A REAL TIME INTELLIGENT RESOURCE MANAGEMENT SYSTEM FOR FACILITATING INBOUND OPERATIONS IN MANUFACTURING

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A Real Time Intelligent Resource Management System for Facilitating Inbound Operations in Manufacturing

By

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Certificate of Originality

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POON Tak Chun (Name of student)

Abstract

In make-to-order (MTO) manufacturing environments, products are customized and production processes are only started upon receiving a customer's order. To satisfy customer requirements and punctually meet the delivery time, it is necessary to handle several customers' orders simultaneously and allocate the appropriate machines and resources before starting production. Production scheduling and planning is an important process for avoiding delay in production and improving manufacturing performance to fulfill customers' needs. Different constraints are considered in formulating the most satisfactory production plan. These constraints are constant and predictable. However, in the actual manufacturing environment, shop floor managers face numerous unpredictable risks in day-to-day operations, such as defects in the supplied components or raw materials, errors, failures, and wastage in various production processes. The unpredictable risks not only entail stringent requirements regarding the replenishment of materials but also increase in the difficulty in preparing material stock. Therefore, it is essential to effectively and efficiently handle such risks to achieve smooth production.

Researchers are considering machines and material handling equipment as constraints when addressing production material demand issues in production scheduling. Their studies consider "off-line" scheduling problems, in which a schedule is generated within a time period and is not expected to involve any changes. However, these studies are not capable of solving stochastic production material demand problems because existing scheduling approaches solely focus on the allocation of production resources, such as machines and workers. These scheduling approaches consider warehouse resources in the form of forklifts, but neglect manpower. Warehouse resources are important in minimizing risks. They are utilized to pick, transfer, and store production materials between the warehouse and production lines when problems occur during the production process. The existing approaches can be seen as processes of allocating equipment to perform specific production tasks before production starts. Such research does not take into consideration real-time equipment, which is used to facilitate production. The consideration of real-time equipment helps improve the visibility of warehouse operations and enhances productivity. Nevertheless, previous research did not consider the allocation of warehouse resources to facilitate production processes. The objective of this research is to effectively and efficiently allocate warehouse resources for replenishing appropriate production materials between these two facilities to assure that the production process can run smoothly.

To efficiently and effectively solve stochastic production material demand problems, a real-time production operations decision support system (R-PODSS) is developed. The proposed system consists of three modules: Real-time Data Collection, Data Storage and Exchange, and Formulation Module of Optimal Pickup and Delivery Route. Real-time Data Collection Module utilizes Radio Frequency Identification (RFID) technology in capturing production operations information. Different RFID reading performance tests are first performed to evaluate the reading performance of all RFID equipment and to verify the most suitable location for the installation of the hardware. A reliable RFID technology implementation plan is formulated to capture real-time production and warehouse information simultaneously. Data Storage and Exchange Module systematically stores captured production and warehouse information in the centralized database and transforms them into meaningful information. Database Management System (DBMS), Query

Optimization, and Structured Query Language (SQL) statement are adopted to provide data retrieval and storage to users. The Formulation Module of Optimal Pickup and Delivery Route provides an optimal resource allocation plan for utilizing appropriate resources to pick/transfer/store production materials from the warehouse to the production lines. Artificial Intelligent techniques, such as Case-Based Reasoning (CBR) and Genetic Algorithm (GA) are adopted to select appropriate warehouse resources and formulate the shortest pickup and delivery routes, respectively.

To validate the feasibility of the proposed system, two case studies are conducted. Through the pilot run of the system in the case studies, the improved visibility of production and warehouse operations is observed. The efficiency of production and warehouse operations is also significantly enhanced. The results reveal that the proposed system effectively achieves the objectives of this research.

The major contribution of this research is the design and development of an effective system, which allows real-time tracking and tracing of production and warehouse resources and corresponding operations, to reduce the effect of stochastic production demand problems and enhance productivity on the shop floor and in the warehouse. The deliverables of this research provide the development of R-PODSS. They also pave the way to future research opportunities for incorporating warehouse resource management in production operation management and implementing emerging RFID technology and artificial intelligent techniques in logistics industry.

Publication Arising from the Thesis

(**7** international journal papers are published or accepted and **1** international journal paper is under review. **9** conference papers are published or accepted)

List of International Journal Paper

1. Poon, T.C., Choy, K.L. and Lau, H.C.W. (2009), "Design of a RFID case-based logistics resource management system for order-picking in warehouse", *Expert Systems with Applications,* 36(4), pp. 8277 – 8301.

2. Poon, T. C., Choy, K. L., Chan, F. T. S. and Lau, H. C. W., "A real-time production operations decision support system for solving stochastic production material demand problems", *Expert Systems with Applications,* 38(5), pp. 4829 – 4838.

3. Poon, T. C., Choy, K. L., Chow, H. K. H., Lau, H. C. W., Chan, F. T. S. and Ho, G. T. S., "A Real-Time Warehouse Operations Planning System for Small Batch Replenishment Problems in Production Environment", *Expert Systems with Applications (Accepted on 18 January 2011).*

4. Poon, T. C., Choy, K. L. and Lau, H. C. W., "An efficient production material demand order management system for a mould manufacturing company", *Production Planning & Control (In Press).*

5. Poon, T.C., Choy, K.L. and Lau, H.C.W. (2007), "A Real-time Shop Floor Control System - An Integrated RFID Approach", *International Journal of Enterprise Network Management*, 1 (4), pp. 331 – 349.

6. Choy, K. L., Leung, Y. K., Chow, H. K. H., Poon, T. C., Kwong, C. K. and Ho G. T. S., "A Hybrid Scheduling Decision Support Model for minimizing job tardiness in a Make-To-Order based mould manufacturing environment", *Expert Systems with Applications*, 38(3), pp. 1931 – 1941.

7. Leung, Y.K., Choy, K.L., Kwong, C.K., Poon, T.C. and Cheung Y.Y. (2009), "A Real-time Business Process Decisions Support Planning System for

Mould Industry – A Case Study", *International Journal of Value Chain Management*, 3(1), pp. 87 – 107.

8. Poon, T. C., Choy K. L, Cheng, C. K., Lao, S. I. and Lam, H. Y., "Effective Selection and Allocation of Material Handling Equipment for Stochastic Production Material Demand Problems Using Genetic Algorithm", *Expert Systems with Applications (Submitted in February 2010).*

List of Conference Paper

1. Poon, T.C., Choy, K.L. and Lau, H.C.W. (2007), "A Real-time Manufacturing Risk Management System - An Integrated RFID Approach", *Portland International Conference for Management of Engineering and Technology 07 (PICMET'07),* Portland, 5-9 August 2007, pp. 2872 – 2879.

2. Poon, T.C., Choy, K.L. and Lau, H.C.W. (2007), "A Real-time Production Risk Management System - An Integrated RFID Approach", *The 5th International Conference on Supply Chain Management and Information Systems, Melbourne,* Australia, 9-12 December 2007, pp. 1 – 13.

3. Poon, T.C., Choy, K.L. and Lau, H.C.W. (2008), "A RFID-Based Location Tracking Scheme for Inbound Operations in Warehouse Environment", *Portland International Conference for Management of Engineering and Technology 08 (PICMET'08),* Portland, 27-31 July 2008, pp. 872 – 877.

