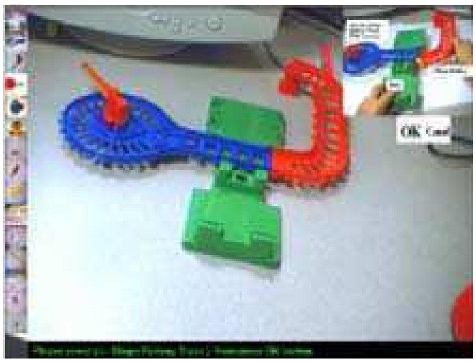
VR-based approaches to FLP are well received in industry. However, as an effective tool for FLP during the shopfloor design stage, VR-based approaches are not efficient for FLPES, where the modeling of the existing constraints requires a tremendous effort. Besides, off-site evaluations are often inadequate, especially for FLPES which may lead to the deviation of the plans from reality. Lastly, the high requirement on expertise and knowledge makes it an unsuitable approach to FLPES.

2.4 AR-based approach

2.4.1 Industrial augmented reality applications

Over the past few decades, extensive research efforts have been devoted to the applications of AR in various fields, e.g., manufacturing, navigation, entertainment, guiding and training, advertising, etc. Nowadays, many AR-based tools and software are available. Among the wide range of application fields, AR applications in industrial processes have been much studied. These applications are known as industrial augmented reality (Fite-Georgel, 2011). Reported research on industrial applications of AR has mainly been focused in several fields, such as product design (Lee *et al*., 2009), assembly training and guidance (Wiedenmaier *et al*., 2003), industrial maintenance (Lee and Rhee, 2008), robot path planning (Chong *et al*., 2008), facility layout planning (Poh *et al*., 2006; Lee *et al*., 2011), construction site planning (Wang, 2007), etc. Figure 2.4.1 shows some of these applications.

(a) AR-assisted product design (Lee *et al*., 2009)



(b) AR-assisted assembly design (Yuan *et al*., 2008)

(c) AR-assisted robot path planning (Chong *et al*., 2006)

(b) AR-assisted construction site planning (Wang, 2007)

Figure 2.4.1: Industrial applications of AR in different fields

AR-based product design allows the users to design and manipulate virtual products in an AR environment, where human intuitiveness can be explored to make modifications and improvements directly in real-time. For AR-based assembly training and guidance, the system can either enable the users to design and examine the assembly plan in AR or allow the users to perform simulated assembly by using both real and virtual parts. Feedback obtained in real-time can be used to make improvements. AR has also been applied in industrial maintenance. By constructing an AR environment in the shopfloor, information on the maintenance status of the tools and machines can be augmented and presented to the users to facilitate the maintenance processes. By using AR technology in robot path planning, the designed paths can be tested in the AR environment where the users can observe the simulated movement of the robot on-site and make improvements. As the AR technology develops, applications of AR in a wider range of fields can be expected.

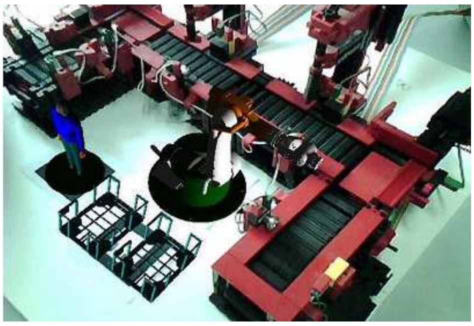
2.4.2 AR-based FLP

Since the development of AR, there have been several reported works on IAR in FLP. The “Build-it” system (Rauterberg *et al*, 1997) is one of the earliest attempts, as shown in Figure 2.4.2. In this system, a table-top tangible user interface was built by superimposing a virtual view of the shopfloor layout map on the real objects and the users can make changes to the layout plans by manipulating these real objects. The sense of reality experienced by the users can facilitate the exploitation of human intuitiveness. During the planning process, movements of the real objects are reflected in the virtual map and the users can design the layout plans cooperatively and interactively.

Figure 2.4.2: The Build-it system (Rauterberg *et al*, 1997)

An important milestone in the development of AR technology is the introduction of the ARToolKit platform (Billinghurst *et al.*, 2000), which has promoted the development of several AR-based FLP tools. As shown in Figure 2.4.3, Gausemeier *et al*. (2002) proposed a table-top AR system to facilitate FLP tasks. In this system, each marker was registered to a 3D virtual model of a facility to be laid out. The users can design the positions and poses of the facilities intuitively in the AR environment. A similar system was presented by Wan *et al*. (2010). In their system, an AR environment was superimposed onto a scaled-down real time model. The users can manipulate the markers to change the locations of the virtual models while assessing the resultant layout plans with respect to the real time model. These studies demonstrated the usefulness of the AR-based tools for FLP tasks for existing shopfloors.

(a) AR-Planning Tool (Gausemeier *et al*., 2002)



(b) AR-assisted FLP system (Wan *et al*., 2010)

Figure 2.4.3: AR-based FLP based on ARToolKit (Billinghurst *et al*., 2000)

In the AR-based FLP system reported by Poh *et al*. (2006), a method to define criteria to evaluate the layout plans is introduced. As shown in Figure 2.4.4, markers are attached to the existing facilities so as to obtain the location information of these facilities. Criteria, such as electrical losses, fluidic losses, total material handling cost, etc., can be defined by establishing mathematical relationships between the new facilities and the existing facilities. As the users change the positions of the new facilities, these criteria can be evaluated and updated in real-time, so as to assist the users in the decision-making process.

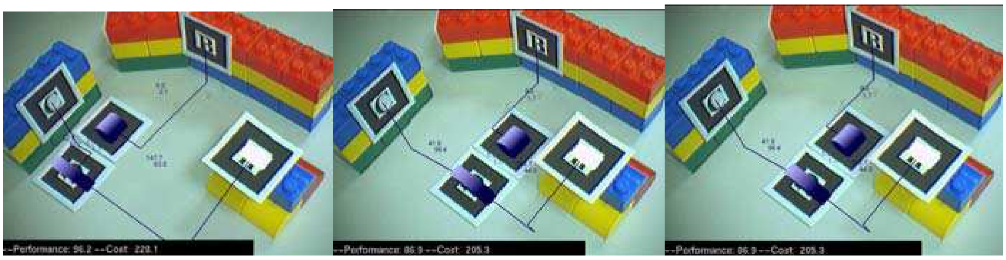
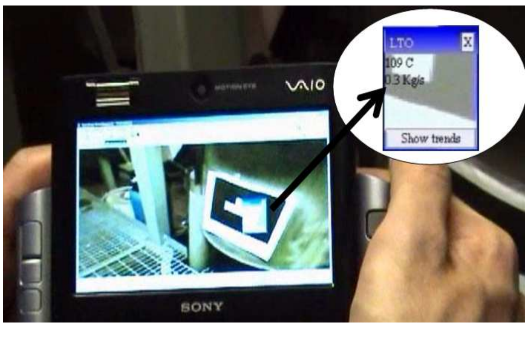


Figure 2.4.4: AR-based FLP system by Poh *et al*. (2006)

There are also studies that investigated AR-based manufacturing schemes (Doil *et al*., 2003; Siltanen *et al*., 2007; Pentenrieder *et al*. 2008) where AR is used to facilitate FLP, as shown in Figure 2.4.5.

(a) ROIVIS (Pentenrieder *et al*., 2008)



(b) AR-assisted factory planning by Siltanen *et al*. (2007)

Figure 2.4.5: AR-based manufacturing planning

AR-Plan is a tool in ARVIKA (Doil *et al.*, 2003) for FLP. AR-Plan establishes an AR interface in a real shopfloor environment using marker-based tracking and a digital manufacturing library is provided from which the users can select the machinery and tools to be rendered on-site. Possible collision of the virtual facilities with the real facilities in the shopfloor can be identified visually through comparing different geometries. Based on the concept of ARVIKA, Pentenrieder *et al*. (2008) proposed ROIVIS, which is an AR-based system to support factory and manufacturing planning. By adopting an image-based AR technique, the proposed system develops an accurate measurement functionality, which can be used for interfering edge analysis, variance comparison, workshop planning, etc. Siltanen *et al*. (2007) proposed a scheme for AR-based plant lifecycle management, where AR is utilized for the verification of layout plans. A web-based client/server framework was developed. As the layout plans are rendered in the real shopfloor, the operators can evaluate these plans remotely on-site in the AR environment and provide feedback to the planners.

More recently, Lee *et al*. (2011) demonstrated the use of AR to facilitate the installation of a robot arm in a shopfloor (Figure 2.4.6). In their system, the virtual models of the existing facilities are constructed *a priori* and registered to the real facilities. A simulation scheme is applied to evaluate the behaviour of the robot arm in the shopfloor to perform interference check.

Figure 2.4.6: AR-based FLP tool proposed by Lee *et al*. (2011)

Table 2.4.1 provides a comparison of different AR-based approaches for FLP. Generally, these systems have demonstrated the advantages of AR technology for FLP, especially for FLPES (FLP for existing shopfloors). However, many of the features proposed are in the conceptual design stage such that they may not be able to handle real FLP tasks.

The significance of the interaction between the real and virtual entities for AR-based FLP, e.g., collision detection, has been emphasized in these works to different extents. However, neither the use of markers for positioning (Pentenrieder *et al*., 2008), nor the construction of virtual models *a priori* (Lee *et al*., 2011) is efficient or effective. Thus, a method that can obtain the information of the real environment in real-time would be an improvement in terms of functionality and adaptability (Navab, 2004).

Table 2.4.1: Comparison of different AR-based approaches

Method/ Group	Objective/aim	Employed media	Physical constraints identification	Hybrid	Methods/features	Application for FLPES
"Build-it" (Rauterberg *et al*, 1997)	1. Optimize production flow 2. Team-based evaluation	Projection	N.A.	No	1. Table-top tangible user interface 2. Use graspable bricks as interaction handlers 3. Collaborative layout design	Yes
AR-Planning (Gausemeier *et al*., 2002)	1, Optimize production flow 2. Design layouts in an intuitive way	Live video	N.A.	No	1. Collaborative planning 2. Defining a set of planning rules 3. Use markers to manipulate facilities	No
ARVIKA (Doil *et al*., 2003)	1. Optimize production flow 2. Validating planning tasks	Live video	N.A.	No	1. Provide a digital manufacturing library 2. A client-server architecture 3. Workspace ergonomics analysis	No
Poh *et al*., (2006)	1. Minimize performance losses 2. Maximize free space for accessibility	Live video	*a priori*	No	1. Apply markers to physical constraints 2. Predefined evaluation criteria	Yes

Siltanen *et al*., (2007)	1. AR-based plant life cycle management 2. Optimize manufacturing planning	Live video	*a priori*	No	1. Use Plamos (Siltanen *et al*. 2006) prototype 2. Incorporate facility information, production data, AR simulation as plugins 3. Visual guidance for facility installation	Yes
ROIVIS (Pentenrieder *et al*. 2008)	1. Optimize manufacturing processes 2. Keep consistency of reality and virtual planning data	Live video; image	*a priori*	No	1. Web-based client-server application with HMD 2. Stationary video-based system 3. Mobile photo-based AR-system	No
Wan *et al*., (2010).	Optimize production process	Live video	N.A.	No	1. WRL format model files 2. XML format data files 3. Layout planning by editing data files	No
Lee *et al*. (2011)	1. Minimize the cost for digital manufacturing 2. Optimize production process 3. Validating planning tasks	Image	*a priori*	AR with simulation technique	1. An image registration method 2. Simulation data extraction and processing 3. Collision detection between virtual facilities	Yes

There is a common procedure that has been formulated in the development of these AR-based FLP systems. In this common procedure, (1) a number of markers are used for the rendering of the new facilities, (2) pre-defined criteria can be used, and (3) a manual planning procedure is adopted. Although these AR-based FLP approaches have successfully provided an alternative solution to the FLP problems, the obvious drawbacks, e.g., the lack of proper evaluation mechanisms, restricted interaction between real and virtual objects, etc., have greatly reduced the adaptability and the usability of the AR-based approach.

Chapter 3 An AR-based hybrid approach to FLP

In this chapter, an AR-based hybrid approach to FLP, namely, the ARHFLP approach is proposed. By employing the AR technology to achieve interactive on-site planning, and mathematical modeling techniques for real-time evaluation, ARHFLP provides an adaptable and effective approach to FLP, especially FLPES. Section 3.1 presents the four-step procedure adopted in ARHFLP, namely, data collection, problem formulation, layout planning, and results evaluation. A comparison of ARHFLP with the existing approaches is provided. The architecture of the ARHFLP is illustrated in Section 3.2.

3.1 Development of the ARHFLP approach

In this research, an AR-based hybrid solution to FLP, namely the ARHFLP approach is proposed. ARHFLP combines the advantages of existing approaches, i.e., the algorithmic approach, the VR-based approach, and the AR-based approach.

The algorithmic approach adopts mathematical models to formulate the FLP problems and uses heuristic algorithms to solve the models to produce the layout plans. The utilization of the mathematical models increases the reliability and the definitiveness of the plans produced. The VR- and AR-based approaches provide a convenient GUI (graphic user interface) for planning the layouts manually, during which the users' knowledge and experience can be utilized to facilitate the planning process. In particular, human intuitiveness can be fully exploited to aid the manual planning process in the AR-based approach.

As shown in Figure 3.1.1, the ARHFLP approach combines advantages of these approaches and integrates the mathematical models with a GUI for implementing manual planning. ARHFLP provides real-time computing of the mathematical model and allows the users to use their experience and knowledge to evaluate the mathematical results simultaneously to facilitate the planning process.

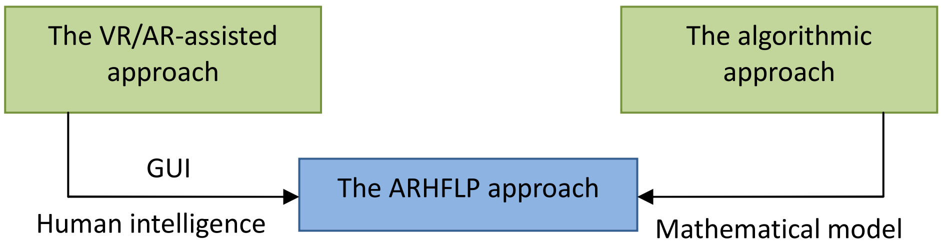


Figure 3.1.1: Incorporating the advantages of the existing approaches

The ARHFLP approach adopts a four step procedure to address the FLP tasks, namely, data collection, problem formulation, layout planning, and result evaluation, as shown in Figure 3.1.2.

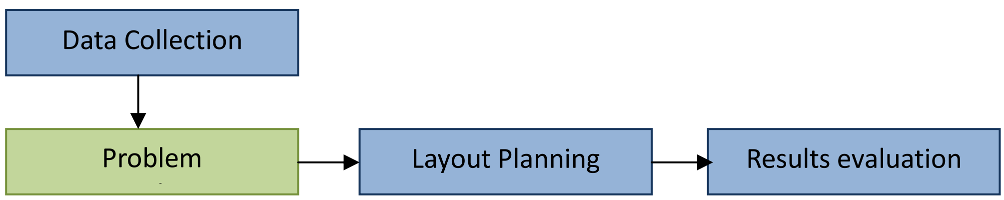


Figure 3.1.2: Four step procedure of ARHFLP

Data collection refers to the process of collecting the data and information necessary for performing the FLP tasks. For existing FLP approaches, data collection is normally a tedious task to be performed. For the algorithmic approach, data of the locations, sizes and poses of the existing facilities need to be collected manually so as to formulate the constraints for the mathematical models. For the VR-based approach, besides the collection of these data, the virtual models need to be constructed, which is often laborious and time-consuming. In this research, a fast real-time modeling technique is developed and adopted in ARHFLP for data collection. Using this modeling technique, the users can build virtual models to define the planning space, the existing facilities, etc., interactively as they examine the results on-site. From these models, the data and information of the existing environment are obtained in real-time.

Problem formulation is the process to define the evaluation criteria, e.g., material handling cost, space occupancy rate, etc., and utilize these criteria to define the mathematical models for the FLP tasks. It is the major task in the algorithmic approaches. However, many reported algorithmic approaches are not generic as the mathematical models adopted are normally limited to certain types of FLP tasks. Moreover, the criteria and constraints need to be predefined. ARHFLP is proposed to bridge this gap. To address a wide range of criteria and constraints, ARHFLP adopts a method for the users to define and customize the criteria and constraints, namely, the GMCC (generic method for defining the criteria and constraints) method. GMCC employs a MADM (multiple attribute decision making) model as the basic mathematical structure and provides an interface for the users to configure the MADM model in terms of the criteria and constraints in real-time. A set of mathematical models is provided in GMCC which can be used to facilitate this process.

For the procedural approach and many VR-based and AR-based approaches, manual planning process is employed, where the users use their knowledge, expertise, experience and intuitiveness (for AR-based approach) to design the layout plans. On the other hand, the algorithmic approach produces the layout plans through solving the mathematical models, making it an automatic planning process. As FLP is a complex design task without exact solutions, manual planning can take advantages of the human intelligence while automatic planning can produce results based on theoretical reasoning. In this research, the ARHFLP approach provides both planning methods, i.e., information-aided manual planning and automatic planning. For manual planning, the MADM model formulated is computed in real-time so that the information reflecting the status of the MADM model is updated to guide the planning process. To solve the model mathematically, a heuristic algorithm, i.e., the AHP (analytic hierarchy process) –GA (genetic algorithm), is integrated to perform automatic planning.

Most of the reported research studies that are based on the procedural approach and algorithmic approach do not have real-time evaluation mechanisms and deviations of the layout plans from reality can only be identified during the implementation stage (Yang and Kuo, 2003). For VR-based approaches, simulation techniques are often used as an evaluation method; discreet event simulation schemes are applied to validate the layout plans through different manufacturing scenarios. However, these simulation schemes are limited to production data. When it comes to the real shopfloor environment, other factors, e.g., the lighting conditions, the personal traits and preferences of the operators, will have impact on the morale of the employees and consequently on the efficiency of the manufacturing system, whereas simulation techniques are not efficient in addressing these issues. ARHFLP adopts an on-site real-time design and evaluation planning strategy. Layout plans produced are evaluated immediately on-site, which facilitates the necessary adjustments and modifications to the layout plans to make them suitable for the shopfloor environment. Furthermore, by interacting with the layout plans augmented in the shopfloor, the users can use their intuition, experience, and knowledge to assess the layout plans and facilitate decision-making. Table 3.1.1 shows a comparison between ARHFLP and the existing approaches.

Table 3.1.1: Comparison between ARHFLP and the existing approaches

	Data Collection	Problem Formulation	Planning Process	Results Evaluation
Procedural approach	*A priori*	N. A.	Manual	N. A.
Algorithmic approach	*A priori*	Pre-defined	Automatic	N. A.
VR-based approach	*A priori*	N. A.	Manual	Off-site
AR-based approach	*A priori*	Pre-defined /N. A.	Manual	On-site
ARHFLP approach	Real-time	Real-time	Manual /Automatic	On-site

The ARHFLP approach can be applied in both FLP and FLPES tasks, and is generic for a wide range of FLP scenarios. It provides two planning modes, and is effective as an on-site planning approach.

3.2 Architecture of the ARHFLP approach

ARHFLP adopts the parallel tracking and mapping (PTAM) system for real-time camera tracking and environment mapping, such that a marker-less AR environment can be established.