4. Choy, K.L., Choy, Edmond L.H. and Poon, T.C. (2008), "A Real-Time Database Management System for Logistics Systems: A Case Study", *Portland International Conference for Management of Engineering and Technology 08 (PICMET'08),* Portland, 27-31 July 2008, pp. 864 – 871.

5. Choy, K.L., Leung, Y.K., Kwong, C.K. and Poon, T.C. (2008), "A Knowledge-based Manufacturing Process Planning System for Automotive Mould Manufacturing", International *Conference on Manufacturing Research 08 (ICMR'08)* , West London, 9-11 Sept 2009, pp. 977 – 985.

6. Poon, T.C., Choy, K.L., Lau, H.C.W. and Lo, K. M. (2009), "A RFID-Based Decision Support System for Monitoring Product Quality in Food Industry", *International Workshop on Successful Strategies in Supply Chain*

Management 2009 (IWSSSCM'09), Hong Kong, 8-9 January 2009, pp. 265 – 272.

7. Poon, T. C., Choy, K. L., Cheng, C. K. and Lao, S. I. (2010), "A real-time replenishment system for vending machine industry", *the 8th IEEE International Conference on Industrial Informatics (INDIN 2010),* Osaka, Japan, 13-16 July 2010, pp. 209 – 213.

8. Poon, T. C. and Choy, K. L. (2010), "Design of a Logistics Costs Analyzer to formulate distribution routes for Freight Forwarders", *the 8th International Conference on Supply Chain Management and Information Systems (SCMIS 2010),* Hong Kong, 6-8 October 2010, pp. 345 – 350.

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List of Abbreviations

AI	Artificial Intelligence
CBR	Case-based Reasoning
COO	Cell of Origin
CRM	Customer Relationships Management
CW	Continuous-Wave
DMS	Database Management System
EAN	European Article Numbering System
EPC	Electronic Product Code
EPCID	EPC Identification
ERD	Entity Relationship Diagram
ERP	Enterprise Resource Planning
GA	Genetic Algorithm
GSL	Group Sense Limited
HF	High Frequency
IT	Information Technology
JCE	Jing Chi Engineering Company Limited
LF	Low Frequency
LP	Linear Programming
MES	Manufacturing Execution System
MILP	Mixed Integer Linear Programming
MRP	Material Requirements Planning

MRPII	Manufacturing Resource Planning
MTO	Make-to-Order
MTS	Make-to-Stock
NNR	Nearest-Neighbor Retrieval
ODM	Original Design Manufacturing
PDA	Personal Digital Assistant
PDF	Portable Data Format
QC	Quality Control
RBR	Rule-Based Reasoning
RF	Radio Frequency
RFID	Radio Frequency Identification
SCM	Supply Chain Management
SFCS	Shop Floor Control System
SKU	Stock Keeping Unit
SOP	Standard Operation Procedure
SQL	Structured Query Language
SRM	Supplier Relationships Management
UHF	Ultra High Frequency
UPC	Uniform Product Code
WIP	Work-in-Progress
WMS	Warehouse Management System

Chapter 1 Introduction

1.1 Research Background

The concept of supply chain is based on the formulation of indivisible network among retailers, distributors, transporters, warehouses, and suppliers, which participate in the sale, delivery, and production of a particular product (Lau and Lee, 2000; Kaihara, 2003). Due to the effects of globalization, supply chain networks are gradually becoming complex. Enterprises have to deal with numerous channel partners located a great distance apart and request greater diversity of products. At present, enterprises also need to deal with more statutory requirements and documentation compared with the past (Vogt et al., 2005). Monitoring and controlling material flow has become a daunting task. As a result, the fulfillment of customers' demands for superior quality products, on time product delivery, and superior logistics services have become difficult to achieve. Organizations tend to implement production control systems, such as the Shop Floor Control System (SFCS) or Manufacturing Execution System (MES), aimed at monitoring the material flow to facilitate production activities for fulfilling customers' demands. These systems maintain shop floor productivity by controlling shop floor manufacturing information to reduce the complexity of data manipulation and to facilitate decision making, with regard to resources and inventory control (APICS, 2004). However, the existing systems solely focus on enhancing the performance of shop floor activities. They are incapable of monitoring other key business processes, such as warehouse operations. It is essential to consider the warehouse operation status during production because the performance of material flow from warehouse to production line affects production activities. Current warehouse management systems (WMSs) are incapable of monitoring the status of production lines. A resource management system is required to aid in managing production and warehouse activities to fulfil customers' demand. This research aims to develop a real-time production operations decision support system (R-PODSS), with a combination of real-time data capturing technology and artificial intelligent techniques, to achieve the objective.

1.2 Statement of Problem

In today's globalized business environment, enterprises must provide better products or services in a cheaper and faster way to sustain their competitive advantage in the globalized business environment (Lau et al., 2004; Manson et al., 2007; Pinto, 2005). On-time product delivery is one of the important issues for enterprises to achieve customers' satisfaction (Fawcett et al., 1998). However, maintaining the flows of customer order deliveries among suppliers and customers within the global supply chain is difficult because supply chain networks are becoming increasingly complex. Moreover, providing high volume production and distribution using minimal inventories throughout the logistics chain within short period of time has become a requirement (Berg et al., 1999). The increasing number and variety of orders, order-lines, and customers who integrate the technology used and processes designed has enhanced the complexity of logistics operations. It is essential to assign appropriate resources for handling low volumes and wide variety of Stock Keeping Unit (SKUs) within a short response time and in an effective manner in different logistics domains.

Many enterprises have adopted barcode-based shop floor control systems and warehouse management systems to monitor the production and warehouse operations status. People mainly rely on their experience, know-how, and knowledge to manage production and warehouse activities. In **Figure 1.1**, several problems observed in the current manufacturing organization are shown.