In the AR environment, the real-time fast modeling technique is applied to construct a virtual model of the shopfloor. Users can construct primitive models interactively to represent the existing facilities. The virtual models are rendered in the shopfloor environment and overlaid onto the existing facilities. A real-time reconstruction and inpainting method is proposed for the users to build virtual replicas of existing facilities so as to use these virtual replicas to design and evaluate the new locations of these corresponding facilities. Next, 3D models of the new facilities to be installed are loaded and augmented onto the real environment. The users can manipulate these virtual models in terms of translation, rotation, etc. After all the necessary facilities have been specified for forming a layout plan, the users proceed to define the criteria and the constraints for the evaluation of this layout plan. GMCC is adopted for the users to define and customize the criteria and constraints so as to meet the specific requirements of the FLP tasks. The criteria and constraints are used to provide real-time evaluation to facilitate manual planning and are processed by a meta-heuristic algorithm to perform automatic planning. Figure 3.2.1 shows a figure of the architecture of the

ARHFLP approach.

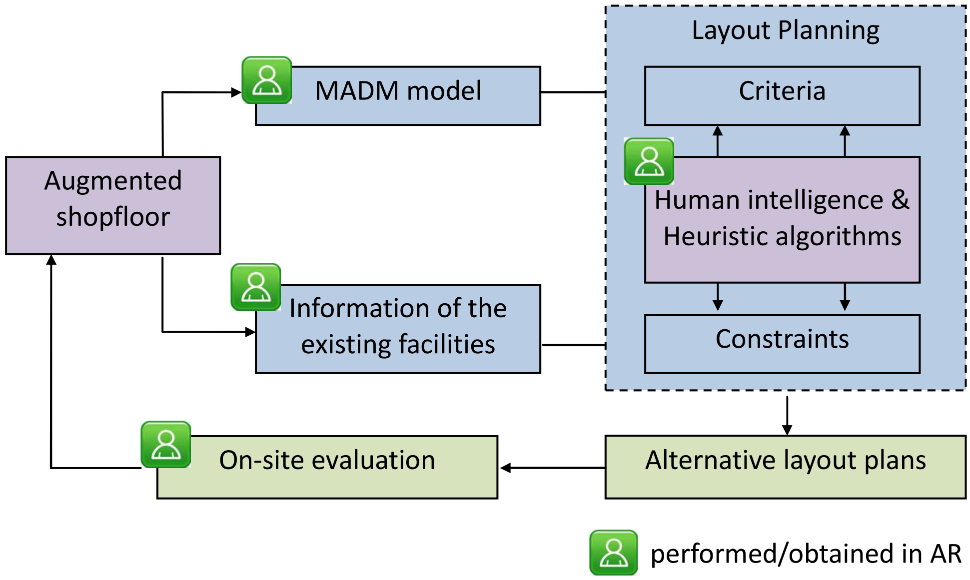


Figure 3.2.1: Architecture of the ARHFLP approach

ARHFLP provides a novel approach to FLP, especially for FLPES. The advantages of ARHFLP are:

1. The integration of a fast real-time modeling method that allows the users to build virtual models of existing facilities. Information of these facilities, such as the locations and sizes, can be obtained in real-time to facilitate the data collection process.
2. GMCC provides an efficient and generic method for defining mathematical models for FLP tasks. Different criteria and constraints can be incorporated and managed to tailor the model to meet the task requirements. The mathematical model is used for both manual planning and automatic planning.
3. Real-time design and evaluation allows the users to make adjustments to the layout plans on-site in real-time to make them fit well in the shopfloor

environment. It also promotes the utilization of the users' intuitiveness, experience, and knowledge to help decision-making.

Chapter 4 An AR-based real-time fast modeling method for FLP

This chapter provides a detailed description on the real-time fast modeling technique developed in this research. Based on a brief review of the current reconstruction techniques, Section 4.1 presents the significance of vision-based reconstruction techniques for AR-based applications. Section 4.2 provides the mechanism to calculate the 3D coordinates of any point in the AR environment. By using this mechanism, the development of the real-time fast modeling technique is provided in Section 4.3. This modeling method is used in ARHFLP to construct the virtual models of existing facilities and collect the data for the formulation of the mathematical model.

4.1 Virtual model construction for AR-based applications

As compared with the VR technology, AR provides a mixed environment where real and virtual contents are aligned with each other seamlessly. This mixed environment provides visualization of both real and virtual entities and facilitates the possible interaction between them. The interaction between real and virtual entities can be used to guide and assist many planning and design tasks, e.g., assembly guidance, robot path planning, etc. A crucial step to implement this interaction is the construction of the virtual models of the real contents. For AR-based applications, virtual constructed models can be used to achieve real-time collision detection, occlusion effects, etc. The usefulness of an efficient construction method for AR-based FLP has been emphasized in (Navab, 2004;

Pentenrieder *et al*., 2008; Lee *et al*., 2011; Fite-Georgel, 2011).

For virtual model construction techniques, the vision-based approach (Tan *et al*., 2008; Pan *et al*., 2009) has been well researched and is the main stream approach. Efforts have been devoted to improve the accuracy of the results, either monocular or binocular in form, to achieve good resemblance of the virtual models to the real objects. To achieve this goal, some approaches adopted algorithms that require high computational cost (Tan *et al*., 2008), while others made use of the human intelligence and required complicated inputs from the users (Pan *et al*., 2009), which have made these approaches not suitable for real-time processing.

For many AR-based applications, the construction of the virtual models is the first step to achieve interaction between the real and virtual entities. Thus, computation time and adaptability are of higher priority over accuracy for the virtual model construction approaches used in AR applications. In other words, techniques that allow the users to construct the virtual objects in a short time with less effort are preferred. In this research, a real-time fast modeling technique is developed to construct virtual models of the real objects as primitive models in real-time. For the development of this technique, a user-aided point positioning method is adopted to access the world coordinate system (CS).

4.2 A user-aided method for point positioning in AR

To construct a virtual model of a real object, information on the coordinates of the object, e.g., the depth information in the world CS needs to be obtained. Algorithms have been reported for the calculation and refinement of this information (Tan *et al.*, 2008; Homography) so as to achieve accurate virtual models representing the real objects. As many of the reported methods are time consuming to process, the virtual models are normally constructed off-line, i.e., post-processing of the recorded videos. The proposed approach makes use of AR to achieve this in real-time.

In the AR interface, the world-to-camera transformation matrix, which is a key factor in calculating the depth information, is updated in real-time. For a point P (X, Y, Z) in the world CS, its coordinates in the camera CS from two different frames A and B are provided as p_{CA} and p_{CB} respectively,

$$P = M_A p_{CA} = M_B p_{CB} \qquad (1)$$

M_A and M_B are the world-to-camera transformation matrices for frames A and B. Based on Equation 1, the coordinates (X, Y, Z) can be obtained. To implement this method, a point can be positioned in the world CS if its 2D coordinates in two different frames can be obtained. In other words, it is a process to locate the same point from the two frames. Human intelligence can be employed to facilitate this process. As shown in Figure 4.2.1, when the users position the same point P in two different frames, its coordinates in world CS can be obtained.

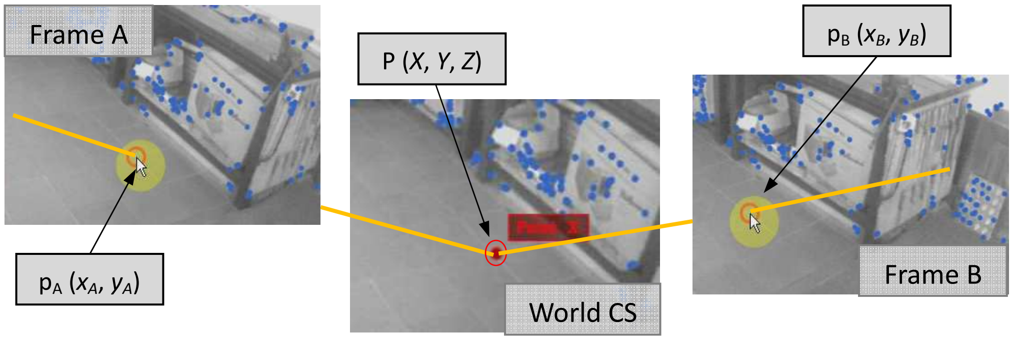


Figure 4.2.1: User-aided point positioning.

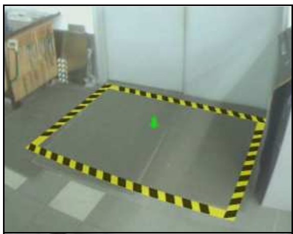
This positioning process can be further simplified if the point to be positioned is on a known plane, e.g., the *x-y* (or *y-z*, *z-x*) plane, where the users will only need to position the point in one frame. This has great value for modeling the objects that are placed on the floor.

4.3 AR-based real-time virtual model construction

An AR-based real-time modeling technique is developed for the users to construct virtual models of the real objects using primitive models. The modeling procedure is performed interactively as the users can examine the results on-site. The modeling process is to construct a primitive model that represents the real object closely.

An interactive modeling procedure is adopted. The modeling procedure starts with the positioning of the points of interest (POIs). In this research, POIs refer to the key points used to define a 2D primitive shape or a 3D primitive model, e.g., the centre of a disc, the vertices of a plane, etc. By defining the POIs, a 2D primitive shape can be defined easily. By extruding a volume based on a 2D primitive shape, a 3D primitive model can be produced. In the current prototype, four types of commonly used primitive models are supported, namely, planes, blocks, discs and pillars. Table 4.3.1 shows the methods used to build these models.

Table 4.3.1: Methods used to build primitives for modeling

	Type: 0-Plane
	Methods: 1. Define two diagonal vertices of the plane; or 2. Define the centre of a default-size plane
	Type: 1-Block
	Method: Extrude a volume along the normal of a plane
	Type: 2-Disc
	Method: 1. Define three points along the edge of the disc; or 2. Define the centre of a default-size disc
	Type: 3-Pillar
	Method: Extrude a volume along the normal of a disc

A user interaction mechanism based on AR is adopted to facilitate the modeling process. Throughout the modeling procedure, a transformation matrix is provided to the users to allow them to manipulate the models to achieve translation, rotation, and scaling of the models. These manipulations can be used to refine the models in terms of size, location, pose, scale, etc., so that they can depict the real objects well. A sample process for building a 3D model is provided in Figure 4.3.1. The utilization of human intelligence and the adoption of the user-aided positioning mechanism have greatly reduced the time and effort needed from the users and made it suitable for real-time processing.

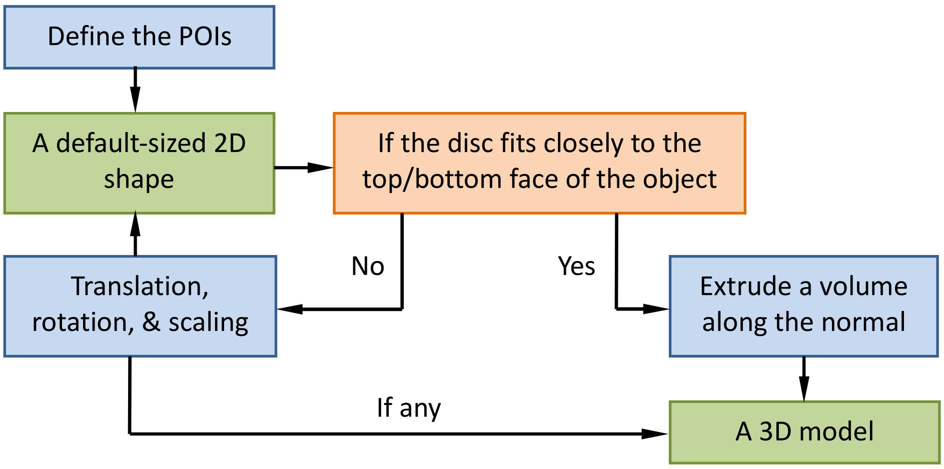


Figure 4.3.1: Building a 3D model

Although the accuracy of the models built using this modeling technique is relatively low as compared to other reconstruction methods (Tan *et al*., 2008; Pan *et al*., 2009), the adaptability and the effectiveness of this techniques makes it suitable for AR-based applications. By using this fast modeling technique to build virtual models of the existing facilities, data reflecting the locations, poses and sizes of these existing facilities can be obtained. Figure 4.3.2 shows a shopfloor environment with existing facilities being modelled.

Figure 4.3.2: Models of existing facilities in a shopfloor

Chapter 5 A generic method for formulating MADM models for FLP

This section provides a detailed description of a generic method for formulating MADM (multiple attribute decision making) models for FLP, namely, the GMCC (generic method for defining the criteria and constraints) method. Based on a brief review of the use of mathematical models to address FLP, the drawbacks of the current methods of using mathematical models are presented. The GMCC method is proposed to address these drawbacks. In GMCC, two methods, namely, the criterion model (CM) and the constraint function (CF) are proposed and used to facilitate the formulation of the MADM model. To solve the model, two planning strategies can be employed, viz., manual planning and automatic planning. A comparison of the planning procedures between the two planning strategies is provided.

5.1 Introduction

Research on the use of mathematical modeling techniques in FLP has been pursued for decades. Various models have been developed to address FLP under different scenarios, which have formed the major contents of the algorithmic approaches. Different schemes have been adopted to formulate the mathematical models. Early studies (Singh and Sharma, 2006; Xie and Sahinidis, 2008) usually adopt single-criterion, e.g., material handling cost or the adjacency relationships, to formulate FLP as a single-objective optimization problem. The mixed integer programming (MIP) model and quadratic assignment problem (QAP) are the commonly adopted models

Bi-criteria models have been reported as well (Kulturel-Konak *et al*., 2007). To solve these models, different algorithms are developed to identify the trade-off between two objectives. With the advancement of technologies, the manufacturing system becomes more and more complicated and this leads to the complexity of the FLP problems. Researchers begin to investigate the use of the MADM model to formulate the FLP problems (Yang and Hung, 2007; Yang *et al*., 2012), where more than two criteria can be considered.

The existing FLP approaches suffer from a common drawback, which is the lack of adaptability. Due to different criteria being considered in different planning scenarios, mathematical models developed for one particular FLP scenario would not be suitable for another scenario. This problem could be exacerbated for FLPES tasks, where the criteria and constraints tend to be of a greater variety and larger in number. Another shortcoming of these methods lies in the dependence on pre-defined criteria. To the best of the author's knowledge, no mechanism has been proposed to facilitate the definition of the layout criteria in real-time. For FLPES, sometimes the users may identify the necessary criteria to use only when they are in the process of planning the layout on-site. In this research, a generic method for defining a mathematical model for FLP, namely, the GMCC method is developed. Using this method, users can define and customize the mathematical model in real-time, which offers more adaptability and usability for FLPES.

5.2 Architecture of the GMCC method

The GMCC method is developed to formulate MADM models. In a MADM model for FLP, each criterion for evaluating the layout plans serves as an attribute in the MADM model. The variables of these criteria are the locations of the new facilities. The values of the criteria will change as the location and pose of these facilities change. Constraints are specified and imposed on the new facilities to define the valid ranges of the location and poses of these new facilities.

In the MADM model, both the criteria and constraints are represented by the mathematical relationships between the facilities. The criteria are used to evaluate the performance of the layout plans, e.g., material handling cost, space occupancy rate, etc., whereas the constraints are used to access the feasibility of the layout plans, e.g., collision detection. In GMCC, the criteria model (CM) and the constraint function (CF) are the two methods for the users to define the criteria and the constraints respectively.

In the AR environment, as the users examine the shopfloor on-site and identify certain layout issues to be used as criteria, e.g., minimization of the material handling cost, optimization of the personnel flow, etc., the corresponding CMs can be invoked and used to define these issues as attributes of the MADM model. The CFs are used to impose different types of constraints on the facilities. As shown in Figure 5.2.1, by using the CMs and CFs, GMCC provides a generic method for the users to formulate and customize a MADM model in terms of the criteria and constraints in real-time.

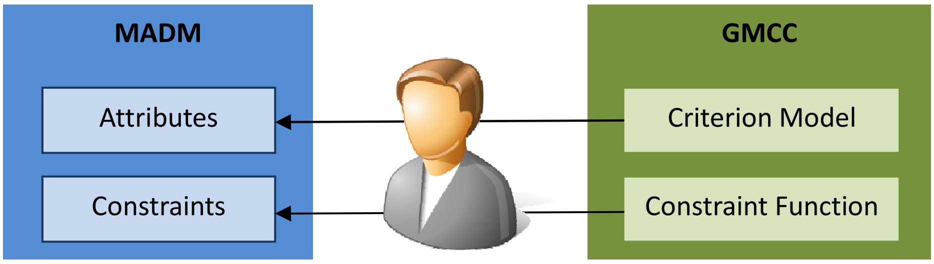


Figure 5.2.1: User-aided MADM definition and customization

5.3 Criterion Model

A CM is a mathematical model used to formulate a criterion. It describes a mathematical relationship that is used to evaluate the layout plans. A CM can be described as Equation 2.

$$C = f(l_{F1}, l_{F2}, \cdots, l_{Fn}, p_0, p_1, \cdots p_m) \quad (2)$$

l_{Fn} is the location vector of the n^{th} facility and p_m is the m^{th} parameter that needs to be obtained *a priori*, e.g., the unit handling cost of a material/product for defining the material handling cost. These parameters are normally specified in the FLP task requirements. The target facilities include both new and existing facilities. After the virtual models representing the existing facilities have been built, the users can use the CMs to define the criteria. Figure 5.3.1 shows the process of using a CM to define a new criterion.

In this research, a set of CMs has been developed for the users to define some commonly used criteria. These are described next.

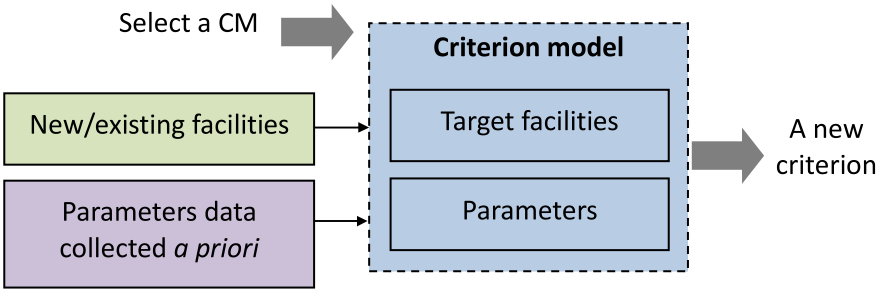


Figure 5.3.1: Procedure of defining a criterion

a. CM#I: <u>Data flow optimization</u> is used to model data flow, which includes the optimization of material handling cost, personnel, information flow, etc. Equation 3 is used.

$$CM_I = \min/\max \sum_{i,j=1}^{n} c_{ij} d_{ij} v_{ij} \tag{3}$$

c_{ij}, d_{ij} and v_{ij} are the unit cost, the distance and the volume of the data transferred from facility i to facility j respectively. Two methods for distance calculation, viz., the Euclidean distance and the rectilinear distance, are supported to cater to different scenarios. c_{ij} and v_{ij} are normally obtained from the shopfloor managers *a priori* (or specified in the layout task requirements) and input by the users in real-time.

b. CM#II: <u>Space occupancy rate</u> is used to assess the 3D space occupied by a group of facilities selected by the users. The criterion uses the ratio between the volume of the bounding box that contains all the selected facilities (V_u) and the volume of the planning space (V_{DS}), as shown in Equation 4.

$$CM_{II} = \min \frac{V_u}{V_{DS}} \tag{4}$$

c. CM#III: Distance maximization/minimization is used to define distance-based criteria, e.g., maximum distances between certain facilities, minimum distance for frequent facility maintenance, etc. Equation 5 is employed.

$$CM_{III} = \min/\max \sum_{i=1}^{m} d_i c \tag{5}$$

d_i is the distance between the facilities considered and c is the cost per unit length, which are obtained from the shopfloor managers (or specified in the layout task requirements) and input by the users in real-time.

The three CMs provided above cover a wide range of criteria that can be used to evaluate the layout plans. An interface is provided to allow the user to define more CMs. Any criterion evaluation method that can be represented using Equation 2 can be defined and used as a CM.

5.4 Constraint Function

A set of constraint functions is provided for the users to define the constraints to be incorporated during the planning process. Unlike the CMs, the constraints define the rules to be imposed on the facilities individually.