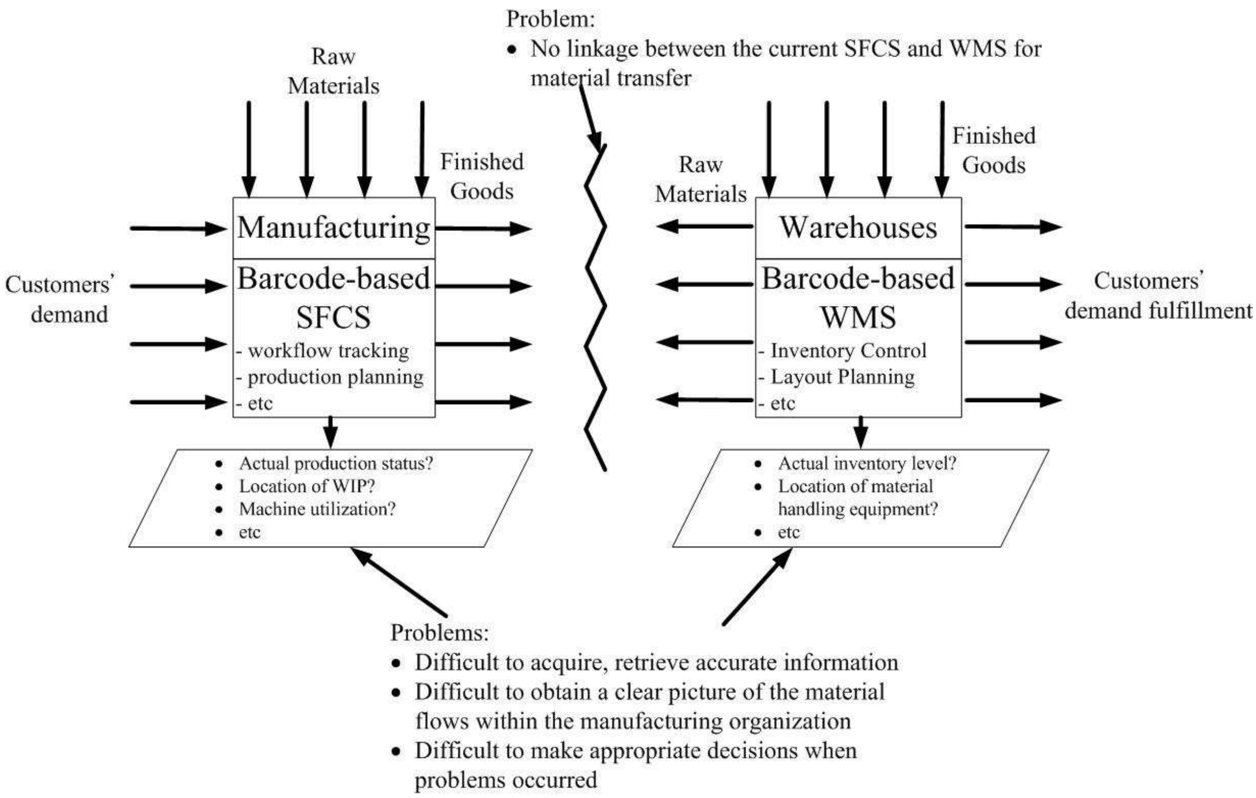


Figure 1.1 Existing problems in the manufacturing organization

(i) It is difficult to acquire, retrieve, and manipulate various types of production and warehouse resource information, such as location and status of the material handling equipment, for monitoring and controlling different manufacturing plans and operations activities.

(ii) Doubt is placed on the accuracy and quality of data input into the systems, resulting in wrong report generation for decision making.

(iii) Human error is inevitable, particularly under stressful conditions. When problems are discovered in the generated reports, decisions would have to be made to address the problems, based on the experience of managers. In general, there is uncertainty about the suitability of the decisions because these may vary due to different education levels, working experiences, and biases.

(iv) The existing systems solely focus on monitoring and controlling the performance of activities in a specific domain. SFCS solely focuses on production activities, whereas WMS focuses on warehouse activities. It is difficult to manage value activities in different areas of an organization. This renders the management incapable of obtaining the full picture of the key business activities as basis for making different decisions and strategies.

With imperfect information and ambiguous production and warehouse operations status, decision making would become a difficult task when problems occur. Enterprises will lose their competitive advantages as they cannot achieve customers' satisfaction. Hence, there is a need to develop an intelligent system for capturing accurate information and suggesting meaningful and useful decisions.

1.3 Research Objectives

The specific objectives of this research are:

- To design an R-PODSS for facilitating inbound operations and subsequently increase the visibility of production and warehouse operations status, and enhance the efficiency and effectiveness of decision making when production problems, e.g., raw material replenishment during production, machine breakdown, etc., occur.

- To conduct different RFID tests to determine the effective RF coverage of RFID technologies during the setup of RFID equipment in shop floor environment.
- To establish a warehouse resource allocation model with a combination of Case-based Reasoning (CBR) and Genetic Algorithm (GA) to optimize the pick-up and delivery routes of production material between shop floor and warehouse environments toward minimizing the effect of stochastic production material demand problems.

1.4 Significance of the Research

Traditional shop floor control and warehouse management systems focus on managing production and warehouse separately. Most research studies focus on a particular operation's improvement or optimization. Optimizing material flow between production and warehouse facilities is rarely addressed. The inbound material flow is directly affected by the information captured by the systems. Therefore, determining the real-time status and material flow between production floor and warehouse is essential for fulfilling customers' increasing demand, and in providing superior products and services. Information visibility is the core capability for the integration of supply chain operations and management during manufacturing and warehousing. Successful implementation of wireless technologies can help improve supply chain operations and create profit in the long run. For these reasons, this research is concerned with the introduction of an R-PODSS, which aims to provide aid for inbound operations in the manufacturing industry. The functions of the system, which include exact resource location tracking, production and warehouse operations monitoring, and production planning and replenishment, are used by decision-makers to formulate accurate production and warehouse operations plans according to real-time operations situation. The system helps manufacturing organizations achieve the objectives of enhancing efficiency and effectiveness of inbound operations.

1.5 Thesis Outline

The thesis is divided into seven chapters. The outline of the thesis is as follows:

(i) Chapter 1 states the problems which occur in existing production operation management, and describes the background and motivation for this research.

(ii) Chapter 2 is an academic review, which shows the existing situation and problems in the manufacturing industry. The chapter identifies the necessary collaboration with warehouse operations to enhance manufacturing performance. The analysis of real-time data collection technologies and expert systems is then reviewed and discussed.

(iii) Chapter 3 is divided into two main sections. The first section describes the operating specification of R-PODSS. The second section introduces the system architecture of R-PODSS, which consists of a Real-Time Production and Warehouse Data Collection, Data Storing and Retrieving, RFID Information Exchange, and Optimal Order Picking and Delivery Modules. These four modules are developed to achieve the research objective of enhancing production and warehouse operations.

(iv) Chapter 4 provides generic implementation guide of R-PODSS from the startup, structural formulation, evaluation and testing, and operation stages.

(v) Chapter 5 focuses on operating the system in the two sample manufacturing companies based in Hong Kong. Parts of the processes within these two companies' workflow are chosen to demonstrate the feasibility of the proposed methodology. The R-PODSS software prototype is developed and system verification of the proposed design methodology is also shown in this chapter.

(vi) Chapter 6 explains the result and presents the analysis. It consists of two sections. The first section discusses the experimental results of system performance in the production-warehouse operation decision support. The second section discusses the overall performance of the two case studies after the implementation of R-PODSS.

(vii) Chapter 7 draws conclusions from the study. Contributions made by this research are presented, and areas for future research are also identified.

Chapter 2 Literature Review

2.1 Introduction

To survive in the worldwide competitive market, manufacturing firms are required to provide superior products within a short period of time. Thus, different types of manufacturing systems have been adopted by companies (Tiwari and Vidyarhi, 2000). Traditional manufacturing systems perform different functions with the help of a computer system. The performance of a company relies heavily on the efficient allocation of resources to its various operations (Tuncel, 2007). To efficiently and effectively perform the company's functions, it is essential to consider the problem of resource allocation. Problems related with resource allocation on the shop floor involve: raw materials and material handling equipment scheduling, execution of production operations, routing of raw material, work-in-process, and final products (Chan and Chan, 2001). Many researchers (Qiu et al., 2003; Shnits and Sinreich, 2006; Tuncel, 2007) have suggested different approaches for solving resource allocation problems on the shop floor. Most of the existing approaches solely focus on managing production resources. However, the support of warehouse resources is also critical because warehouse resources are used to select the production materials from the warehouse and deliver them to the production shop floor. **Figure 2.1** illustrates the production material demand problems in production and warehouse environments. Under a traditional manufacturing system, it is difficult to identify which production stations experience production failure and what kind of production materials are needed in the workstations in a real-time manner. It is also sometimes impossible to determine where the production material is stored in the warehouse and which item of material handling equipment is most appropriate for a particular production demand order. Therefore, it is necessary to consider the management of both production and warehouse resources to improve the performance of manufacturing systems.