Each CF contains two sets of information, the evaluation rules and the resulting actions (if any). The evaluation rules define the methods to be used to evaluate the constraints and the resulting actions impose the specified restrictions on the facility. For example for collision detection, the evaluation rule is to detect whether any vertices of the active facility (during manual planning, users can only manipulate one facility at a time; the active facility refers to the facility that is being manipulated by the users) which are located within other facilities, and the resulting action is to revoke the latest movement command. The target facilities of CFs are the new facilities only. Figure 5.4.1 provides the flowchart of a CF.

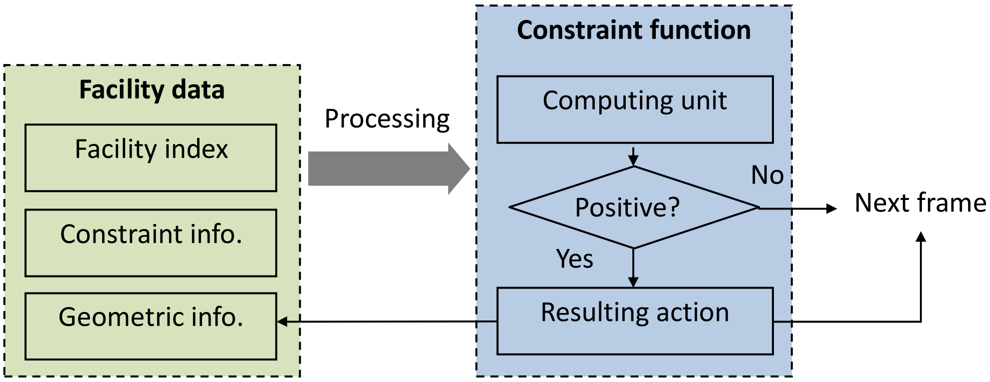


Figure 5.4.1 The working mechanism of the constraint function

In this research, four CFs have been developed, which can cover a number of commonly used constraints for FLP. New CFs can be defined through an interface by designing a constraint rule and a resulting action.

a. CF#I: Collision detection is used to examine any possible interference between the facilities. For each new facility, the data representing its bounding boxes is calculated upon the loading of the 3D model of this facility. During the planning process, if any vertex of the bounding box of this facility is detected to be located within the bounding box of another facility, collision is detected. The resulting action is to revoke the current transformation command as shown in Figure 5.4.2. During the manual planning process, collision detection can be simulated and augmented onto the shopfloor to facilitate and help the user in the decision making process.

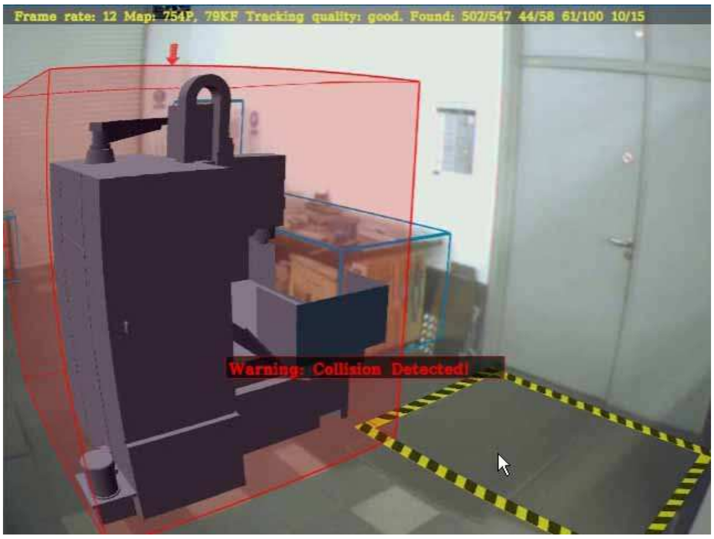


Figure 5.4.2: Simulated collision detection to assist manual planning

b. CF#II: Orientation constraint imposes restrictions on the poses of the facilities. For FLP, certain facilities have to be installed in a specific orientation, e.g., facing the back of a facility to a wall. To impose this constraint on a facility, the users will be prompted to input via the keyboard the CFII parameters in the facility data. During the planning process, the evaluation module will perform the following steps:

1. Determine the index of the nearest wall from the facility and calculate the rotation matrix r_0 from the real-time orientation to the required orientation.

2. Obtain the current orientation matrix r_t and calculate the rotation matrix $r_{CF}=r_o \cdot r_t^{-1}$.

The resulting action is a rotation command to apply r_{CF} to the facility to achieve the correct orientation.

c. CF#III: Space constraint defines the bounding boxes of the facilities. For some facilities, a certain amount of space may have to be provided for the purpose of maintenance, safety issues, etc. This constraint allows the users to resize the bounding box of a facility interactively in real-time as shown in Figure 5.4.3.

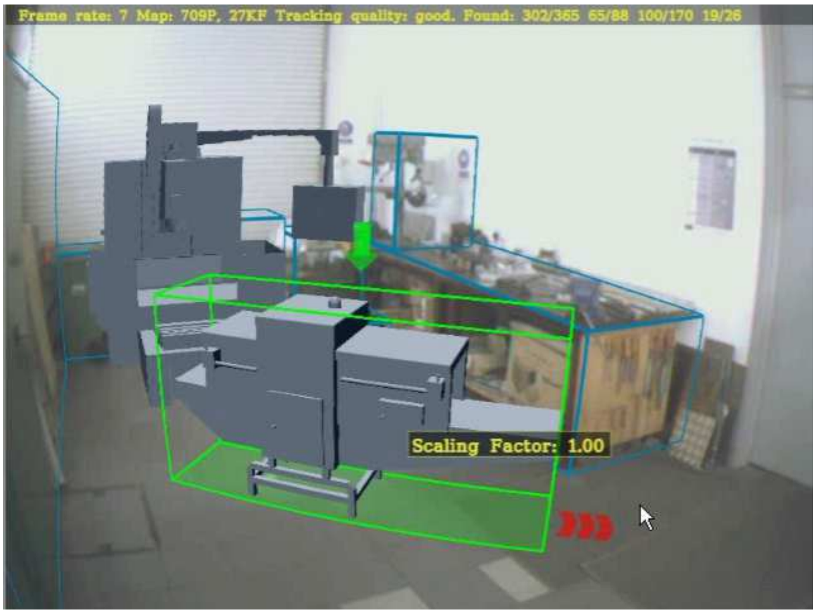


Figure 5.4.3: Definition of the space constraint

d. CF#IV: Location constraint defines the valid regions for locating a facility. To initialize the location constraint, the users need to define a planar surface in the shopfloor, e.g., the floor, and the contacting face (one of the six faces of the bounding box of the facility that contacts the defined regions for locating) of the facility, e.g., the bottom face for a facility to be installed on the floor. For manual planning, the resulting action is to revoke the most recent transformation command. The location constraint is useful during an automatic planning process.

5.5 The MADM model

In GMCC, to formulate the MADM model, the attributes are combined linearly by using the weighted sum method (Yang and Hung, 2007). The MADM model is thus formulated as follows.

$$Minimize\ C(L_{Fn}) = \{\alpha_1 w_1 cm_1(L_{Fn}) + \ldots + \alpha_m w_m cm_m(L_{Fn})\} \quad (6)$$

subject to

$$L_{Fn} = \{F(L_{Fn}) : L_{Fn} = \{l_{F1}, l_{F2}, l_{F3}, \ldots, l_{Fn}\}, l_{Fn} \in R^3\} \quad (7)$$

where,

$$F(L_{Fn}) = \{f_1(L_{Fn}), \ldots, f_k(L_{Fn})\} \quad (8)$$

C is the collection of the criteria/attributes; L_{Fn}={l_{F1}, l_{F2}, …l_{Fn}} is a feasible layout plan with l_{Fn} representing the location of the nth facility in this plan; cm_m is the mth attribute defined by using the CM; w_m is weight/priority value of the mth attribute; α_m=1 if the attribute is a minimization problem, and -1 if the attribute is a maximization problem; F is the collection of the constraints; and f_k is the kth constraint defined by using CF.

The weighted sum method has been widely applied in FLP (Yang and Hung, 2007, Shahin, 2010). In this research, the weighted sum method is employed for GMCC based on two reasons.

Firstly, the criteria to be applied for FLP/FLPES tasks are widely ranged. For the purpose of formulating different FLP/FLPES tasks using one generic method, the MADM modeling method adopted in GMCC needs to be scalable to problems with different number of attributes, and adaptable to combine attributes of varied types. By using the weighted sum method, the formulated MADM model is scalable as it imposes no constraints on the number of attributes; any criteria defined by the users can be added into the model. Moreover, by applying a weight value, attributes of different types can fit into the model easily, which makes it generic and adaptable for the FLP/FLPES tasks.

Secondly, GMCC is developed for interactive planning and evaluation, where human intelligence plays an important role in designing the MADM models. By using the weighted sum method, the users can design the MADM models and prioritize different attributes. The MADM is thus a straightforward representation of the FLP task, which can help the users evaluate the models during the planning process.

To solve the MADM model and obtain the layout plans, two planning modes can be implemented, viz., manual planning and automatic planning.

For manual planning, the users can manipulate the new facilities, e.g., translation, rotation, etc. These changes will be reflected in the criteria and the constraints. All the CMs and CFs are processed in real-time to provide immediate feedback to the users in the form of updated values of the criteria and the simulation and augmentation of the resulting actions. The users can use the feedback to guide their planning. During this information-aided manual planning process, both human intelligence and mathematical evaluation are used to facilitate the design of the layout plans.

Automatic planning refers to the use of heuristic algorithms to solve the model. There are several reported methods and algorithms to solve MADM models, e.g., the generic algorithm (Kamalinia *et al*., 2007), the simulated annealing algorithm (Abdelghani, 1995), etc. Results obtained by using automatic planning are purely based on the quantitative criteria defined by using the CMs and CFs.

By employing heuristic algorithms to solve the MADM model mathematically, automatic planning can typically be more efficient than manual planning. However, as automatic planning can only address the quantitative aspect of the layout plans described by the CMs and CFs, manual planning has the advantage of allowing the users to take qualitative aspects into consideration. Figure 5.5.1 shows a comparison between manual and automatic planning.

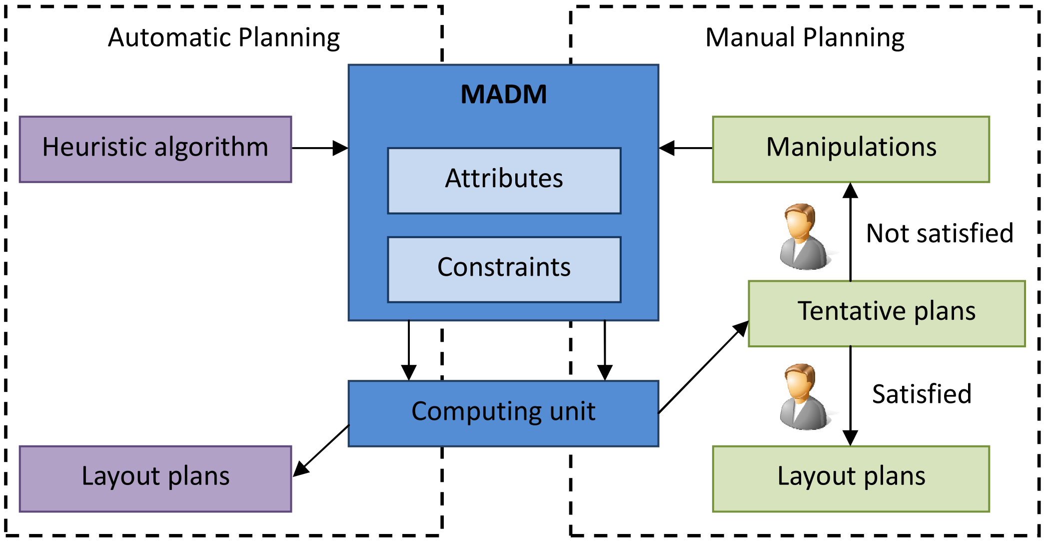


Figure 5.5.1: Manual vs. automatic planning

Chapter 6 A real-time reconstruction and inpainting method for AR applications

The aim of the real-time reconstruction and inpainting method (RRI) is to enhance user interactions in AR by allowing the users to reconfigure an augmented scene through manipulating the virtual replicas of real objects in the augmented scene. In RRI, a real-time reconstruction technique is used to create virtual replicas of the real objects and a real-time inpainting technique is used to conceal the original real objects. Hence, using the RRI method, the users can manipulate the virtual replicas in an augmented scene as though they are manipulating the real objects.

6.1 Method

The proposed RRI methodology is illustrated in Figure 6.1.1. The mapping result produced by the tracking module will be processed using a point clustering technique to obtain information on the distribution of the physical objects in the real scene. Using this information, physical objects in the scene can be reconstructed individually with less user intervention. Virtual replicas of the real objects can thus be produced.

Based on the camera tracking result, the 2D areas of these objects in the frames can be obtained. To conceal these areas, an inpainting technique (Criminisi *et al.*, 2003) is executed for each frame. Consequently, in the camera view, the real objects are inpainted leaving their virtual replicas. Using an object manipulation mechanism, the users can manipulate the virtual replicas to “reconfigure” the scene. In this framework, the two key techniques are real-time tracking and reconstruction, and real-time inpainting.

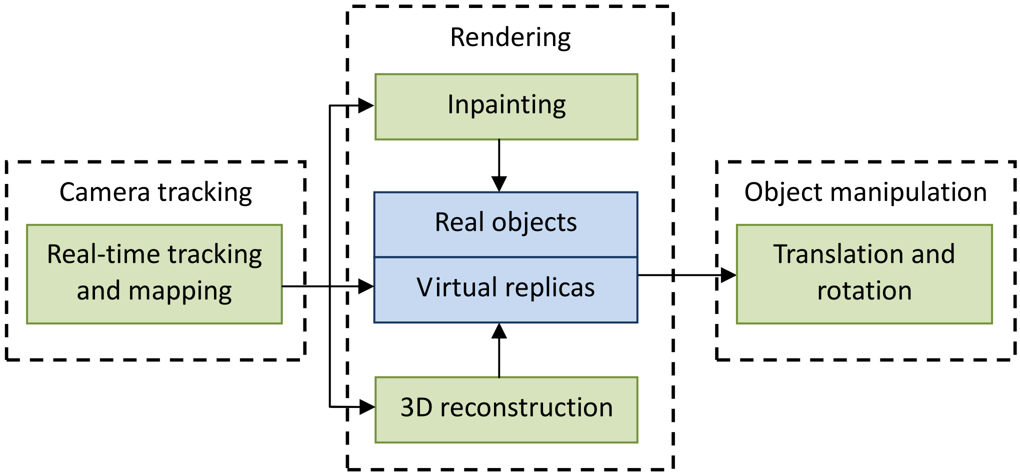


Figure 6.1.1: The RRI method

6.1.1 Real-time reconstruction

The parallel tracking and mapping system (PTAM) is adopted for camera tracking. Based on the mapping result of the real scene, a point clustering technique is employed to detect possible point clusters in the map. From the clustering result, the location and a possible shape of each real object can be obtained. To implement this process, a rudimentary distance-based point clustering technique is employed and the bounding box of each point cluster is used for reconstruction. The ultimate aim of the reconstruction method is to reconstruct each object automatically without user intervention.

6.1.2 Real-time inpainting

For the RRI methodology, image inpainting has to be performed at high frame rates, which means real-time inpainting. In this research, real-time inpainting is defined as the process to remove a number of unwanted objects from the real scene (in the camera view) simultaneously as the camera captures a live video of the scene. It is more difficult to carry out a spatial-temporal analysis in real-time inpainting tasks than in off-line tasks since the frames are not pre-captured. Moreover, to inpaint a specific object in a real scene, object tracking is a critical issue.

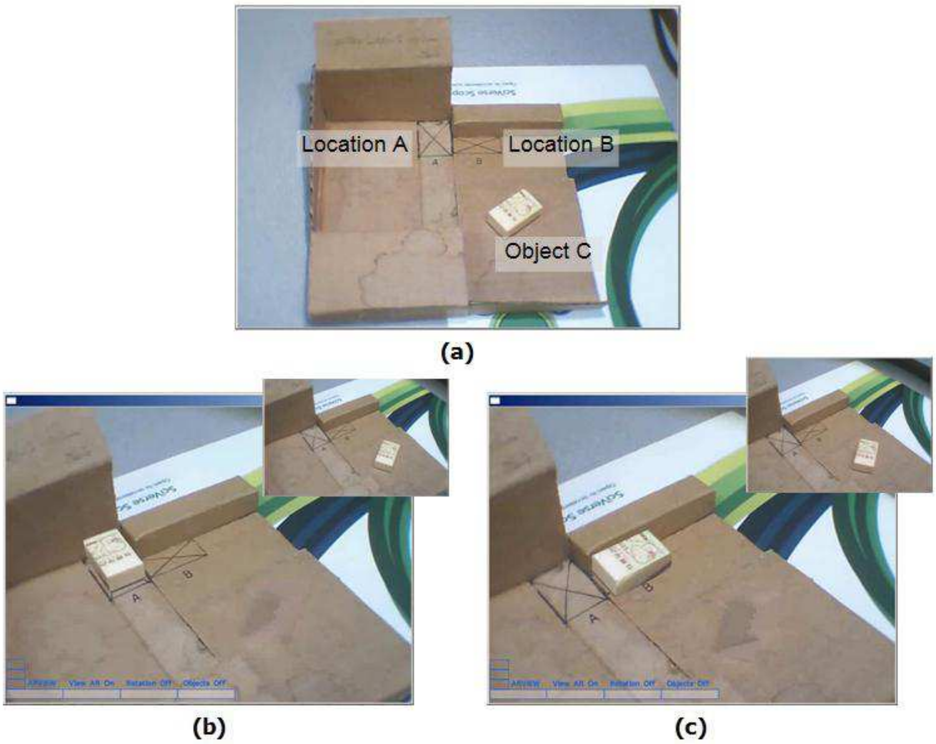
One straightforward approach is to employ a camera tracking technique to obtain the region of the object to be inpainted and execute an image inpainting algorithm for each frame. The regions occupied by the target objects can be obtained and updated in real-time. To inpaint these regions, the exemplar-based image technique reported in (Criminisi *et al*., 2003) is performed for each frame. In addition, to accelerate the processing speed, an exemplar pool is utilized which stores the exemplars used for inpainting the first frame. In real-time, by using the exemplar pool instead of the entire frame as the source region, the time spent on searching for valid exemplars can be greatly reduced.

6.2 Demonstration

The proposed RRI method has been tested on a laptop with a 2.56GHz Intel Pentium III Xeon Processor and a NVIDIA GeForce 9600M GT video card. Figure 6.2.1 and Figure 6.2.2 shows two experiments that demonstrate the utilization of RRI.

*The window on the lower right corner of each figure shows the real scene

Figure 6.2.1: Experiment I



*The window on the upper right corner of each figure shows the real scene

Figure 6.2.2: Experiment II

Figure 6.2.1 shows Experiment I where RRI is used to move a real stamp from one envelop to another. In Experiment II, as shown in Figure 6.2.2, RRI is used to move the eraser (Object C) to Location A and Location B.

Due to the high computational burden required by the inpainting technique, the current RRI method can only inpaint a relatively small area (about 40 pixels by 40 pixels) in real-time, which makes it not suitable for FLP tasks. Future research will investigate into fast inpainting techniques for large areas.

Chapter 7 An AR-based facility layout optimization and evaluation system

In this chapter, the architecture of the AFLOE system (AR-based facility layout optimization and evaluation) is presented. The AFLOE is developed based on the ARHFLP approach. The system consists of four modules, namely, user interaction, real-time modeling, evaluation, and optimization modules. The user interface, the use of the system, and the hardware requirements are provided.

7.1 Introduction

AFLOE adopts the ARHFLP approach to address the characteristics of FLPES, such as the wide range of the criteria and constraints, the presence of existing facilities, etc. PTAM is adopted for real-time marker-less camera tracking. Virtual models of the new facilities to be laid out need to be constructed *a priori*. In AFLOE, new facilities are augmented onto the real shopfloor and layout planning is the process of planning the locations of these facilities. AFLOE provides an easy-to-use and effective tool for FLPES tasks.

7.2 File systems in AFLOE

In AFLOE, information representing the virtual models, the criteria, the constraints, etc., are sorted and stored as different objects. A unique file type is designed for each type of object. The main objects and their file types are presented next.

7.2.1 Facility object

Facility objects represent the facilities to be considered during the planning process, and they include both the existing and the new facilities. When a new facility is loaded in the system, or a primitive model representing an existing facility has been built, a facility object is created. Table 7.2.1 shows the contents of a facility object.

Table 7.2.1: Contents of a facility object

Facility index	Fixed
Facility type	Fixed
Geometric data	Fixed
Location/pose	Updated in real-time for new facilities; Fixed for existing facilities
Constraints data	Updated in real-time

The facility type indicates whether it is an existing facility or a new facility. The geometric data refers to the virtual models of the new facilities and the primitive models of the existing facilities. The location/pose data for the new facilities can be updated in real-time to reflect the manipulation of these facilities, whereas the location/pose data cannot be modified for the existing facilities. The location and pose data can be accessed by the system for computing the criteria and constraints. The constraints data store the information on the types of the CFs that have been defined for this facility and the real-time status (positive or negative) of these constraints.

7.2.2 Criterion object

When the user defines a CM to represent a new criterion, a criterion object is created. A criterion object provides information on the type and contents of the criterion. Table 7.2.2 shows the contents of the criterion object.

Table 7.2.2: Contents of the criterion object

Criterion index	Fixed
Criterion name	Defined in real-time
CM Type	Defined in real-time
Target facilities	Defined in real-time
Parameters	Pre-defined
Current values	Updated in real-time

During the definition of a new criterion object, the users need to provide a criterion name. The types and parameters of the CM indicate the type of the CM and its parameters, such as the indices of the target facilities, the data of the parameters, etc. The criterion is processed in real time and the results are updated in the current values.

7.2.3 Layout plan object

A layout plan object stores the information of a layout plan. Plan objects are produced in both manual and automatic planning. Table 7.2.3 shows the contents in a layout plan object.

Table 7.2.3: Contents of the layout plan object

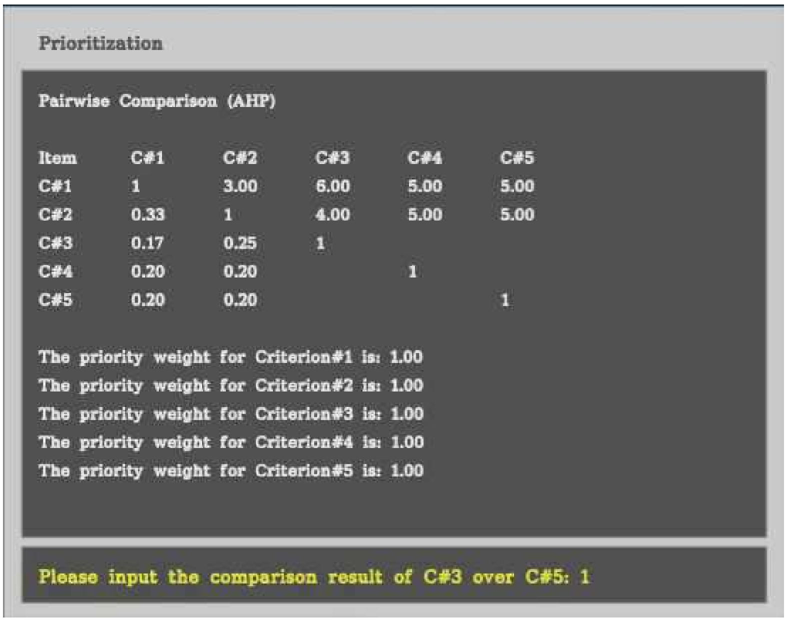
Plan index	Fixed
Plan type	Defined in real-time (manual/auto.)
Indices of the new facilities	Real-time updated
Indices of the existing facilities	Fixed
Criteria information	Updated in real-time
Constraints information	Updated in real-time

The plan type indicates whether the plan is produced manually or automatically. The criteria information provides the achieved values for each criterion.

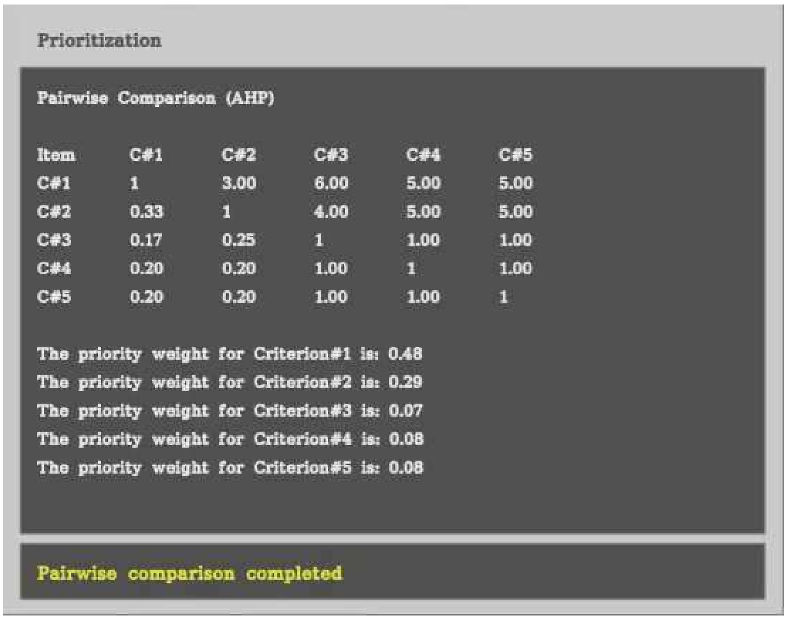
7.3 Optimization strategy

By using GMCC, AFLOE formulates FLP problems as MADM models. During automatic planning, heuristic algorithms are used to solve the models. As a well-developed algorithm for MADM, AHP-GA is employed in AFLOE.

In addressing MADM problems, AHP can be adopted to produce weighting schemes for the different attributes. As shown in Figure 7.3.1, the users will need to input pair-wise comparisons between the attributes. The comparison results are used to form a comparison matrix. By using the eigenvector method (Saaty, 1980), prioritized weights for the attributes can be obtained. In AHP-GA, the weighting schemes are applied to combine the attributes of the MADM model, a single-objective optimization problem can be obtained, which can be solved using GA.



a. Making pair-wise comparison



b. The obtained weighting scheme

Figure 7.3.1: Use the command window to implement AHP

For FLP, when the criteria are assigned with weights based on the users' knowledge and preferences, different weighting schemes can be formed to produce layout plans with varied characteristics, which may be very valuable for decision making. The design of the GA adopted in AFLOE is presented next. Figure 7.4.1 shows the workflow of the GA.

a. Encoding

By using GA, each layout plan is represented as a chromosome. The location of a facility in a layout plan is coded as a gene of the chromosome. For example, for a layout plan L_N, the chromosome representation for GA is (F_{N0}, F_{N1}, F_{N2}, … F_{Ni}), where F_{Ni}=(X_{FNi}, Y_{FNi}, Z_{FNi}) is the coordinates of the facility i in the world CS.

b. Initial population

The initial population of size P_{size} is a randomly generated population of chromosomes. In AFLOE, the default population size is set to 50 (Zakaria *et al*., 2011).

c. Fitness function

The fitness function evaluates the qualities of the chromosomes. In AHP-GA, the combination of the weighted attributes is used as the fitness function (Equation 9).

$$\min \sum_{i=1}^{m} \alpha_i \cdot w_i \cdot \frac{C_i - C_{i\min}}{C_{i\max} - C_{i\min}} \tag{9}$$

m is the number of the criteria defined by the users. For the i^{th} criterion, w_i is the weight assigned; α_i is 1 if the criterion is a minimization problem or -1 if it is a maximization problem; C_i is the value of the criterion; C_{imax}/C_{imin} is the maximum/minimum value that the criterion can achieve. In the first execution of the optimization module, an initial run is performed to obtain estimated values of C_{imax} and C_{imin}.

d. Selection

The commonly used fitness proportionate selection method is used. By using this method, for a chromosome *i* in a population, its probability to be selected P_i is calculated by using Equation 10.

$$P_i = \frac{F_i}{\sum_{n=1}^{m} F_n} \tag{10}$$

e. Crossover and mutation

The single point crossover method is used. In this crossover method, one crossover point is selected from the parent chromosomes and the offspring is produced by exchanging the parents' genes from the beginning of the chromosomes to the crossover point. The mutation is implemented by swapping two randomly selected genes. The default crossover rate and mutation rate are set to 0.8 and 0.01 respectively (Zakaria *et al*., 2011).

f. Termination condition

The ages of the propagation is used as the termination condition, i.e., the number of generations. The default termination generation is set to 200^{th}. As the algorithm is performed in real-time, the number of the reproduction generation determines the time that the automatic planning needs to take. In AFLOE, an interface is provided for the users to customize the GA parameters, such as population size, mutation and crossover rates, and termination generations.

g. Penalty

For each chromosome, constraints are imposed as penalties. After a new offspring is produced, the imposed CFs will be processed to examine the feasibility of the offspring (a layout plan). If a CF is violated, the penalty will be activated to set the fitness value as -1.

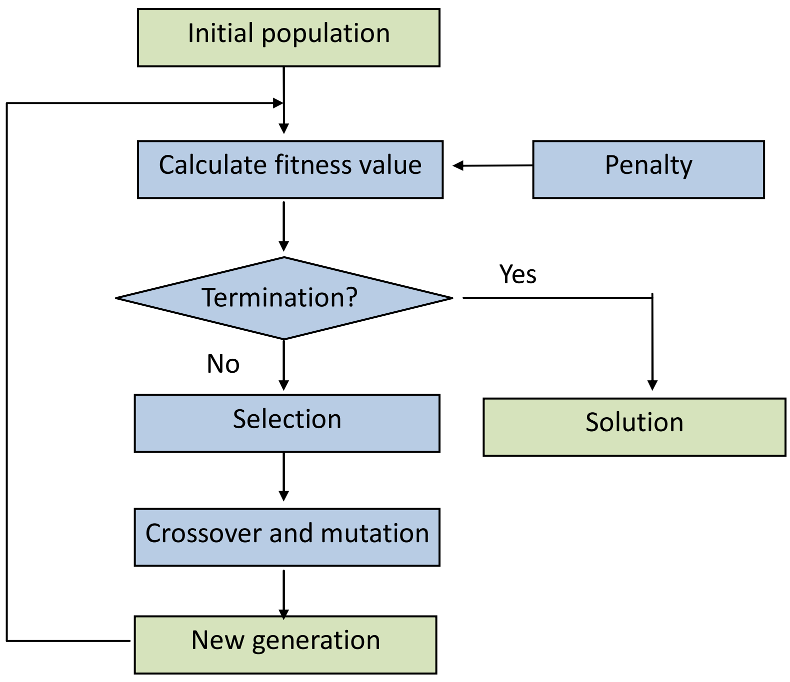


Figure 7.4.1: Workflow of the GA adopted in AFLOE.

7.4 Architecture of the AFLOE system

PTAM is used for real-time marker-less camera tracking in AFLOE. Virtual models of the new facilities to be laid out need to be constructed *a priori*. These models will be augmented onto the real shopfloor for manipulation during the planning process. As shown in Figure 7.4.2, four modules are used to implement the AFLOE system, viz., user interaction, real-time modeling, evaluation, and the optimization modules.

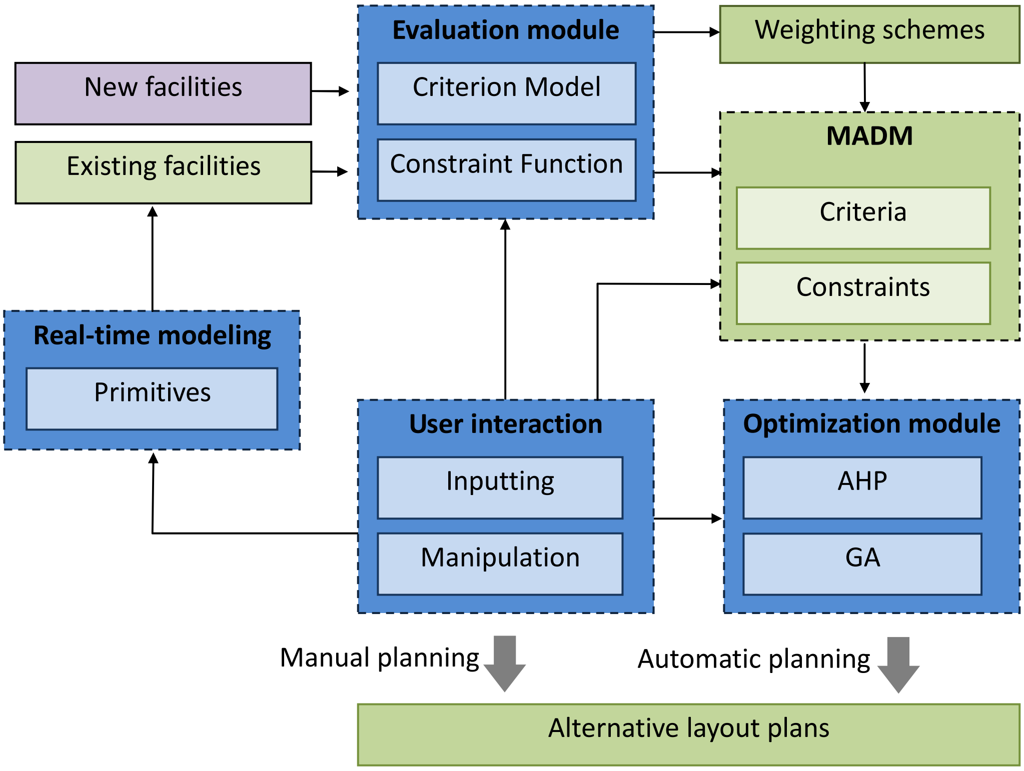


Figure 7.4.2: Architecture of the AFLOE system

The user interaction module provides an interface for the users to communicate with the system. By using the mouse and the keyboard, the users can send different commands to the system, such as the manipulation of the models, input the required parameters, edit the names, etc. In particular, the manipulation command provides a wide range of transformations, such as translation, rotation, scaling, extruding (for building models), etc.

The real-time modeling module provides an implementation of the modeling method presented in Chapter 4. The users can use the transformation commands provided by the user interaction module to control the modeling module to construct virtual models of the shopfloor environment. In AFLOE, the modeling module is used to model the planning space as well as all the existing facilities in this space. The planning space is a 3D open space in the shopfloor that contains all the new/existing facilities to be considered during the planning process.

The evaluation module implements the GMCC method (Chapter 5). The three CMs and the four CFs presented in Chapter 5 are provided in the evaluation module. The user interaction module allows the users to input and edit the parameters in the mathematical models in real-time. All the criteria and constraints are processed frame by frame from the video stream captured using the web camera, and the results are presented to the users either in terms of numerical values for the criteria or resulting actions for the constraints.

The optimization module uses the AHP-GA algorithm (Section 7.3) to implement automatic planning. After the users have defined the criteria and constraints, the optimization module can be invoked to solve the MADM model. As shown in Figure 7.4.3, the users will be first prompted to make pair-wise comparisons between the criteria via the command window (Figure 7.3.1). The comparison results will be processed by AHP to obtain a weighting scheme. By employing the weighting scheme, GA can produce an optimized solution, which will be adopted by the new facilities immediately and rendered on-site.

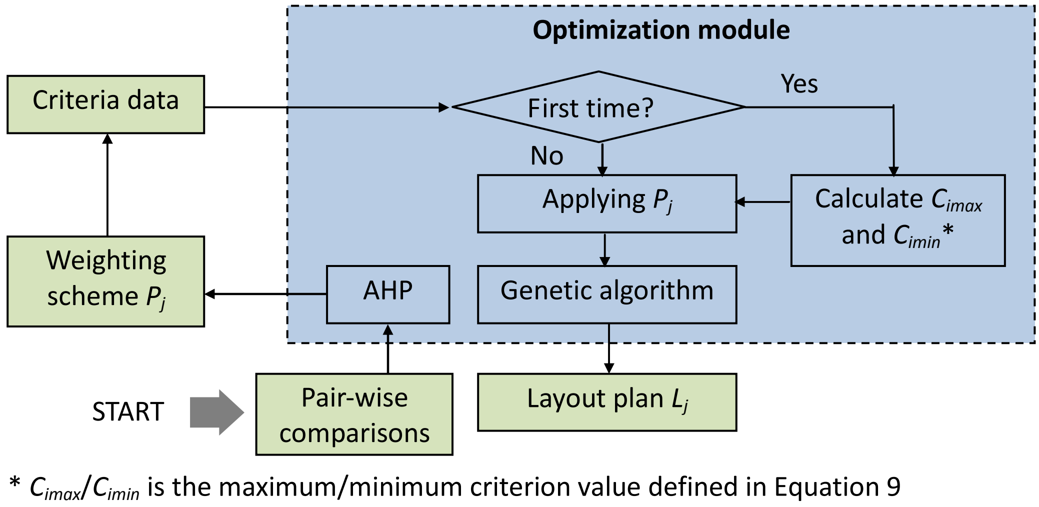


Figure 7.4.3: Workflow of the AHP-GA in the optimization module.

7.5 Hardware configuration

Two types of hardware configurations can be used, as shown in Figure 7.5.1 and Figure 7.5.2.

In Figure 7.5.1, a tripod is used to support the web camera to obtain a static view of the scene. During the planning process, as the users need to interact with the system via the mouse, a static view of the scene would be easier for the users. During the planning process, the users need to view the shopfloor through the camera from different perspectives. However, with the camera fixed on a tripod, this hardware configuration is not portable.