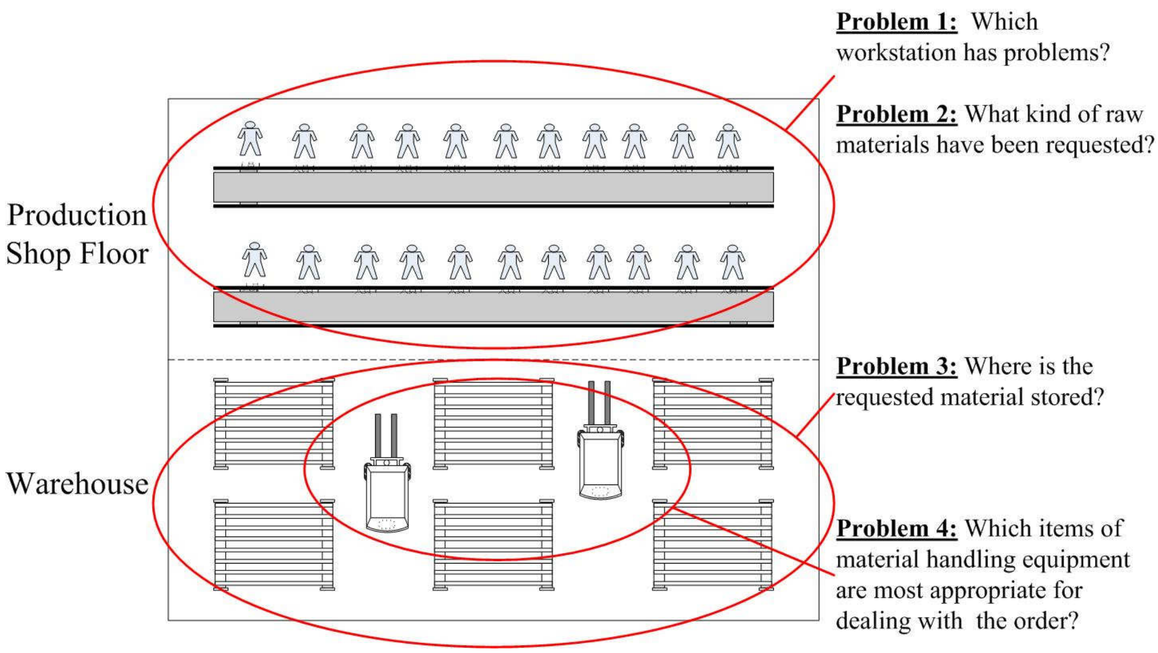


Figure 2.1 Traditional production material demand problems in production and warehouse environments

This chapter addresses the needs of real-time intelligent resource management system in the manufacturing industry. First, the evolution and challenges faced by current enterprises are discussed. Second, systems adopted in key business processes, such as production and warehouse activities, are evaluated. Various information technologies, such as data management and artificial intelligence, are also reviewed to provide a foundation for the development of an R-PODSS to aid in managing production and warehouse activities.

2.2 Evolution of the Current Supply Chain Environment

According to Kaihara (2003) and Liu et al. (2005), a supply chain is a valuable information sharing channel among suppliers, manufacturing and storage facilities, distributors, and customers for facilitating the key business activities of the sale, production, and delivery of a particular product. It is a network of upstream and downstream organizations involved in different processes and activities in providing products and services to ultimate consumers (Christopher, 1992). In traditional supply chains, firms operate independently to deal with suppliers and customers without considering the interests of other parties. This results in the phenomenon called bullwhip effect or Forrester effect as described by Forrester (1958). Bullwhip effect is the magnification of fluctuations of the demand patterns (in the form of orders) from downstream (customers) to upstream (suppliers), and the supply variations (in the form of lead time) from upstream to downstream. This phenomenon would cause supply uncertainty, which results in a major negative impact on the supply chain (Mason et al., 2003). To efficiently and effectively manage supply chain activities, supply chain management (SCM) has been proposed. SCM involves materials and supply management from the supply of raw materials to the final consumer products. It focuses on the utilization of suppliers' processes, technology, and capability to enhance competitive advantage (Tan et al., 1998). The main principle of SCM is to effectively integrate the material flow and related information within the demand and supply processes (Soroor and Tarokh, 2006). There have been numerous literature on the adoption of material requirements planning (MRP), manufacturing resource planning (MRPII), enterprise resource planning (ERP), supplier relationships management (SRM), and customer relationships management (CRM) to improve the performance of supply chain activities, which include material sourcing, production scheduling, warehousing, and product distribution (Choy et al., 2004; Koh, 2004; Ketikidis et al., 2008; Loh and Koh, 2004; Stevenson et al., 2005; Tang et al., 2005). However, due to the global extension of supply chain networks, enterprises need to collaborate with suppliers, customers, or even competitors in different time zones, across numerous organizational boundaries, and in a variety of cultures. Under these circumstances, the challenge of allocating production, transportation, and inventory resources to satisfy demand is daunting (Simchi-Levi et al., 2004).

In a supply chain, manufacturing is responsible for receiving raw materials from the suppliers, transforming the materials into final products, and delivering the products to end users. It entails a set of coordinated functions, such as molding, casting, assembling, and so on, to produce a product. Since all manufacturing functions are interdependent, and most of the revenue-generating activities of the company, such as business development, product and relationship management, and pricing, take place in the production facility, the performance of manufacturing functions affects the enterprise and the whole supply chain. Thus, it is essential to simultaneously consider these functions to effectively produce superior products.

2.2.1 Current Situation in Production Shop Floor Environment

According to Scherer (1998), manufacturing is an interface between the external market of an enterprise and its internal value-adding areas. The aims of manufacturing are to: i) transform customer demand into production orders, ii) release orders to production area, iii) manage orders on their way to the factory, iv) ensure that orders are completed on-time, v) monitor production status, vi) control lead times, vii) set order priorities, viii) plan the capacity at each work centre, ix) control queue time and work-in-process (WIP), x) record performance of actual results to compare with standards and targets, and xi) help the managerial level staff adjust daily operations when something goes wrong in the manufacturing process, such as workers' absenteeism, machine breakdowns, loss of materials, and so on (Schroeder and Flynn, 2001; Wassweiler, 1997). Effective approaches are then required to monitor and control manufacturing operations. For years, shop floor control system (SFCS) has been essential for manufacturing organizations because it controls the production activities on the shop floor. SFCS also manages material flows to perform several activities, such as throughput tracking, work forecasting, quality control, capacity feedback, status monitoring, and WIP tracking (Poon et al., 2007). SFCS is an interface between the external and internal value-added areas. Based on Wassweiler (1997) and Scherer (1998), the other functions of SFCS are:

- To transform direct customer demands or marketing sales plan into production orders
- To release orders to the production area
- To manage orders on their way to the factory
- To ensure the orders are completed on-time
- To collect production status
- To monitor and control lead times
- To establish and receive order priorities
- To plan the capacity at each work center
- To control queue time and WIP
- To record the performance of the actual results so they can be compared with standards and targets

- To help the management adjust daily operations once something goes wrong in the manufacturing process, such as workers' absenteeism, machine breakdowns, loss of materials, and so on.