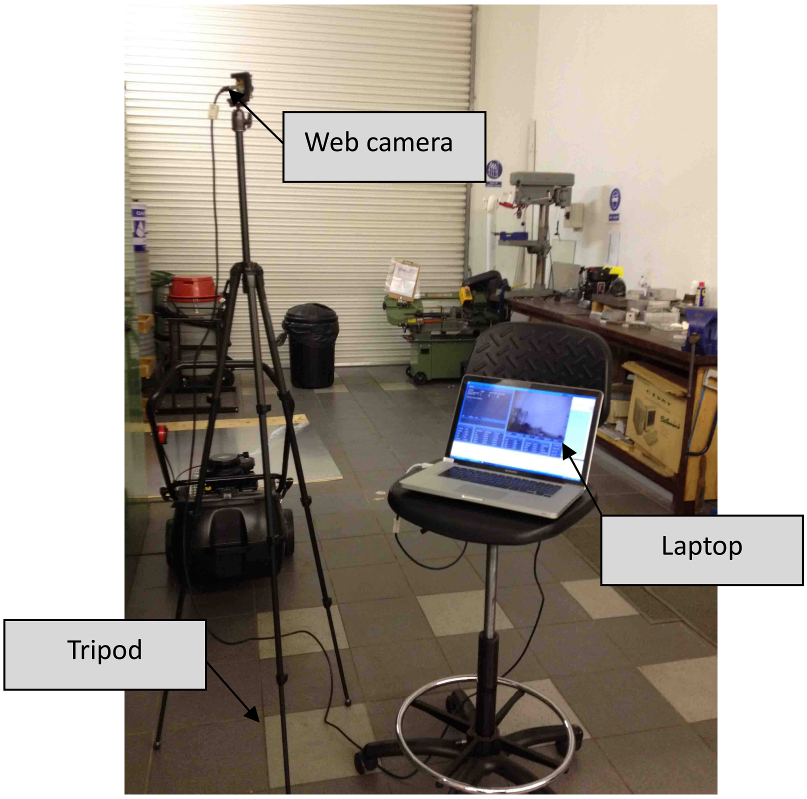


Figure 7.5.1: Hardware setting - Configuration A

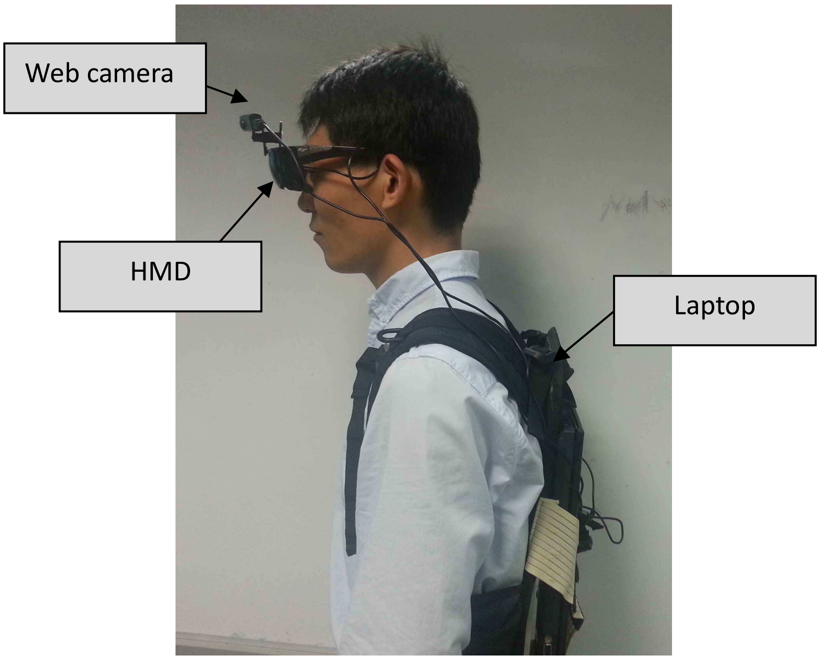


Figure 7.5.2: Hardware setting - Configuration B

In Figure 7.5.2, Configuration B uses a head-mounted display (HMD) to capture the live video streams and display the results to the user, and the user carries a laptop. In this configuration, it may not be easy for the user to keep the camera still to provide static views of the scene, which may cause problems in the execution of the modeling technique. However, when compared with Configuration A, Configuration B is wearable and thus provides more freedom for the users to move.

7.6 System Overview

The interface of the AFLOE system is depicted in Figure 7.6.1.

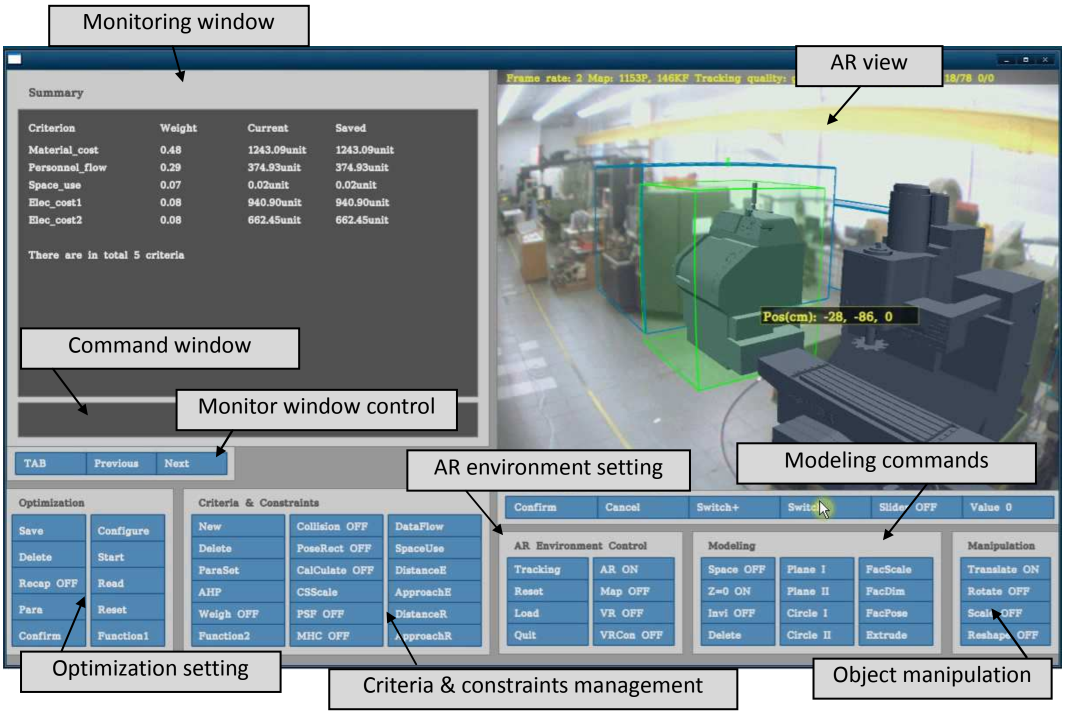


Figure 7.6.1: System interface of AFLOE

Based on the mapping results produced using PTAM, AFLOE starts with inserting a CS into the shopfloor environment. The users can define a CS by specifying its origin and any two points on the *x*-*y* plane. The location, pose and scale of the CS can be adjusted manually. After the definition of the CS, the users will be prompted to input the length of the axis of the CS L_W. A global scaling factor S_G is defined as Equation 11.

$$S_G = L_S / L_W \tag{11}$$

L_S is the length of the axis measured in the system unit. The global scaling factor is used to scale all the necessary measurements to the actual dimensions before they are presented to the users.

Next, the system will prompt the users to define the planning space and construct the existing facilities in this space. Using the real-time modeling technique, the planning space can be defined interactively as the user walks in the shopfloor. The planning space should be a 3D volume that contains all the usable regions for the new as well as existing facilities. In the planning space, the user can construct approximate primitive models and refine them manually through transformations in terms of translation, rotation, scaling, etc., until they represent the facilities well. After the shopfloor has been constructed, the new facility models can be loaded and rendered onto the real shopfloor. In the AR view, the facility models might not have been rendered to the real-scale; they could either be larger or smaller than the actual size. The users will be prompted to input the real dimensions of the new facilities. By applying the global scaling factor, the new facilities can be rendered to the real scale correctly.

When all the facilities have been defined, the users can use GMCC to define the MADM model to carry out FLP and evaluate the layout plans. The users can invoke the evaluation module and choose appropriate CMs to define the criteria according to the task requirements. These criteria are normally the objectives defined in the FLP task requirements, such as the minimization of the material handling cost. As the user walks in the shopfloor and examines the surroundings, he may identity additional layout issues, which he can use the CMs to define these issues as criteria. Constraints can be imposed on the facilities individually. As constraint simulation is provided as functions, the users can choose to turn on/off the functions as needed.

With the definition of the criteria and all the necessary constraints, the MADM model is constructed. The users will proceed to the planning stage. Two planning modes are supported, namely, manual and automatic planning. For manual planning, the users can manipulate the new facilities in the real shopfloor environment. The users' intelligence, knowledge, expertise, and intuitiveness can be fully employed to facilitate the planning process. Besides, the evaluation of the criteria and the constraints is processed and presented to the users in real-time, which will help the users in making the final decision. To perform automatic planning, the optimization module can be invoked. The users will be prompted to make pair-wise comparisons between the criteria, based on which the AHP will be executed to produce the weighting scheme, and GA will be used to produce an optimized layout plan. The optimization module can be implemented multiple times to generate different layout plans based on different weighting schemes. Figure 7.6.2 shows the workflow of the AFLOE system.

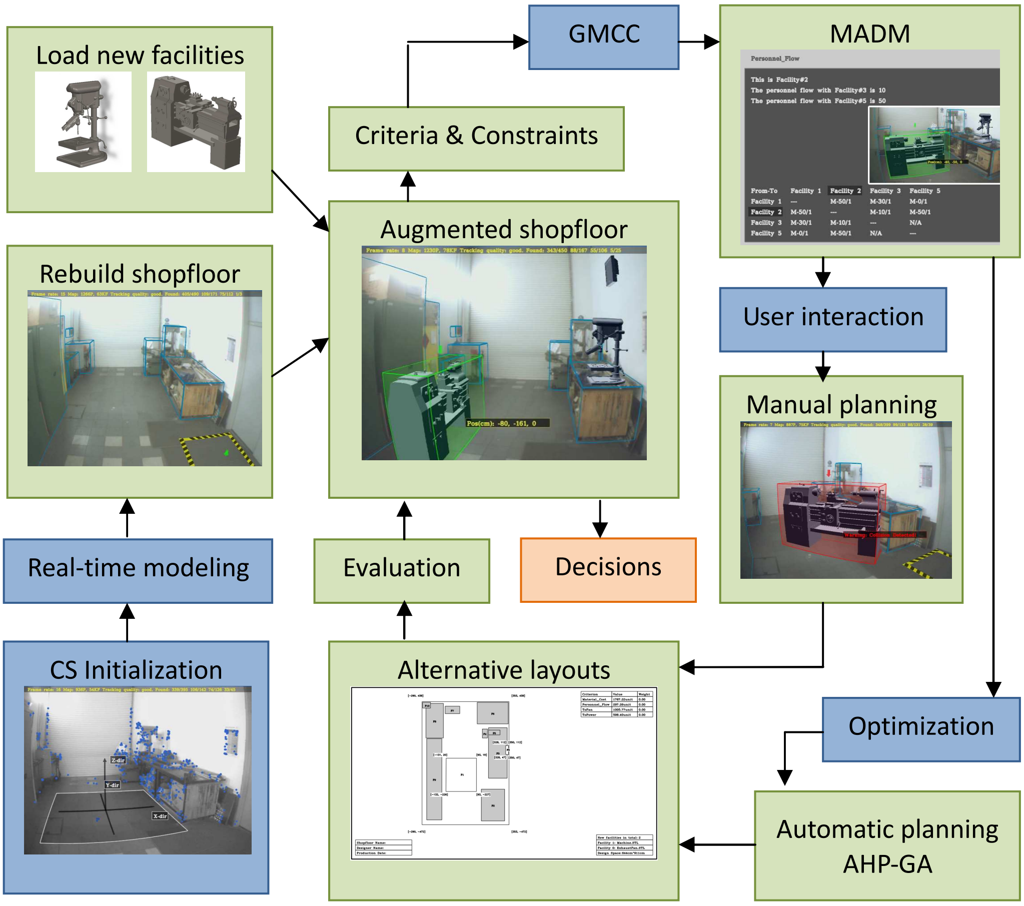


Figure 7.6.2: Workflow of the AFLOE system

Chapter 8 Case study and discussion

In this chapter, two case studies are presented to demonstrate the system under different FLP scenarios. For evaluation purposes, user studies have also been conducted and presented. The questionnaire used for the user study is provided in Appendix A. The AFLOE system is developed on a laptop with a 2.56GHz processor and an NVIDIA GeForce 9600M GT video card. A 1394 webcam is used to capture live videos.

8.1 Case study I

In this case study, a simplified FLPES task is conducted (Figure 8.1.1).

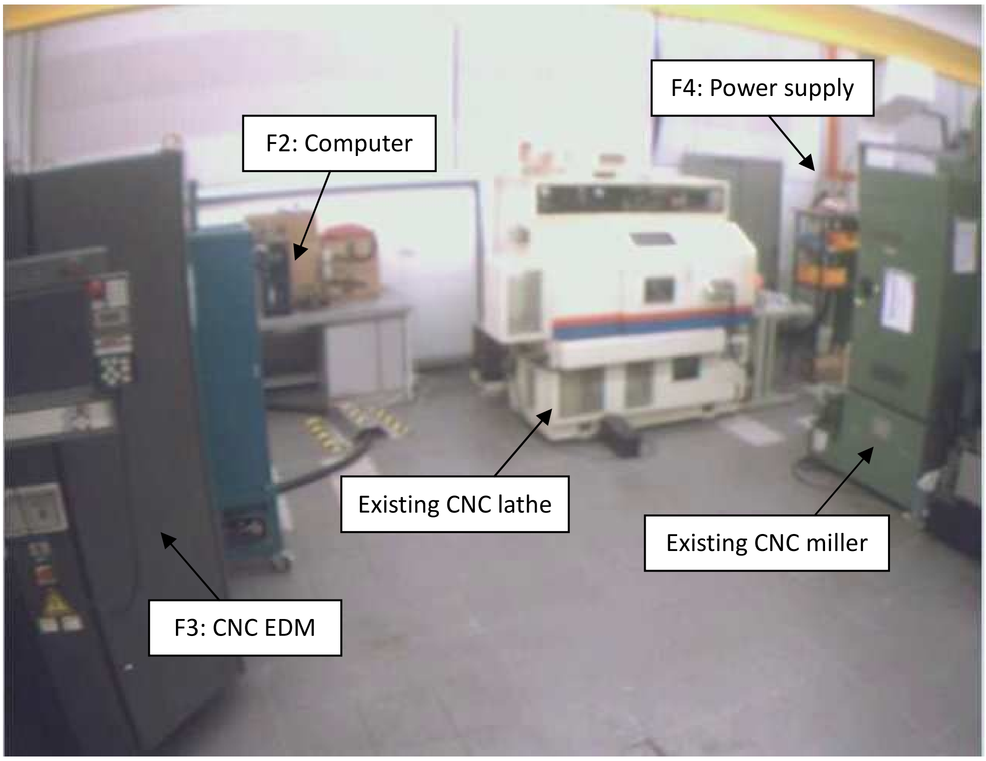
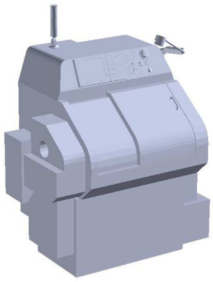
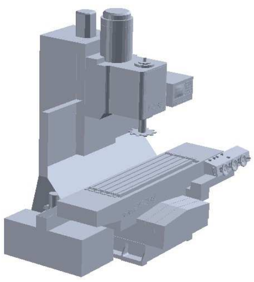


Figure 8.1.1: The shopfloor environment

As shown in Figure 8.1.1, two new facilities, viz., a CNC lathe (Facility#0) and a CNC miller (Facility#1) needs to be installed in the shopfloor to replace the existing CNC lathe and CNC miller. The FLPES task is to design a new shopfloor layout consisting of these two facilities.

Table 8.1.1 shows the constraints to be imposed on the two facilities. The criteria required by the task are provided in Table 8.1.2. Figure 8.1.2 shows the snapshots captured during the use of the AFLOE system to address the FLPES task.

Table 8.1.1: Constraints to be imposed on the facilities

	CNC lathe (Facility#0)
	Con#1: Orientation constraint: the back facing the walls. Con#2: Location constraint: on the floor. Con#3: Space constraint for operation and maintenance purposes. Con#4: Collision detection.
	CNC miller (Facility#1)
	Con#1: Orientation constraint: the back facing the walls. Con#2: Location constraint: on the floor. Con#3: Space constraint for operation and maintenance purposes. Con#4: Collision detection.

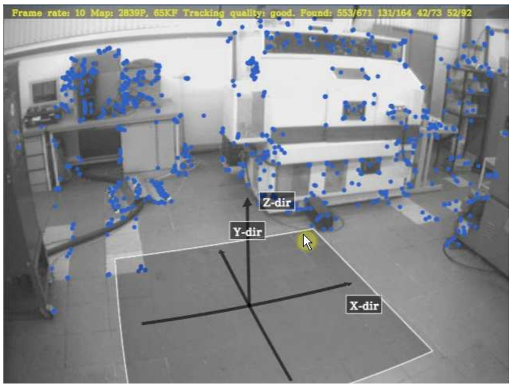
As shown in Figure 8.1.2, the users firstly define a CS in the shopfloor, of which x-y plane is coplanar with the floor. By using the fast modeling technique, the users build virtual models for the existing facilities. Models of the new facilities are loaded. Next, the user invokes GMCC to define the criteria and constraints and the MADM model is thus defined. Table 8.1.3 shows the utilization of the CMs/CFs in defining these criteria and constraints.

Table 8.1.2: The criteria required in the task

Criterion	Contents and data (specified by the task requirement)
Cri#1: Minimize the material handling cost	From the EDM to the lathe: 40/2 From the EDM to the miller: 60/1 From the lathe to the miller: 80/1 (unit: pcs per day/unit cost*)
Cri#2: Minimize the personnel flow	From the EDM to the lathe: 10 From the EDM to the miller: 10 From the EDM to the computer: 40 From the lathe to the miller: 5 From the lathe to the computer: 30 From the miller to the computer: 30 (unit: pers. per day)
Cri#3: Minimize the space occupancy	The space occupied by the CNC lathe and the CNC miller
Cri#4: Minimize the distance between the CNC lathe and the power supply	Rectilinear distance from the lathe to the power supply (unit: cm)
Cri#5: Minimize the distance between the CNC miller and the power supply	Rectilinear distance from the miller to the power supply (unit: cm)

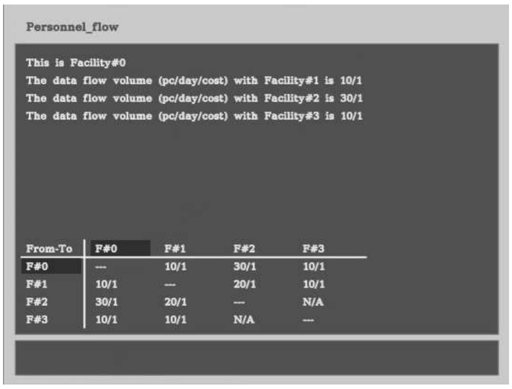
*The unit cost is a relative value

During the manual planning process, as the users manipulate the models of the new facilities, the criteria and constraints are computed and updated in real-time. As shown in Figure 8.1.3, the monitoring window provides the values of the criteria. Based on these values and the users' knowledge and experience, a manual planning design (Plan A as shown in Figure 8.1.4) is produced. The plan is saved as a JPG file.

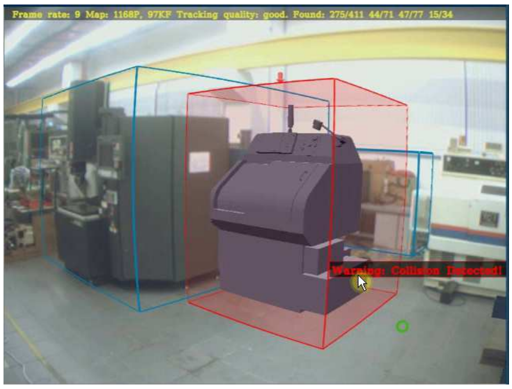


(a) Initialization

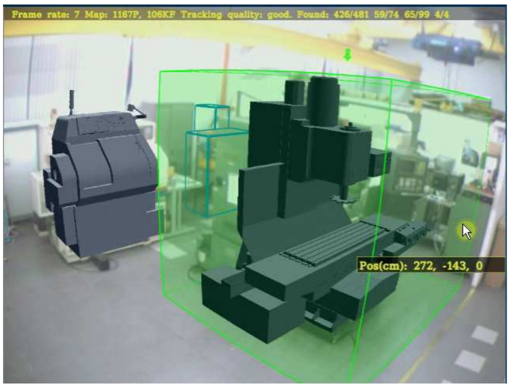
(b) Real-time modeling



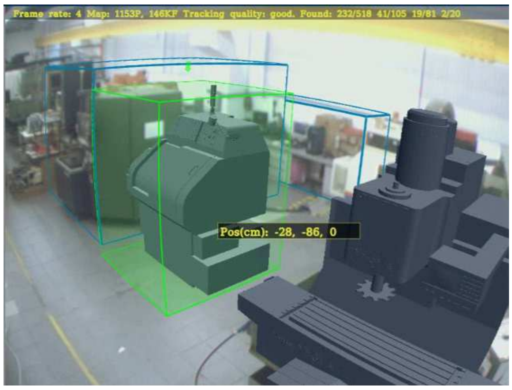
(c) Defining the criteria



(d) Collision detection



(e) Plan A (manual planning)



(f) Plan B (automatic planning)

Figure 8.1.2: Using AFLOE to address the FLPES task

Table 8.1.3: Utilization of the CMs/CFs

Criteria/constraints	CM/CF
Criteria: Cri#1-Cri#2-Cri#3-Cri#4-Cri#5	CM#I-CM#I-CM#II-CM#III-CM#III
Constraints for the lathe: Con#1-Con#2-Con#3-Con#4	CF#II-CF#IV-CF#III-CF#I
Constraints for the miller: Con#1-Con#2-Con#3-Con#4	CF#II-CF#IV-CF#III-CF#I

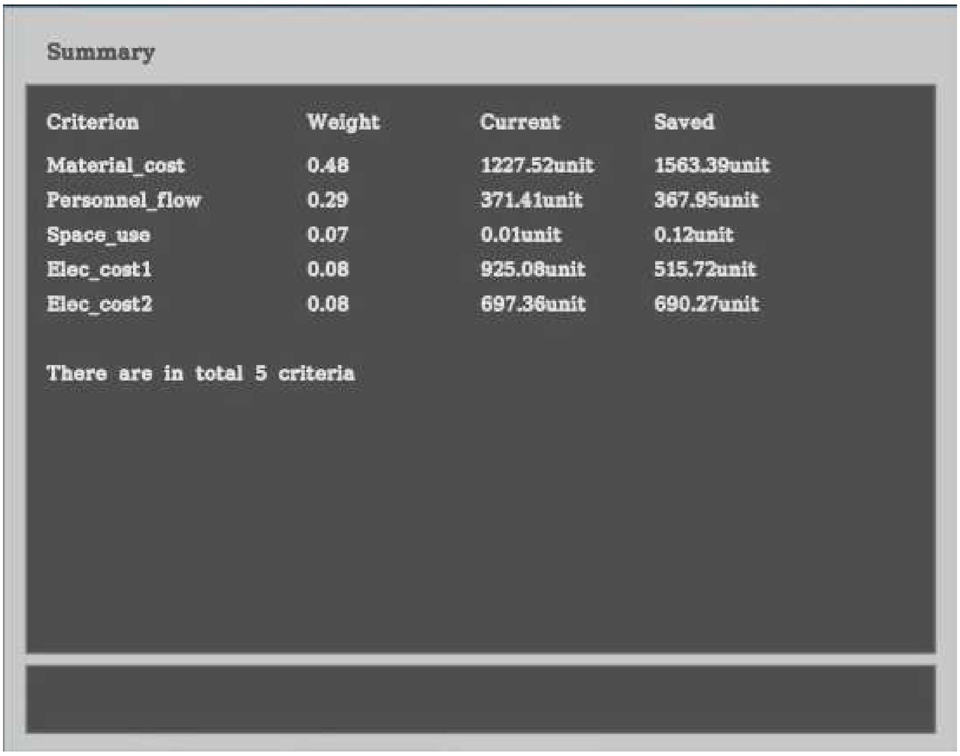


Figure 8.1.3: The monitoring window updates the criteria values

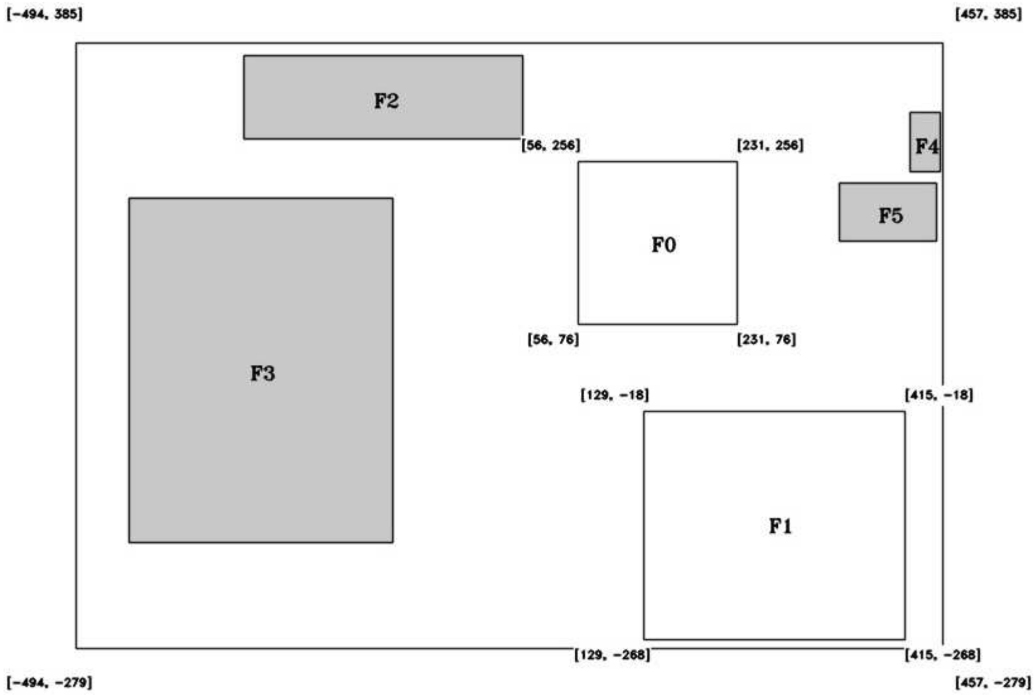


Figure 8.1.4: Plan A (manual planning)

To perform automatic planning, the optimization module is invoked. The users are prompted to make pair-wise comparisons between the criteria though the command window. The comparison result is shown in Figure 7.3.1. Next, AHP is invoked to process this result and a weighting scheme is produced as Cri#1-0.48, Cri#2-0.29, Cri#3-0.07, Cri#4-0.08, and Cri#5-0.08. The system loads the weights and generates an automatic planning design (Plan B), as shown in Figure 8.1.5.

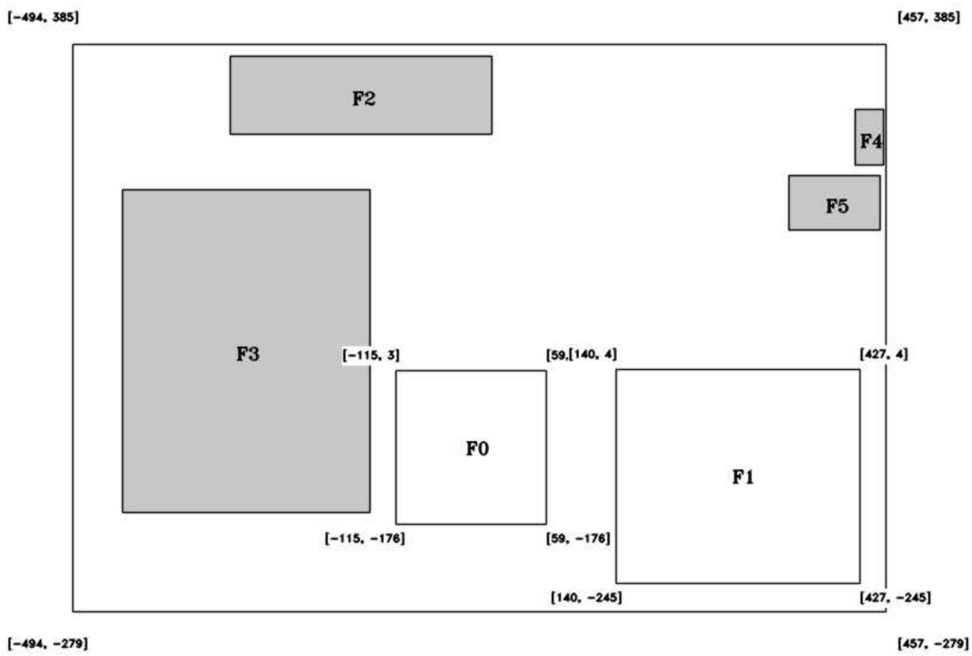


Figure 8.1.5: Plan B (automatic planning)

Table 8.1.4 provides a comparison of the two layout plans in terms of the defined criteria. From Table 8.1.4, Plan B makes improvement for Cri#1, Cri#3, and Cri#5, whereas the advantage of Plan A lies in Cri#4. For Cri#2, the two plans are comparable. With Cri#1 and Cri#2 carrying almost 80% of the total weights, Plan B is more efficient.

Table 8.1.4: Quantitative comparison between Plan A and Plan B

Criterion (unit)	Weight	Plan A	Plan B
Cri#1 (pcs. per day × unit cost × cm)	0.48	1563.39	1243.09
Cri#2 (pers. per day × cm)	0.29	367.95	374.93
Cri#3 (1)	0.07	0.12	0.02
Cri#4 (cm)	0.08	515.72	940.90
Cri#5 (cm)	0.08	690.27	662.45

The major difference between the two plans lies in the location of the CNC lathe (Facility#0). With the heavy material flow between the CNC lathe, the CNC miller, and the CNC EDM, locating the three facilities near each other can reduce the material handling cost. However, although Plan A has a higher material handling cost, it satisfies the layout preference that the new CNC lathe is located at the location of the old CNC lathe. This preference may have positive effects on maintain current work practise. The final decision between the two plans lies with the users.

8.2 Case study II

In this case study, three new facilities are to be installed in the shopfloor, viz., a display monitor (Facility#0) a bench drill press (Facility#1), and a lathe (Facility#2). The shopfloor is shown in Figure 8.2.1.

Table 8.2.1 shows the constraints to be imposed on these facilities. The criteria required by the task are provided in Table 8.2.2. Figure 8.2.2 provides some snapshots captured during using AFLOE to address the FLPES task.

During the definition of the criteria, besides the four criteria required by the task, as the users inspect the shopfloor on-site, an additional issue is identified, i.e., the display monitor is preferred to be located near the power supply; this is defined as Criterion#4 (Cri#4). The utilization of the CMs/CFs in defining the criteria and constraints is presented in Table 7.2.3.

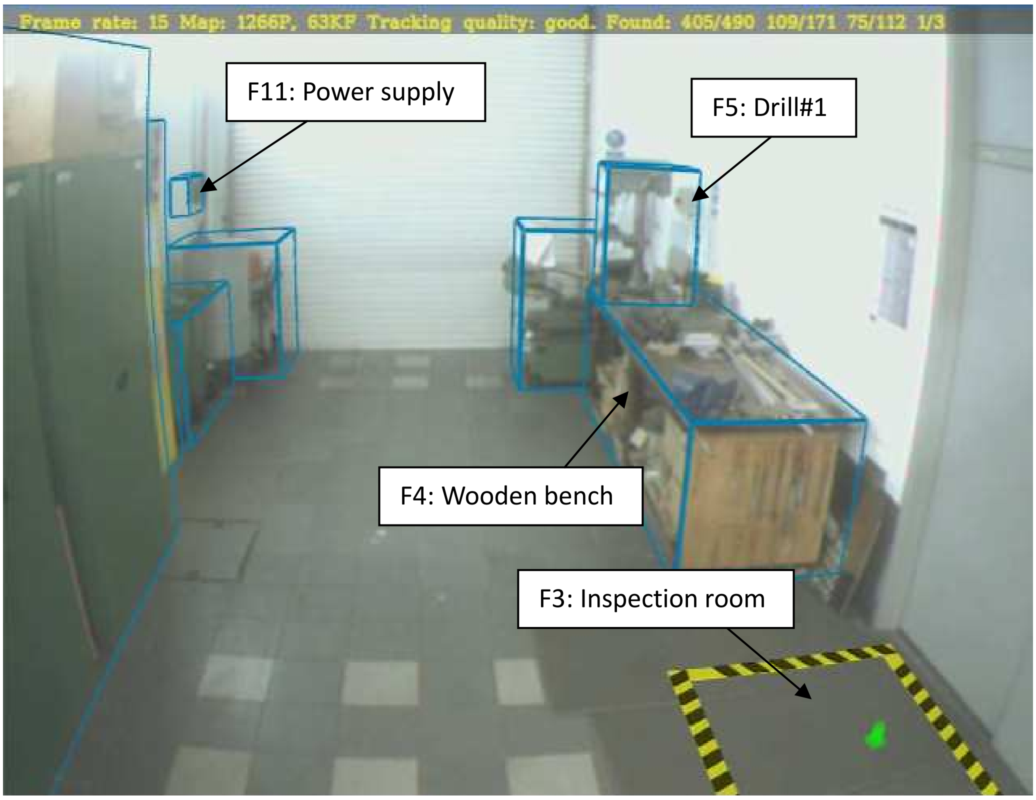


Figure 8.2.1: The shopfloor environment in Case Study II

Table 8.2.1: Constraints to be imposed on the facilities

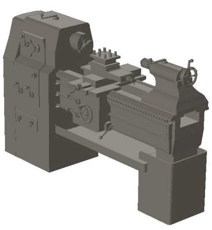
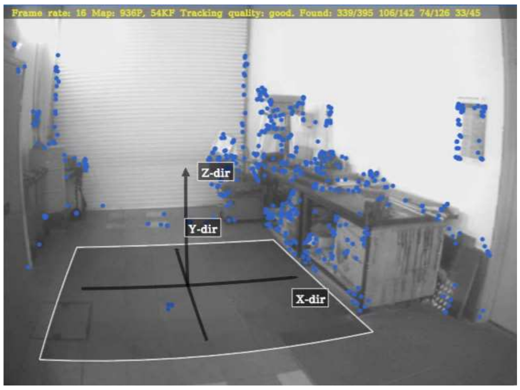
	Display monitor (Facility#0)
	Con#1: Orientation constraint: the base facing the floor. Con#2: Location constraint: on the walls. Con#3: Collision detection.
	Bench drill press (Drill#2/Facility#1)
	Con#1: Orientation constraint: the back facing the walls. Con#2: Location constraint: on top of a wooden bench. Con#3: Collision detection.
	Lathe (Facility#2)
	Con#1: Space constraint for operation and maintenance purposes. Con#2: Location constraint: on the floor. Con#3: Collision detection.

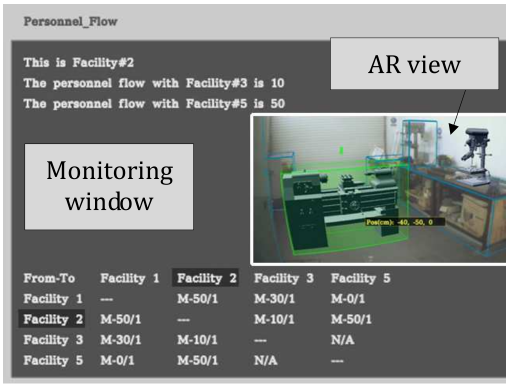
Table 8.2.2: The criteria required in the task

Criterion	Contents and data (collected *a priori*)
C1: Minimize the material handling cost	From Drill#1/Drill#2 to the lathe: 80/3 From the lathe to the inspection room: 100/2 From Drill#1 to the inspection room: 10/2 (unit: pcs. per day/unit cost*)
C2: Minimize the personnel flow	From Drill#1/Drill#2 to the lathe: 50 From the lathe to the inspection room: 10 From Drill#1 to the inspection room: 30 (unit: pers. per day)
C3: Minimize the space occupancy	The space occupied by the two bench drill presses and the lathe.

*The unit cost is a relative value

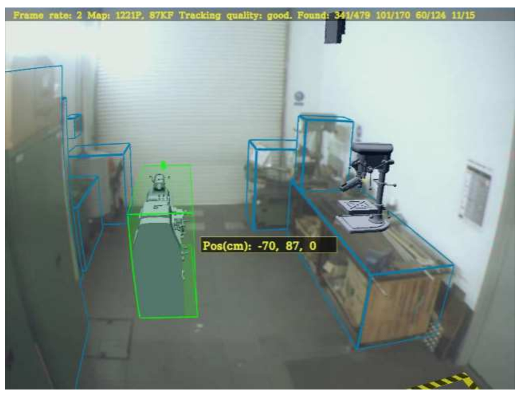


(a) Initialization



(b) Defining the criteria

(c) Plan A (manual planning)



(d) Plan B (automatic planning)

Figure 8.2.2: Using AFLOE to address the FLPES task

Table 8.2.3: Utilization of the CMs/CFs

Criteria/constraints	CM/CF
Criteria: Cri#1-Cri#2-Cri#3-Cri#4	CM#I-CM#I-CM#II-CM#III
Constraints for the display monitor: Con#1-Con#2-Con#3	CF#II-CF#IV-CF#I
Constraints for the drill press: Con#1-Con#2-Con#3	CF#II-CF#IV-CF#I
Constraints for the lathe: Con#1-Con#2-Con#3	CF#3-CF#IV-CF#I

By manipulating the three new facilities in the AR environment interactively, the users produced Plan A manually. Next, the users invoked the optimization module and produced a weighting scheme as Cri#1-0.34, Cri#2-0.34, Cri#3-0.21, and Cri#4-0.10. An automatic planning design (Plan B) is thus obtained. The two plans are shown in Figures 8.2.3 and 8.2.4. Table 8.2.4 provides a comparison between the two plans with respect to the criteria.

Table 8.2.4: Quantitative comparison between Plan A and Plan B

Criterion(unit)	Weight	Plan A	Plan B
Cri#1(pcs. per day × unit cost × cm)	0.34	3267.29	2254.13
Cri#2(pers. × cm)	0.34	493.29	417.67
Cri#3(1)	0.21	0.35	0.27
Cri#4(cm)	0.10	10.04	7.75

As can be seen from the table, Plan B outperforms Plan A for all criteria. Hence, Plan B is more efficient than Plan A. As the main difference between the two layout plans by comparing Figure 8.2.3 and Figure 8.2.4, the change of the location of F2 (the long facility in the middle of the both plans) has led to the reduction of the material handling cost (Cri#1) and the improvements of the personnel flow (Cri#2), which together account for 68% of the total weights.