Traditional SFCS uses bar-code based systems to manually scan and input data. However, due to increase in the scale of manufacturing systems and the complexity of shop floor control software, a number of disadvantages have been discovered. Huang et al. (2007) illustrate that the traditional system is time consuming, prone to errors, and tedious for the manual systems of data collection and capturing. Human error is inevitable, particularly under stressful conditions (Poon et al., 2009). The manufacturing processes require different types of operations and activities on machines and involve more workers (Pongcharoen et al., 2004). Tracing and tracking WIP items in a large manufacturing plant is a daunting task. Moreover, manual worksheets are frequently damaged, lost, and misplaced. Since shop floor operators are busy with other operations, they are hardly motivated to input data of their operations. Mistakes are frequent in manual recording. The information does not accurately reflect production performance. Hence, it is difficult for production managers to make appropriate shop floor decisions. Son et al. (2001) state that, it is difficult to make simultaneous decisions based on the shop floor status as reported by equipment controllers who have different educational levels. Since the job tasks are done by people from various educational backgrounds, interpretation or understanding of production status often varies.

Due to the effect of the present financial crisis, firms are facing the challenges of providing high quality products with short lead times to meet the growing requirements of customized production. In this sense, the traditional SFCS is incapable of fulfilling the requirements. Therefore, it is essential to ensure effective and efficient production processes during manufacturing. However, unpredictable risks, such as defects in the supplies of components or raw materials, or errors, failures, and wastage, always occur in the production process (Poon et al., 2007). It is necessary to replenish appropriate production material in the production lines to maintain productivity when problems occur. This can be defined as a "stochastic production demand problem." Christensen (1994) states that providing better and faster recognition of and response to machine malfunctions, rush orders, unpredictable process yields, human errors, etc., is one of the key requirements for maintaining competitiveness. In terms of risk, reducing the volatility of production time is critical to maintaining or even increasing productivity (Sanajian and Balcıoğlu, 2009). Therefore, many researchers have suggested different approaches to minimize the effect of the stochastic production demand problem. One of the common approaches is production scheduling. By allocating appropriate resources, production operations and activities are effectively and efficiently performed (Baker, 1974). Numerous articles in literature mention that production planning and scheduling plays a significant role in improving the performance of manufacturing (Fayad and Petrovic, 2005; Guo et al., 2006; Modarres and Sharifyazdi, 2009; Morita and Shio, 2005). According to Józefowska and Zimniak (2008), the task of production planning and scheduling includes planning and control of the manufacturing processes and related resources, such as materials, machines, and others. The existing production scheduling approaches mainly focus on allocating production resources only. The support of production materials is an essential catalyst to ensure the execution of a production plan within an effective and efficient schedule. It is essential to consider simultaneously the planning decisions on material supply, production and product delivery to reduce the high risk from market uncertainty (Wang and Cheng, 2009). As production materials are generally stored in a warehouse, the operation performance of a warehouse becomes critical in facilitating the planning and scheduling of jobs on the production floor. Due to the fast development of the global market and its competitive nature, most manufacturing enterprises are transforming and organizing themselves into networks of manufacturing, warehouse facilities, and distribution sites (Gumus and Funeri, 2009). It is essential to consider simultaneously different operation statuses in these facilities toward providing high quality products with short lead time. Therefore, the operational efficiency of a warehouse is important in facilitating the planning and scheduling of jobs on the production floor. Emphasis has been given to managing the operations in both production and warehouse environments to maximize the productivity of enterprises.

2.2.2 Current Situation in Warehouse Environment

According to Gu et al. (2007), a warehouse is the most important function for linking the partners to formulate seamless integration of the whole supply chain and for ensuring the smooth flow of products inside the network. A warehouse has different functions, such as a make-bulk/break-bulk consolidation terminal, a cross-dock operation, a transshipment node, an assembly facility, a product fulfillment center, and a returned goods depot (Higginson and Bookbinder, 2005). Basic warehouse operations comprise four processes: (i) receiving SKUs from a source, (ii) storing the SKUs, (iii) picking the SKUs when required by orders, and, (vi) shipping the orders to the customers (Rouwenhorst et al., 2000). Some of the warehouses provide packaging and assembly functions as value-added services.

Since a warehouse is an essential link between upstream (production) and downstream (distribution) entities, and most warehouse operations are either labor- or capital-intensive, the performance of these operations affects the productivity and operation costs of a warehouse and the whole supply chain. With such an arrangement, it is essential to handle efficiently and effectively the warehouse resources, such as SKUs, pallets and racks, pallet trucks and forklifts, and warehouse staff members, to achieve smooth manufacturing operations, reduce inventory, lower processing, storage, and transshipment costs, and increase productivity within facilities (Vogt et al., 2005). A highly efficient warehouse management is embodied through accelerating the flow of materials, reducing the stock in the supply chain, ensuring shorter lead times, and improving customer satisfaction (Min and Zhou, 2002). Within the chain, warehouse management systems (WMSs) are adopted to handle warehouse resources and operations. WMS is a computer application used to record warehouse transactions and maintain accurate inventory to improve the efficiency of the warehouse (Shiau and Lee, 2010). WMS contains information on supplier and customer warehouse inventory levels and key customer ordering patterns, wherein a product is received in a facility and shipped to the end customers (Mason 2003; Napolitano, 2001).

Nowadays, many companies adopt WMS in their warehouses to monitor the warehouse operations of receiving, storage, order picking, packing process, and shipping process. However, the current WMSs are incapable of providing timely and accurate warehouse operations information or of visualizing the actual working status because they do not have real-time and automatic data retrieval features (Huang et al., 2007). Instead, the systems heavily rely on manual inputting of operation information or on bar-code systems. Incorrect information is unavoidable from time to time as human error is inevitable (Sexton et al., 2000). Moreover, it is difficult to formulate reliable material handling solutions to handle different orders either by warehouse staff members (who may be biased) or through WMS (Chow et al., 2006). Based on the input of incorrect information in inventory level on warehouse capacity and storage location, inaccurate reports are generated from WMSs. Consequently, warehouse staff members create unreliable material handling solutions for managing the daily warehouse operations. In addition, the positions of the resources are not accurately located by current data collection techniques (Shih et al., 2006), resulting in inappropriate resource allocation as regards warehouse operations. Thus, an effective resource allocation model is necessary.

2.2.3 Resource Allocation Model in Production and Warehouse Environment of the Current Study

Approaches to solving resource planning and capacity allocation problems can be divided into two categories: mathematical programming and soft-computing methods (Wang et al., 2008). In the mathematical programming category, linear programming (LP) and mixed integer linear programming (MILP) are the most common approaches. According to Makowski et al. (2000), an LP model is defined by:

$$Min\{z = a^{\mathrm{T}} x\}$$

Subject to

$$Bx \le c$$

$$x \ge 0$$

where scalar z is the objective function, a and x are two m-dimensional vectors, and c is an n-dimensional vector. B is matrix $m \times n$. The o elements of the vector x are the values of the decision variables. The outputs of such models are optimal solution $\bar{x}$ and optimal value of the objective function $\bar{z}$.