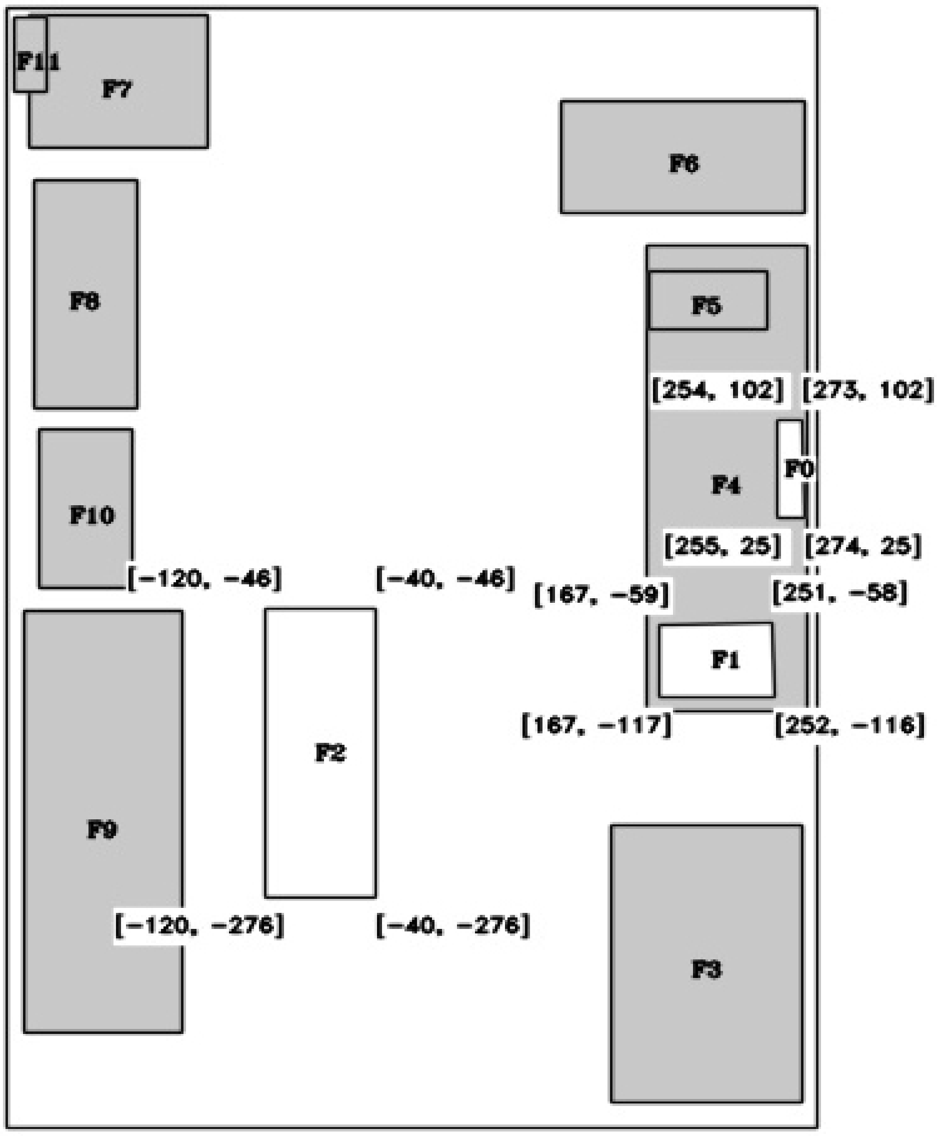


Figure 8.2.3: Plan A (manual planning)

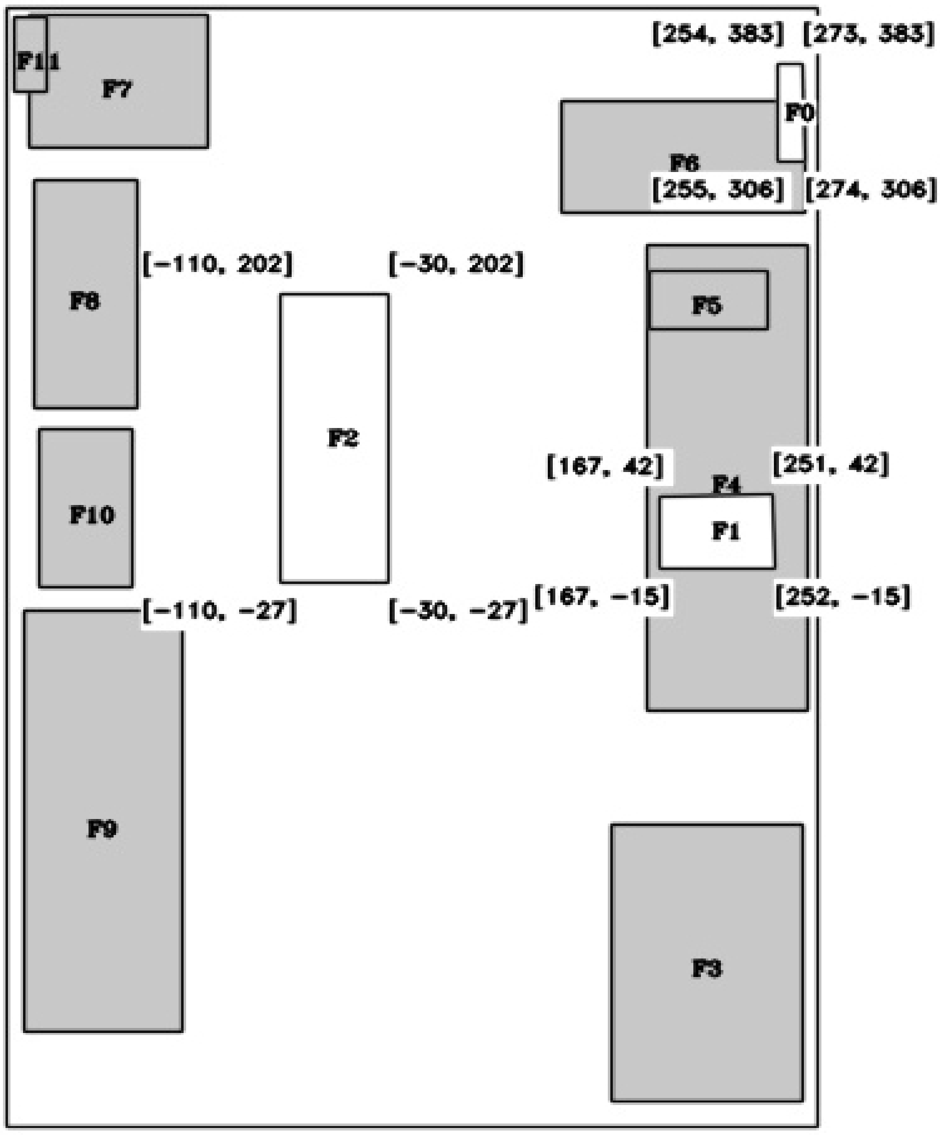


Figure 8.2.4: Plan B (automatic planning)

Automatic planning can typically outperform manual planning with the use of AHP-GA, whereas manual planning can incorporate users' experience, e.g., personal preference and heuristics, which automatic planning has difficulty in addressing. To this extent, during the manual planning, the users avoid locating F2 in the middle of the shopfloor, as contrast to the locating of F2 in Plan B, which makes the shopfloor neater. The final decision on the selection of the final plan lies with the users.

8.3 Discussion

To analyse the usability of the AFLOE system, a user study was conducted. Six researchers (three males and three females) in the ARAT laboratory of the National University of Singapore participated in the user study. These participants use computers regularly and are familiar with AR technology, but do not have much experience with FLP. In the user study, they are asked to conduct the FLP task presented in Case Study II individually. Table 8.3.1 shows the average time the participants spent on the system during the different planning stages.

Table 8.3.1: Average time for different planning stages

Planning stage	Average time (min)
AR environment initialization	8
Modeling existing facilities	4
Criteria and constraints definition	8
Manual planning	13
Automatic planning	1
Total	41

The time the participants spent on initialization the AR environment, which includes the initialization of the real-time tracking, the definition of the CS, etc., accounts for nearly 1/5 of the total planning time. It is found during the user study that the tracking stability of PTAM for large areas, e.g., a shopfloor, is not as comparable as for small areas, e.g., a corner of an office, and the participants would normally need two to three trials until they can establish a stable tracking result. On average, 1/10 of the time is used for modeling the existing facilities, which indicates the efficiency of the developed modeling technique. Another 1/5 of the planning time is spent on the definition of the criteria and constraints. As observed during the user study, the typing of the numerical values for specifying the CM parameters has taken a considerable amount of time. Next, more than 1/4 of the time is spent on manual planning. It is observed during the user study that the participants firstly manipulate the facilities to test the manipulation commands and check the different CFs. After the participants are familiar with the various functions, they proceed to design the layout plans as they examine the criteria values simultaneously. Lastly, the automatic planning takes around 1 min, which including the time the participants spent on pair-wise comparison and the time the GA processing the MADM model. As for the entire planning time, 41 min is required to complete the FLPES task, which indicates the efficiency of the system.

A questionnaire (Appendix A) is designed to ask the participants to evaluate the AFLOE system from different aspects, which covers the usability of the modeling technique, the efficiency of the GMCC, the effectiveness of AFLOE.

In the questionnaire, a convincing AR environment (Q4) refers to the quality of the AR environment. In a well-established AR environment, virtual entities are merged with the real scene seamlessly, which can enhance the sense of reality so as to facilitate the users to explore their intuition to the full extent. Usability of the modeling technique (Q5) looks into the utilization of the modeling technique. As the developed modeling technique requires interaction with the users, the ease of conducting the modeling process is very important. Next, understanding the usage of GMCC (Q6) depends on the users' familiarity with MADM for solving the FLP tasks, which is essential for using the AFLOE system to the full extent. Usefulness of GMCC (Q7) is based on Q6, which collects feedback on the users' evaluation of the GMCC method. Achieving the desired layout plan (Q8) reflects the users' personal assessment on the quality of the layout plans produced by using the AFLOE system. Finally, the usability and the effectiveness of the AFLOE system (Q9 and Q10) investigate the overall performance of the system in terms of the ease of use and the usefulness for FLP tasks. Table 8.3.2 shows the average scores given by the participants on these questions.

The usability of the modeling technique is well accepted. However, as observed during the user study, the mouse is not easy to use without a planar surface, which may have affected the usability of the modeling technique to some extent. As not many participants are familiar with FLP, the score on the understanding of GMCC is relatively low. Nonetheless, as a method to help the users define the criteria and constraints, GMCC received 4.1/5 for its usefulness. All the participants have achieved their desired layout plans. In particular, two participants chose manually designed plan as the final decision, whereas four participants selected the plan produced by automatic planning as the final decision. 4.2/5 for Q9 suggests that the participants agree that the AFLOE is easy to use. Lastly, the effectiveness of the AFLOE system is acknowledged by the participants.

Table 8.3.2: Average scores given by the participants (Q4 to Q10)

Question	Average score
Q4: Convincingness of the AR environment	4.8/5
Q5: Usability of the modeling technique	4.1/5
Q6: Understanding the usage of GMCC	3.5/5
Q7: Usefulness of GMCC	4.1/5
Q8: Achieving the desired layout plans	Yes-6; no-0
Q9: Usability of the AFLOE system	4.2/5
Q10: Effectiveness of AFLOE for FLP	4.5/5

Some feedbacks have been received as well. One participant suggested the utilization of wireless cameras that can improve the flexibility of the hardware configurations. Another feedback received is on the disadvantages of GMCC, which indicates that typing the parameter values in real-time is not a convenient method. Future research will investigate these problems.

Due to limited resources available, this user study can be improved from several aspects. Firstly, the size of the subject sample (six participants) is relatively small. A larger sample size would have made the user study more comprehensive and complete. Moreover, the representativeness of the user group is limited. Since the target users for the AFLOE system are both novice and experienced layout designers, both layman designers and professional layout designers should have been invited to participate in the user study. Furthermore, to obtain more information from the user study, the user group can be divided into subgroups based on several criteria, e.g., gender, age, level of knowledge on VR/AR, level of expertise on FLP etc. A comprehensive user study not only can present a more convincing validation of the proposed solution but also help identify drawbacks for improvement purposes. Future research will look into these aspects.

Chapter 9 Conclusions and recommendations

The primary objective of this research is the application of the AR technology for FLP. It aims to develop an AR-based approach to address FLP, especially in FLPES. By integrating an AR-based real-time modeling technique and a generic method for formulating MADM models, the ARHFLP approach provides an adaptable and effective solution to the FLPES problem. A system has been developed to implement the approach and case studies have been conducted for validation purposes.

9.1 Research contributions

This thesis has made contributions in the following aspects.

9.1.1 An AR-based hybrid approach to FLP

Based on the integration of the algorithmic approach and the AR-based approach, an improved AR-based approach for FLP has been formulated, namely, the ARHFLP approach. By using a four-step procedure, namely, data collection, problem formulation, layout planning, and results evaluation, the ARHFLP approach takes advantages of the AR technology and provides a feasible solution to the FLPES tasks. Issues such as the presence of the existing facilities and the wide range of the criteria types can be addressed. Two planning modes are supported, namely, manual and automatic planning.

9.1.2 An AR-based real-time fast modeling technique

This AR-based real-time modeling technique is tailored for AR-based applications. In the AR environment, with camera pose and the mapping results being updated in real-time, the procedure of positioning 3D points in the world CS (coordinate system) can be simplified. Based on this positioning mechanism, a user-aided modeling technique is developed for the users to construct primitive models interactively in the AR environment. Adjustments to these models can be made manually until the primitive models are good representations of the real objects. In this research, this modeling technique is adopted to construct the virtual models of the existing facilities.

9.1.3 A generic method for formulating MADM models

The GMCC method is developed to address the FLPES problem. It provides a generic method for the users to define and customize the criteria and constraints in real-time. A set of models, namely the CMs and the CFs, are provided to facilitate the definition of the criteria and constraints and make it a comprehensive tool to address different types of FLP tasks. By using GMCC, the MADM model can be formulated to better meet the specific requirements of the FLP tasks.

9.1.4 An AR-based facility layout optimization and evaluation system

The AFLOE system adopts the ARHFLP approach and implements both manual and automatic planning. For manual planning, as the criteria and constraints are processed in real-time and the results are presented to the users to guide the planning process. An AHP-GA–based optimization scheme is used to implement automatic planning. The AFLOE system takes advantages of the AR technology and the mathematical modeling techniques and utilizes both human intelligence and heuristic algorithms to facilitate the FLP process.

9.2 Recommendations

For further exploration, the following aspects can be investigated for improvement and enhancement.

9.2.1 Accurate modeling techniques

Although the modeling technique developed in this research is fairly fast for real-time processing, improvements can still be made with regards to the modeling results. By using models of higher accuracy, the effectiveness of the constraints as well as the final layout plans can be further improved. Besides user-aided modeling, the method reported by Newcombe and Davison (2010) can be considered. For the FLP purposes, user input is required to identify facility objects from the non-facility objects. The details of the shopfloor environment need to be provided.

9.2.2 Alternative MADM models and algorithms

In this research, the AFLOE system adopts the weighted sum method to formulate a linear MADM model and the AHP-GA algorithm to solve the model. The effectiveness of this method has been demonstrated in this research. However, due to the complexity of the FLP problem, different MADM models can be used to produce more alternative layout plans to facilitate decision-making. This rationale also applies to the algorithms. Among the existing algorithms for solving MADM problems, no solution has dominant advantages. Improvements to these algorithms can be made to incorporate artificial intelligence techniques, which have great potential for solving FLP problems more efficiently. Results produced by algorithms that are comparable to or better than human intelligence would be more useful.

9.2.3 Re-layout the existing facilities

This research considers only the scenario of adding new facilities. Another scenario that is of the same significance is the removal of or the re-layout of the existing facilities. AR technology can provide a feasible method to address this scenario. By constructing the virtual models of the existing facilities to be re-layout or removed, and inpainting (Criminisi *et al.*, 2003) them from the real scene, the real facilities can be manipulated by the users. A proposed methodology is presented in Chapter 6. Similar concepts have been reported in (Herling and Broll, 2010). However, the currently available inpainting technologies are restricted as only a small region of the image can be inpainted in real-time. Future research can be conducted on the development of this technique.

List of Publications from this Research

Jiang, S., Ong, S. K., and Nee, A. Y. C. (2012). A Framework for Augmented Reality Assisted Shopfloor Facility Layout Planning. 25th Annual Conference on Computer Animation and Social Agents (CASA 2012), Singapore, May 9-11, pp. 50-53.

Jiang, S. and Nee, A. Y. C. (2013). A Novel Facility Layout Planning and Optimization Methodology. CIRP Annals – Manufacturing Technology, 62-1, pp. 483-486.

Jiang, S., Ong, S. K, and Nee, A. Y. C. An AR-based Hybrid Approach for Facility Layout Planning and Evaluation. International Journal of Advanced Manufacturing Technology, under review.

References

Abdelghani, S. (1995). Simulated Annealing for Manufacturing Systems Layout design, European Journal of Operational Research, 3-82, pp. 592-614.

Ahlers, K. H., Kramer, A., Breen, D. E., Chevalier, P. Y., Crampton, C., Rose, E., Tuceryan, M., Whitaker, R. T. and Greer, D. (1995). Distributed Augmented Reality for Collaborative Design Applications. Computer Graphics Forum, 14-3, pp. 13-14.

Aiello, G. and Enea, M. (2001). Fuzzy Approach to the Robust Facility Layout in Uncertain Production Environments. International Journal of Production Research, 39-18, pp. 4089-4101.

Aiello, G., Enea, M., and Galante, G. (2006). Multi-objective Approach to Facility Layout Problem by Genetic Search Algorithm and Electre Method. Robotics and Computer-Integrated Manufacturing, 22-1, pp. 447-455.

Apple, J. M. (1977). Plant Layout and Material Handling, 3rd edition. John Wiley & Sons, Inc., New York.

Armour, G. C. and Buffa, E. S. (1963). A Heuristic Algorithm and Simulation Approach to Relative Allocation of Facilities. Manage Sciences, 9-2, pp. 294-300.

Azadivar, F. and Wang, J. J. (2000). Facility Layout Optimization Using Simulated and Genetic Algorithms. International Journal of Production Research, 38-17, pp. 4369-4383.

Azuma, R. T. (1997). A Survey of Augmented Reality. Presence: Teleoperators and Virtual Environment, 6-4, pp. 355-385.

Back, M., Childs, T., Dunnigan, A., Foote, J., Gattepally, S., Liew, B., Shingu, J, and Vaughan, J. (2010). The Virtual Chocolate Factory: Building a Real World Mixed Reality System for Industrial Collaboration and Control. IEEE International Conference on Multimedia and Expo, Singapore, July 19-23, pp. 1160-1165.

Balakrishnan, J., Cheng, C. H., and Wong, K. F. (2003). FACOPT: A User Friendly Facility Layout Optimization System. Computers and Operations Research, 30-11, pp. 1625-1641.

Banerjee, A., Banerjee, P. and Mehrotra, S. (1996). An Enabling Environment for Inputting Qualitative Information in Manufacturing Systems Layout Design. Proceedings of the VR in Manufacturing Research and Education Symposium, Chicago, USA, October 7-8, pp. 62-69.

Baykasoglu, A., Dereli, T., and Sabuncu, I. (2006). An Ant Colony Algorithm for Solving Budget Constrained and Unconstrained Dynamic Facility Layout Planning Problems. Omega, 34-4, 385-396.

Benjaafar, S., Heragu, S. S. and Irani, S. A. (2002). Next Generation Factory Layouts: Research Challenges and Recent Progress. Interface, 32-6, pp.58-76.

Billinghurst, M., Imamoto, K., Kato, H. and Tachibana, K. (2000). Virtual Object Manipulation on a Table-Top AR Environment. Proceedings of the IEEE and ACM International Symposium on Augmented Reality, Vienna, Austria, October 5-6, pp. 111-119.

CAD Shroer. MPDS4 Factory Layout, http://www.ppmashow.co.uk/en/Exhibitors/67175/CAD-Schroer-UK-Ltd, last accessed on 18 January, 2013.

Cagan, J. (1994). A Shape Annealing Solution to the Constrained Geometric Knapsack Problem. Computer Aided Design. 28-10, pp.763-769.

Calderon, C., Cavazza, M. and Diaz, D. (2003). A New Approach to Virtual Design for Spatial Configuration Problems. Proceedings of the Seventh International Conference on Information Visualization (IV'03), pp. 518-523.

Chen, C. W., and Sha, D. Y. (2005). Heuristic Approach for Solving the Multi-objective Facility Layout Problem. International Journal of Production Research, 43-21, pp. 4493-4507.

Chiang, W. C. and Kouvelis, P. (1996). An Improved Tabu Search Heuristic for Solving Facility Layout Design Problems. International Journal of Production Research, 34-9, pp. 2565-2585.

Chong, J. W. S., Ong, S. K., Nee, A. Y. C., and Youcef-Youmi, K. (2008). Robot Programming Using Augmented Reality: An Interactive Method for Planning Collision-free Paths. Robotics and Computer-Integrated Manufacturing, 25-3, pp. 689-701.

Chung, G. K. M., So, R. H. Y., and Lee, N. K. S., (1998). A PC-based Virtual Reality System for Facility Layout Planning, Proceeding of the 1st World Congress on Ergonomics for Global Quality and Productivity, Hong Kong, July 8-11, pp. 205-208.