The MILP model is an advanced LP model, which is a linear objective function subject to linear equality and inequality constraints (Tarău et al., 2010). A general MILP model is defined by:

$$Min\{z^{'} = d^{S} y\}$$

Subject to

$$E^{eq} y = f^{eq}$$

$$Ey \leq f$$

$$y^{''} \leq y \leq y^{'}$$

where scalar z' is the objective function, and d, y, y', and y'' are the m-dimensional vectors. Symbols f and f^{eq} *are* n-dimensional vectors, whereas E and E^{eq} *are* matrices $m \times n$. Symbols y' and y'' are the upper and lower boundaries of y, respectively.

Many companies adopt LP and MILP to solve various kinds of practical problems in transportation, production planning, investment decision, blending, location, and allocation (Jansen et al., 1997). Aghezzaf (2007) adopts a mixed integer programming model for developing a capacity and warehouse management plan that satisfies the expected market demand with the lowest possible cost. Krüger and Scholl (2009) integrate integer linear programming with a rule-based approach to solve resource constrained multi-project scheduling problems with transfer times. Jolayemi and Olorunniwo (2004) construct a mixed integer linear programming model for planning production and transportation quantities in multi-plant and multi-warehouse environments with extensible capacities. Özpeynirci and Azizoğlu (2009) adopt a mixed integer linear programming model to maximize the total weight over all operation assignments for solving operation assignment and capacity allocation problems.

There is no doubt that linear programming can easily obtain optimum solutions using related and well-defined variables. However, although existing mathematical-based modelling and exact solution methods are accurate, these are extremely time consuming due to the complexity of the problems. In a real-life dynamic production environment, large numbers of small batch production material demands frequently occur. By using LP, computational time in searching for possible solutions becomes lengthy (Lau et al., 2008) and can be easily trapped into local optima (Kwong et al., 2009). It is essential to solve the problems effectively and efficiently within a short period of time. Hence, soft computing methods have rapidly emerged to address capacity allocation and expansion problems (Wang et al., 2008).

2.3 Soft Computing Techniques Adopted in Production and Warehouse Activities

As previously mentioned, it is difficult for humans to make decisions during production and warehouse operations. Thus, soft computing-based decision support approaches have been widely adopted to assist in decision making. In this section, several types of soft computing techniques are outlined and investigated. Some possible techniques are determined for the development of R-PODSS.

In the soft computing methods category, there are various well-known Artificial Intelligence (AI) technologies for the development of decision support systems to manage the production and warehouse resources and operations. They are: i) rule-based reasoning (RBR), ii) CBR, iii) fuzzy logic, and vi) GA.

2.3.1 Rule-based Reasoning

RBR is a particular type of reasoning, which uses rules to solve problems. With reference to Looney and Alfize (1987), the term in AI can be defined as an IF-THEN structure, which relates given information or facts in an IF part, called the antecedent (premise of condition), to some action in a THEN part, called the consequent (conclusion or action). The RBR mechanism is illustrated in **Figure 2.2**. There are four main processes involved in RBR. When a new problem is identified, the pattern of the problem is matched against the rules in the knowledge base. A set of applicable rules is then found and used to solve the problem. After that, intermediate results are generated for testing the feasibility of the solution. The process is repeated until the desired solution state is reached (Dutta and Bonissone, 1993).

RBR is an AI problem-solving approach whose rules have merits of easy implementation and cheap computational cost (Park, 2006). Using a set of “rules,” the decision-making behavior of management can be easily simulated (Kerr and Ebsary, 1988). A rule-based approach brings logic, conceptual simplicity, and ease of communication for decision-makers (Janssen et al., 2005; Oglethorpe et al., 2000).

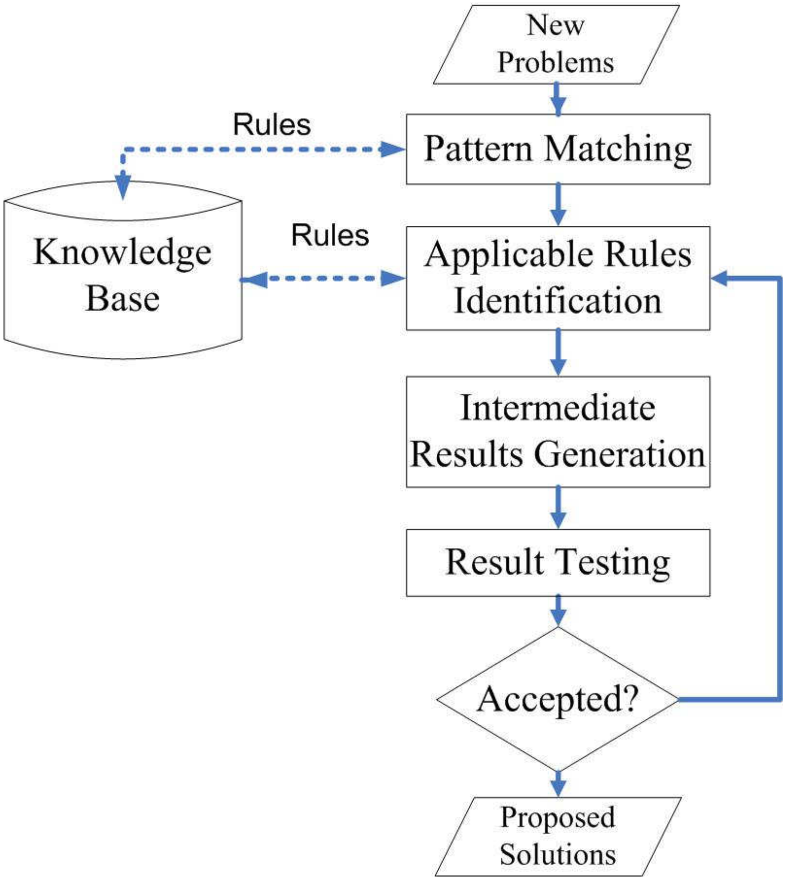


Figure 2.2 RBR mechanism

RBR has been widely applied in different studies. Shankar and Zhong (2006) propose a rule-based approach to detect and classify the defect patterns, which appear on semiconductor wafer surfaces. Ballis and García-Vivó (2006) present a rule-based system to specify the correctness and completeness of websites, and check whether the properties are automatically fulfilled. By combining rule-based and memory-based learning, Park (2006) proposes a model to tackle the problem of automatic word spacing in mobile phones. Huang *et al*. (1995) develop a rule-based matrix framework for re-entrant flow-shop scheduling problems, whereas Kerr and Ebsary (1988) implement a rule-based system for improving production schedules.

RBR has been used in building expert systems applying knowledge acquisition techniques (e.g., interviewing, protocol analysis, simulation, personal construct theory, card sorting, etc.) for eliciting tacit knowledge from domain experts (Hendriks and Vriens, 1999). However, the rule base needs to be refined when the problems become complex. When the knowledge repository collects a large amount of knowledge, RBR is affected by low response speed and inflexibility, and requires a modification of or addition on the rules to attain better reasoning. Unlike RBR, CBR has a high level of independence from specialists and domain experts (Tiwana, 2000). The reasoning principle is to solve new problems by reusing past cases. CBR is simple and can be used in a complex environment, such as the situation in supply chain management.

2.3.2 Case-based Reasoning

CBR is an AI technique utilizing previous experience to solve problems (Kolodner, 1993). Previous problems and corresponding solutions are stored as cases for reference. Case representation, retrieval, and adaption are the major issues for developing a CBR system (Liao, 2004). **Figure 2.3** shows the CBR mechanism which involves four main processes. They are: i) retrieving cases with highest scores of similarity from the case base repository, ii) reusing the potential cases to solve the problems, iii) revising the cases if new information is uncovered during the process of creating the new solution, and iv) retaining the new solution as a new case and storing it in the case base repository (Pal et al., 2001).

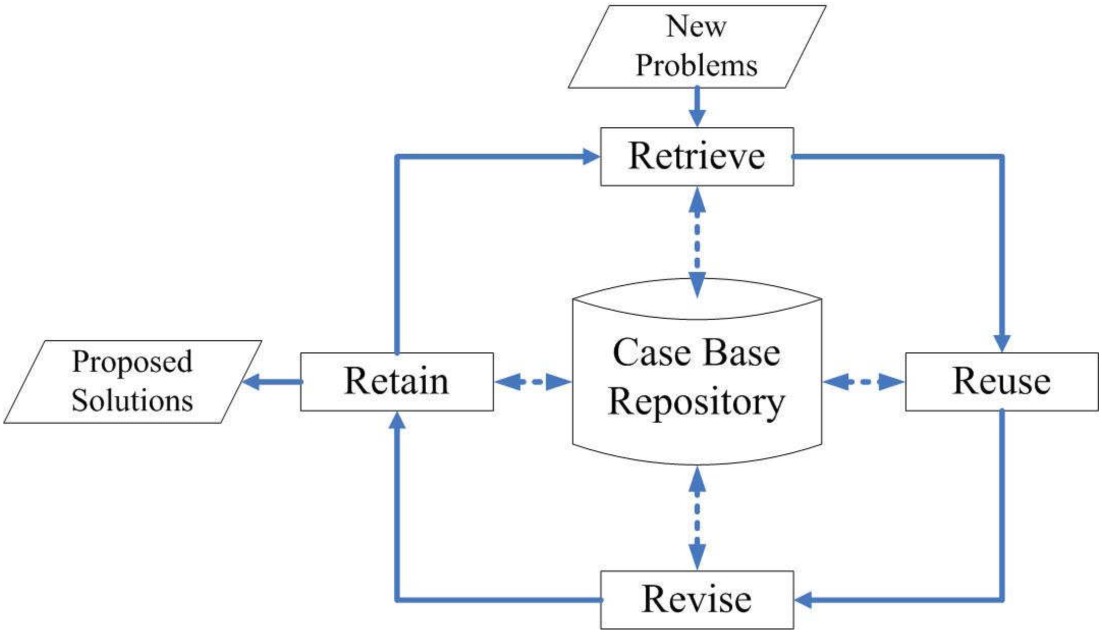


Figure 2.3 CBR mechanism

This learning mechanism of CBR has successfully contributed to different domains including manufacturing (Tsai and Chiu, 2007; Wu et al., 2008), warehousing (Chow et al., 2006), purchasing (McIvor et al., 1997), and vehicle maintenance (Kuo et al., 2005). There are various case retrieval methods employed in these domains. Some of the methods are for fast retrieval time, whereas others are for high accuracy of case retrieval. Sun and Finnie (2004) illustrate that the nearest-neighbor retrieval (NNR) system is one of the most simple and common CBR techniques, which can provide an assessment of the degree of similarity between problem descriptions attached to a case in the case base repository and the description of the current problems which need to be solved. Cheung et al. (2006) propose a nearest-neighbor-based service automation system for providing high quality customer services with fast and efficient customer responses in a semi-conductor equipment manufacturing company. However, the time spent on retrieving potential solutions for a new query is directly proportional to the number of cases stored in the case base repository. This means that it will take a long time to retrieve the case if there is large number of cases stored in the repository. Kolodner (1993) shows the difficulty of determining the most appropriate case to represent the current query case when only few cases are available in the case base. Thus, NNR is a technique which can be used to find the most appropriate case for the new query, despite the lengthy retrieval time. Several researchers have tried to reduce the retrieval time because managers do not have the time to wait for solutions in the actual working environment. Hence, Watson (1997) explains that the inductive approach is a technique which determines the most important features in discriminating cases, and generates a decision tree-type structure to organize the cases in the case base repository. Shin and Han (2001) demonstrate the effectiveness of the inductive learning approach to case indexing for business classification tasks in a bonding company. Although fast retrieval speed is achieved by this approach, a long time is needed for indexing the features of a case. As a result, a hybrid approach is proposed for solving the problems. Chow et al. (2006) propose an NNR-Inductive CBR engine to solve the order picking problems for enhancing the performance of warehouse operations. Wang et al. (2007) suggest utilizing the NNR-Inductive retrieval approach for predicting the actual restoration cost, solving order change problems, and reducing the budget review time. Another approach is to adopt a case clustering method with the NNR technique. Kim and Han (2001) and Can et al. (2004) mention that there are two steps in case retrieval of the clustering approach. The queries are first compared with the clusters or centroids, which are associated by similar problem descriptions. Detailed querying is then performed on the retrieved cases. Although the time for case retrieval varies according to the number and the size of the centroids, it is relatively faster than the other retrieval approaches. Using this clustering approach eliminates the time spent on case indexing and shortens the case retrieval time.

2.3.3 Genetic Algorithm

Among the soft computing techniques, GA is the most popular method to solve resource planning and capacity allocation problems. GA is a global meta-heuristic search technique introduced by Bagley in 1967. According to Maulik and Bandyopadhyay (2000), GA is a randomized search and optimization technique capable of determining the most appropriate solution for a large-sized problem within a reasonable period of time. The typical procedure of a GA includes randomly generating chromosomes, checking for violation of chromosomes with rules, evaluating the fitness of individuals in the population, reproducing chromosomes, and terminating the algorithm when the desired result is obtained. The procedure is shown in **Figure 2.4**.