Chwif, L., Pereira, B. M. R., and Moscato, L. A. (1998). A Solution to the Facility Layout Problem Using Simulated Annealing. Computers in Industry. 36-1, pp. 125-132.

Clough, M. and Buck, R. (1993). Plant Layout Ergonomics: Impact of Problem and Solver Features on Layout Quality. Proceedings of the Human Factors and Ergonomics Society, pp. 468-471.

Criminisi, A., Perez, P. and Toyama, K. (2003). Object Removal by

Exemplar-based Inpainting. Proceedings 2003 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, pp.721-728.

Das, S. K. (1993). A Facility Layout Method for Flexible Manufacturing Systems. International Journal of Production Research, 31-2, pp. 279-297.

Davison, A., Reid, I., Molton, N. D. and Stasse, O. (2007). MonoSLAM: Real-time Single Camera SLAM. IEEE Transactions on Pattern Analysis and Machine Intelligence, 29-6, pp. 1052-1067.

Dilworth, J. B. (1996). Operation Management. McGraw Hill.

Dweiri, F., and Meier, F. A. (1996). Application of Fuzzy Decsion-making in Facilities Layout Planning, International Journal of Production Research, 34-11, pp. 3207-3225.

Doil, F., Schreiber, W., Alt, T. and Patron, C. (2003). Augmented Reality for Manufacturing Planning, Proceeding of the Workshop on Virtual Environment, pp. 71-76.

Drezner, Z. (1987). A Heuristic Procedure for the Layout of a Large Number of Facilities. International Journal of Management Sciences, 33-7, pp. 907-915.

Drira, A., Pierreval, H. and Hajri-Gabouj, S. (2007). Facility Layout Problems: A Survey. Annual Reviews in Control, 31-2, pp. 255-267.

Eade, E. and Drummond, T. (2006). Edge Landmarks in Monocular SLAM. Proc. British Machine Vision Conference, Edinburgh, pp. 588-596.

Electre, Wikipedia, http://en.wikipedia.org/wiki/ELECTRE, last accessed on 6 July 2013.

Erel, E., Ghosh, J. B., and Simon, J. T. (2003). New Heuristic for the Dynamic Layout Problem. Journal of the Operational Research Society, 54-12, pp.

1275-1282.

Ertay, T., Ruan, D., Tuzkaya, U. R. (2006). Integrating Data Development Analysis and Analytic Hierarchy for the Facility Layout Design in Manufacturing Systems. Information Sciences, 176, pp. 237-262.

Fite-Georgel, P. (2011). Is There a Reality in Industrial Augmented Reality? Proceedings of the 10th International Symposium on Mixed and Augmented Reality, Basel, Switzerland, October 26-29, pp. 201-210.

FlexSim. FlexSim, http://www.flexsim.com/, last accessed on 18 January, 2013.

Francis, R. L., McGinnis, F. and White, J.A. (1991). Facility Layout and Location: An Analytical Approach, Second Edition, Prentice-Hall.

Fuji, T., Mitsukura, Y. and Moriya, T. (2012). Furniture Layout AR Application Using Floor Plans Based on Planar Object Tracking. The 21st IEEE International Symposium on Robot and Human Interactive Communications, pp. 670-675.

Gausemier, J., Fruend, J., and Matysczok, C. (2002). AR-Planning Tool-Design Flexible Manufacturing Systems with Augmented Reality. 8th Eurographics Workshop on Virtual Environment, pp. 19-25.

Heragu, S.S. (1997). Facilities Design. Boston: BWS.

Herling, J. and Broll, W. (2010). Advanced Self-Contained Object Removal for Realizing Real-time Diminished Reality in Unconstrained Environment, 9th International Symposium on Mixed and Augmented Reality, pp. 207-211.

Homography, Wikipedia, http://en.wikipedia.org/wiki/Homography, last accessed on 18 January, 2013.

Hu, M. H., Ku, M. Y. and Chen, C. C. (2007). A Genetic Algorithm for

Optimizing Facility Layout in a Water Fab. International MultiConference of Engineering and Computer Scientists, pp. 2026-2031.

Igboanugo, A.C. and Amiebenomo, S. (2006). Design of a Process Layout for a Pilot Alkyd Resin Production Plant. Advances in Materials and Systems Technologies: Developing the Niger Delta Transport System Using Adequate Geo-Spatial Information, pp. 435-441.

Ignacio, U.A. and Jung, C.R. (2007). Block-based Image Inpainting in the Wavelet Domain. Visual Computer, 23-9, pp. 733-741.

Immer, J. R. (1950). Layout Planning Techniques, McGraw-Hill Book Company, New York.

Iqbal, M. and Hashmi, M. S. J. (2001). Design and Analysis of a Virtual Factory Layout. Journal of Material Processing Technology, 118, pp. 403-410.

Jolai, F., Taghipour, M. and Javadi, B. (2011). A Variable Neighborhood Binary Particle Swarm Algorithm for Cell Layout Problem. International Journal of Advanced Manufacturing Technology, 55-1, pp. 327-339.

Kamalinia, S., Afsharnia, S., Khodayar, M. E., Rahimikian, A. and Shabafi, M. A., (2007). A Combination of MADM and Genetic Algorithm for Optimal DG Allocation in Power Systems, Proceedings of the Universities Power Engineering Conference, pp. 1031-1035.

Klein, G. and Murray, D. (2007). Parallel Tracking and Mapping for Small AR Workspaces. In Proc. International Symposium on Mixed and Augmented Reality, ISMAR.

Koopmans, T. C., and Beckmann, M. (1957). Assignment Problems and the Location of Economic Activities. Econometrica, 25-1, pp. 53-76.

Korves, B. and Loftus, M. (1998). The Application of Immersive Virtual Reality for Layout Planning of Manufacturing Cells. International Journal of Engineering Manufacture, 213-3, pp. 87-91.

Krishnan, K. K, Cheraghi, S. H., and Nayak, C. N. (2008). Facility Layout Design for Multiple Production Scenario in a Dynamic Environment. International Journal of Industrial and Systems Engineering, 3-2, pp. 105-133.

Kuhn, W. (2006). Digital Factory – Simulation Enhancing the Product and Production Engineering Process. Proceedings of the 2006 Winter Simulation Conference, Monterey, USA, December 3-6, pp. 1899-1906.

Kulturel-Konak, S., Smith, A. E. and Norman, B. A. (2007). Bi-objective Facility Expansion and Relayout Considering Monuments. IIE Transactions, 39-7, pp. 747-761.

Lee, J., Han, S. and Yang, J. (2011). Construction of a Computer-Simulated Mixed Reality Environment for Virtual Factory Layout Planning. Computers in Industry, 62-1, pp. 86-98.

Lee, R., and Moore, J. M. (1967). CORELAP-Computerized Relationship Layout Planning. The Journal of Industrial Engineering, 18-1, pp. 195-220

Lee, J.Y. and Rhee, G. (2008). Context-aware 3D Visualization and Collaboration Services for Ubiquitous Cars Using Augmented Reality. International Journal of Advanced Manufacturing Technology, 37-5, pp. 431-442.

Lee, J. Y., Rhee, G. W., and Park, H. (2009). AR/RP-based Tangible Interactions for Collaborative Design Evaluation of Digital Products. International Journal of Advanced Manufacturing Technology, 45-7, pp. 649-665.

Leonard, J. J., and Durrant-Whyte, H. F. (1991). Mobile Robot Localization by

Tracking Geometric Beacons. IEEE Transactions on Robotics and Automation, 7-3, pp. 376-382.

Liu, X., Yu, Y., and Shum, H. Y. (2001). Synthesizing Bidiretional Texture Functions for Real-world Surfaces. Computer Graphics Proceedings, SIGGRAPH 2001, pp. 97-106.

Lu., SC-Y, Shpitalni, M., and Gadh, R. (1999). Virtual and Augmented Reality Technologies for Product Realization. CIRP Annals 48-2, pp. 471-495.

Mahdavi, I., Shirzi, B. and Paydar, M. (2008). A Flow Matrix-based Heuristic Algorithm for Cell Formation and Layout Design in Cellular Manufacturing System. International Journal of Advanced Manufacturing Technology, 39-9, pp. 943-953.

Meller, R. D., and Gau, K. Y. (1996). Facility Layout Objective Functions and Robust Layouts. International Journal of Production Research, 34-10, pp. 2727-2742.

Meng, G., Heragu, S. S., and Zijm, H. (2004). Reconfigurable Layout Problem. International Journal of Production Research, 42-22, pp. 4709-4729.

Muther, R. (1961). Systematic Layout Planning. Industrial Education Institute, Boston.

Nadler, G. (1961) Work Design: A Systems Concept, Richard D. Irwin, Inc., Homewood, Illinois.

Navab, N. (2004). Developing Killer Apps for Industrial Augmented Reality. Computer Graphics and Applications, 24-3, pp. 16-20.

Nee, A. Y. C., Ong, S. K., Chryssolouris, G. and Mourtzis, D. (2012). Augmented Reality Applications in Design and Manufacturing. CIRP Annals 61-2, pp.

657-679.

Neira, J. and Tardos, J. (2001). Data Association in Stochastic Mapping Using the Joint Compatibility Test. In IEEE Trans. on Robotics and Automation, 17-6, pp. 890-897.

Newcombe, R. A. and Davison, A. J. (2010). Live Dense Reconstruction with a Single Moving Camera, 2010 IEEE Conference on Computer Vision and Pattern Recognition, pp. 1498-1501.

Ong, S. K., Pang, Y., and Nee, A. Y. C. (2007). Augmented Reality Aided Assembly Design and Planning. CIRP Annals 56-1, pp. 49-52.

Pan, Q., Reitmayr, G., and Drummond, T. W. (2009) Interactive Model Reconstruction with User Guidance. Proceedings of the 8th IEEE International Symposium on Mixed and Augmented Reality, Orlando, USA, October 19-22, pp. 209-210.

Pang, Y., Nee, A. Y. C., Ong, S. K., Yuan, M., and Youcef-Toumi, K. (2006). Assembly Features Design in an Augmented Reality Environment. Assembly Automation, 26-1, pp. 34-43.

Pentenrieder, K., Bade, C., Doil, F., and Meier, P. (2008). Augmented Reality-based Factory Planning - an Application Tailored to Industrial Needs. Proceedings of the 6th IEEE and ACM International Symposium on Mixed and Augmented Reality, Cambridge, UK, September 15-18, pp. 76-84.

PDMS, AVEVA, www.aveva.com/pdms, last accessed on 20 May 2013.

Pfefferkorn, C.E., (1975). A Heuristic Problem Solving Design System for Equipment or Furniture Layouts. Communications of the ACM, 18-5, pp. 286-297.

Plant 3D, Autodesk, http://www.autodesk.com/products/autodesk-autocad-plant-3d/overview, last accessed on 20 May 2013.

Plant Simulation, Siemens, http://www.plm.automation.siemens.com/en_us/products/tecnomatix/plant_design/plant_simulation.shtml, last accessed on 20 May 2013.

Poh, Y. L., Nee, A. Y. C., Ong, S. K., and Youcef-Toumi, K. (2006). Augmented Reality (AR) for Facilitating Layout Design. Singapore-MIT Alliance Symposium, pp. 17-18.

Rauterberg, M., Bichsel, M., Meier, M. and Fjeld, M. (1997). A Gesture-based Interaction Technique for a Planning Tool for Construction and Design. IEEE International Workshop on robot and Human Communication, pp. 212-217.

Reed, R. (1961). Plant Layout: Factors, Principles, and Techniques, Richard D. Irwin, Inc. Homewood, Illinois.

Reinhart, G., and Patron, C. (2003). Integrating Augmented Reality in the Assembly Domain-Fundamentals, Benefits and Applications. CIRP Annals 52-1, pp. 5-8.

Saaty, T. L. (1980). The Analytic Hierarchy Process. RWS Publications, Pittsburgh, Pennsylvania, USA.

Salmun, H., Molod, A., and Ira, A. (2007). Observational Validation of an Extended Mosaic Technique for Capturing Subgrid Scale Heterogeneity in a GCM. Tellus, Series B, 59B-3, pp. 625-632.

Seehof, J. M., and Evans, W. O. (1967). Automated Layout Design Program. The Journal of Industrial Engineering, 18-1, pp. 690-695.

Shahin, A. (2010). Facility Layout Simulation and Optimization: an Integration of

Advanced Quality and Decision Making Tools and Technologies. Modern Applied Science, 5-4, pp. 95-111.

Shayan, E., and Chittilappily, A. (2004) Genetic Algorithm for Facilities Layout Problems Based on Slicing Tree Structure. International Journal of Production Research, 42-19, pp. 4055-4076.

Siltanen, P., Karhela, T., Woodward, C., Savioja, P., and Jappinen, J. (2006). Augmented Reality Plant Model Services for Mobile Maintenance Worker. 3rd Intuition International Workshop, Stuttgart, Germany, November 30 – December 1, poster presentation.

Siltanen, P., Karhela, T., Woodward, C., and Savioja, P. (2007). Augmented Reality for Plant Lifecycle Management. 13th International Conference on Concurrent Enterprising, Sophia, France, June 4-6, pp. 407-414.

Singh, S. P. and Sharma, R. R. K. (2006). A Review of Different Approaches to the Facility Layout Problems. International Journal of Advanced Manufacturing Technology, 30-5, pp. 425-433.

Sirinaovakul, B., and Limudomsuk, T. (2007). Maximum Weight Matching and Genetic Algorithm for Fixed-shape Facility Layout Problem. International Journal of Production research, 45-12, pp. 2655-2672.

Smith, R., Self, M., and Cheesman, P. (1987). Estimating Uncertain Spatial Relationships in Robotics. IEEE international Conference on Robotics and Automation, pp. 850-850.

Smith, R. P. and Heim, J. A. (1998). Virtual Facility Layout Design: the Value of an Interactive Three-dimensional Representation. International Journal of Production Research, 37-17, pp. 3941-3957.

SolidWorks. http://www.solidworks.com/, last accessed on 18 January, 2013.

Tan, P., Fang, T., Xiao, J., Zhao, P. and Quan, L. (2008). Single Image Tree Modeling. ACM Transactions on Graphics, 27-5, pp. 108-115.

Teamcenter. Manufacturing Plant Simulation. http://www.slideshare.net/plmxsolucoes/teamcenter-manufacturing-15920727, last accessed on 18 January, 2013.

Tecnomatix. Factory Layout Simulation, http://www.directindustry.com/prod/siemens-plm-software/plant-design-software-5148-385429.html, last accessed on 18 January, 2013.

Venkatesh, M., Cheung, S. S. and Zhao, J. (2009). Efficient Object-based Video Inpainting. Pattern Recognition Letters, 30-2, pp. 168-179.

Wan, S., Lu, J. and Zhang, H. (2010). The Application of Augmented Reality Technologies for Factory Layout. 2nd International Conference on Audio, Language and Image Processing, Shanghai, China, November 23-25, p 873-876.

Wang, M. J., Hu, M. H., and Ku, M. H. (2005). A Solution to the Unequal Area Facility Layout Problem by Genetic Algorithm. Computers in Industry, 56-2, pp. 207-220.

Wang, X. (2007). Using Augmented Reality to Plan Virtual Construction Worksite. International Journal of Advanced Robotic Systems, 4-4, pp. 501-512.

Wang, Z. and Quan, Y. (2008). An Improved Method for Feature Point Matching in 3D Reconstruction. 2008 International Symposium on Information Science and Engineering, pp. 159-162.

Wascher, G. and Merker, J. (1997). A Comparative Evaluation of Heuristics for the

Adjacency Problems in Facility Layout Planning. International Journal of Production Research, 35-2, pp. 447-466.

Wiedenmaier, S., Oehme, O., Schmidt, L. and Luczak, H. (2003). Augmented Reality for Assembly Process Design and Experimental Evaluation, International Journal of Human-Computer Interaction, 16-3, pp. 497-514.

Xie, W. and Sahinidis, N.V. (2008). A Branch-and-bound Algorithm for the Continuous Facility Layout Problem, Computers and Chemical Engineering, 32-4, pp. 1016-1028

Yang, L., Deuse, J., and Jiang, P. (2012). Multiple Attribute Decision Making Approach for an Energy-Efficient Facility Layout Design. 45th CIRP Conference on Manufacturing System, 3-1, pp. 149-154.

Yang, T. (1998). Flexible Machine Layout Design for Dynamic and Uncertain Production Environments. European Journal of Operational Research, 108-1, pp. 49-64.

Yang, T. and Hung, C. C. (2007). Multiple Attribute Decision Making Methods for Plant Layout Design Problem. Robotics and Computer-Integrated Manufacturing, 1-23, pp. 126-137.

Yang, T and Kuo C. (2003). A Hierarchical AHP/DEA Methodology for the Facilities Layout Design Problem. European Journal of Operational Research, 147-1, pp. 128-136.

Yang, T., Peters, B. A. and Tu, M. (2005). Layout Design for Flexible Manufacturing Systems considering Single-loop Directional Flow Patterns. European Journal of Operational Research. 164-2, pp. 440-455.

Yang, T., Zhang, D., Chen, B., and Li, S. (2008). Research on Plant Layout and

Production Line Running Simulation in Digital Factory Environment. IEEE Pacific-Asia Workshop on Computational Intelligence and Industrial Application, Wuhan, China, December 19-20, pp. 588-593.

Yoshiyama, K., Tanji, K., Sato, Y., Sugita, K., Kawai, S., and Sugimura, Y. (1984). Digital Image Layout System for Color Printing. NEC Research and Development, 1-82, pp. 110-117.

Yuan, M. L., Ong, S. K., and Nee, A. Y. C. (2008). Augmented Reality for Assembly Guidance Using a Virtual Interactive Tool. International Journal of Production Research, 46-7, pp. 1745-1767.

Zakaria, M. Z., Jamaluddin, H., Ahmad, R., and Muhaimin, A. H. (2011). Effects of Genetic Algorithm Parameters on Multi-objective Optimization Algorithm Applied to System Identification Problem. 4th International Conferences on Modeling, Simulation and Applied Optimization, Kuala Lumpur, Malaysia, April 19-21, pp. 1-5.

Zetu, D., Schneider, P., and Banerjee, P. (1998). Data Input Model for Virtual Reality-aided Factory Layout. IIE Transactions, 30-7, pp. 597-620.

Appendix A Questionnaire on AFLOE

Name: ____

Email Address: _______________________________________

Date: ____

Part I Background Information

Instructions: Please tick the appropriate answer.

1. Do you have any knowledge or experience on facility layout planning?

A. Yes, knowledge only.

B. Yes, knowledge with experience.

C. No.

2. Describe your knowledge on the Augmented Reality technology.

A. Expert

B. Beginner

C. Unknown

3. Describe your skills of computer-aided modeling tools such as SolidWorks, AutoCAD, etc.

A. Expert

B. Beginner

C. Unknown

Part II User study

Instructions: Please provide your ranks to the following questions.

4. Is the AR environment produced by AFLOE convincing? (   )

(1 – Not convincing at all, 5 – Very convincing)

5. Is the modeling technique easy to use? (   )

(1– Very difficult, 5 – Very easy)

6. How much do you understand the usage of GMCC? (   )

(1 – I don’t understand it at all, 5 – I fully understand it)

7. How do you rank the usefulness of the GMCC method? (   )

(1 – Not useful at all, 5 – Very useful)

8. Have you reached your desired layouts during the user study? (   )

(1 – Yes, 0 – No)

9. How do you rank the usability of the AFLOE system? (   )

(1– Very difficult to use, 5 – Very easy to use)

10. How do you rank the overall effectiveness of AFLOE for FLP? (   )

(1 – not useful at all, 5 – very useful)

Part III Feedbacks

Instructions: Please provide any additional comments or suggestions on the AFLOE system