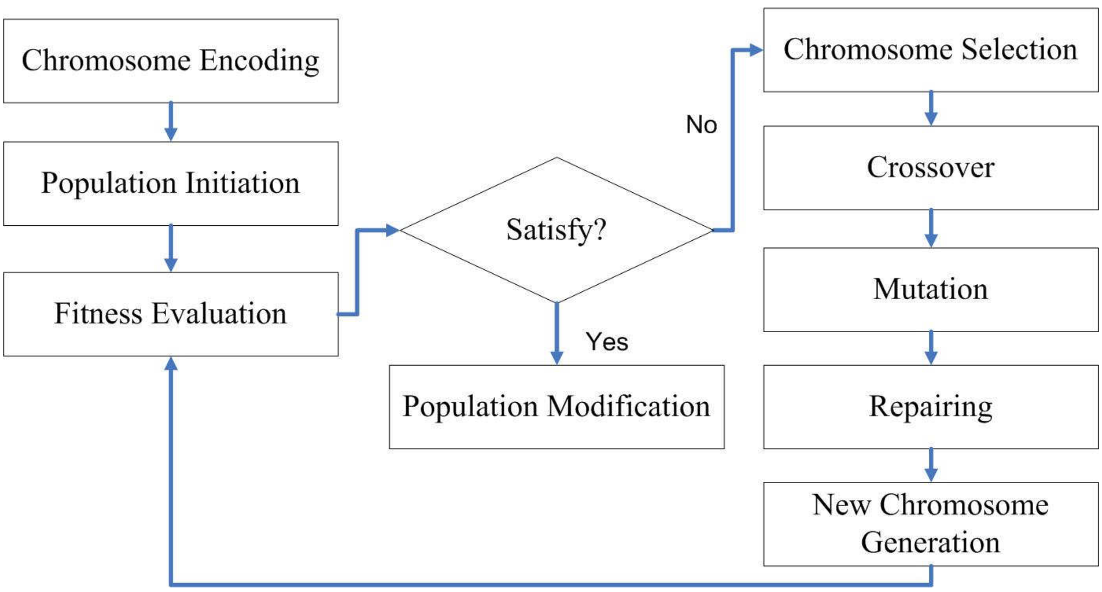


Figure 2.4 GA mechanism

In the domain of production-and-warehouse environments, numerous GA-related studies have found solutions to different problems. Thus, many researchers adopt this search technique to solve complex problems in different domains, especially in production and warehouse environments.

With the help of GA, the problem of capacity expansion and allocation has been solved in the semiconductor testing industry (Wang and Lin, 2002). Mendes et al. (2009) integrate a GA with heuristic priority rules to solve resource-constrained project scheduling problems. Guo et al. (2008) propose a GA for solving order scheduling with multiple constraints for maximizing the total satisfaction level of all orders while minimizing total throughput time. Kämpf and Köchel (2006) presented a GA simulation-based sequencing and lot size optimization for a multi-item Capacitated Stochastic Lot-Sizing Problem in a production-and-inventory system. Hong and Kim (2009) illustrate a GA for determining the replenishment order policy of the items so as to minimize the average inventory cost. Cha et al. (2008) propose a hybrid GA approach to solve the joint replenishment problem and provide a delivery schedule for a case of one warehouse and multiple retailers. Mirhosseyni and Webb (2009) develop a Fuzzy-GA hybrid system for solving material handling equipment selection and assignment problems. A set of GA heuristics is introduced for solving integrated production scheduling and preventive maintenance planning problems (Sortrakul et al., 2005). Rau and Cho (2009) propose a GA approach to tackle the inspection allocation problems for re-entrant production systems. Hsu et al. (2005) design a GA-based order batching method to handle order batching problems by minimizing the total travel distance within a warehouse. Yao and Chu (2008) demonstrate a genetic algorithm approach to minimize the warehouse space requirements by identifying the optimal raw material replenishment cycles. Ni et al.

(2007) propose a GA-based approach to solve multi-objective scheduling problems in utilizing resources and minimizing mold manufacturing time. Rajkumar and Shahabudeen (2008) suggest an improved GA, which tailors various GA operators to solve the flow shop problem on the production shop floor.

The current GA-based solution highlights the importance of using a GA in solving scheduling and replenishment problems simultaneously (Khouja and Goyal, 2008). Although existing GA approaches are able to provide optimal replenishment solutions in maximizing the utilization of warehouse resources, minimal attention has been paid to adopting GA for simultaneous solving of scheduling and replenishment problems. Hence, in this research, GA is adopted to formulate feasible small batch pick-up solutions, so as to solve the stochastic production material demand problems.

Existing mathematical programming and soft-computing methods utilize historical information to model and solve material planning and capacity allocation problems. Two assumptions are considered in the current production-and-warehouse solutions. These are, (i) all products manufactured are of perfect quality, and (ii) unlimited inventories are stored in a warehouse (Chung et al., 2009). Missing information is revealed through historical decisions (Marar and Powell, 2009), and inappropriate solutions would then be provided by the existing methods. It is a usual practice to handle various warehouse operations simultaneously using a small number of material handling items of equipment. Arranging limited warehouse resources and ensuring the capability of these warehouse resources to handle such demands are complex tasks. Therefore, it is essential to adopt a real-time data capturing technique and advanced AI to monitor the changes during production operations and provide feasible solutions within a short period of time.

2.4 Current Automatic Data Capture Techniques

To enhance the speed of data sharing, automatic data capturing techniques are required. In this section, existing automatic data capture techniques are investigated. Several automatic data capture techniques are adopted for facilitating information sharing in the existing market. Some of the techniques are capable of providing object location information. In the outdoor environment, the most well-known technology in location tracking is the Global Position System (GPS). It is a space-based radio-navigation system, which uses 24 satellites orbiting around the Earth and receivers to locate objects, in terms of height, longitude, and latitude coordinates (Postorino et al., 2006). The main application of GPS is to determine the location of vehicles and the actual traffic condition. Although it accurately locates an object in the outdoor environment, it is unable to locate objects inside buildings. Hence, Cell of Origin (COO) or Cell-ID is proposed to locate objects between indoor and outdoor environment. COO is a network-based location system, which uses the latitude and longitude coordinates of the base station and transmitters serving the mobile device, as the location of the user (Jagoe, 2003). However, it is inaccurate in locating a moving object, as "blind points" always occur due to defective coverage of the network, especially in indoor environment. Hence, various technologies have been developed to locate objects in the buildings. Barcode and RFID technologies are the most common approaches (Xu and Gang, 2006).

2.4.1 Barcode Technology

A barcode is a scheme in which printed symbols represent textual information. The printed symbols generally consist of vertical bars, spaces, squares, and dots. Based on a particular encoding and decoding rule, such kinds of symbol can be transformed to meaningful characters and numbers. This is also called symbology. Lahiri (2006) claims, that about 270 different symbologies have been invented to support specific requirements. Approximately 50 symbologies are widely used today.

A barcode scanner is the main tool used to recognize the barcode. It uses a light beam to scan the barcode. During the scanning process, the reader measures the intensity of the reflected light by the black and white regions of the barcode. A dark bar absorbs light and white space reflects light. A light sensitive electronic device called photodiode or photocell translates this light pattern into electrical. Electric circuits then decode this generated electrical current into digital data.

- **Barcode Standard**

There are several types of barcode standards in the industry. These standards can be mainly divided into linear and two dimensional. Examples of linear standard are Uniform Product Code (UPC), European Article Numbering System (EAN), and Code 128. Two-dimensional standard consists of Portable Data Format (PDF) 417, Aztec code, and DataMatrix.

Linear Barcode Standard

UPC has UPC-A and UPC-E versions, as shown in **Figure 2.5**. UPC-A consists of 12 digits, and the last digit is used as a check digit. The first digit represents the product type and the next five digits, the manufacturer code. The rest of the digits identify the actual product. UPC-E consists of seven digits, and its structure is similar to UPC-A. UPC-E compresses a UPC-A code into a six-digit code by suppressing its trailing zeros for the manufacturer code and leading zeros of the actual product.

Figure 2.5 UPC-A (left) and UPC-E (right)

EAN is the European version of UPC. There are two types of EAN, namely, EAN-13 and EAN-8, as illustrated in **Figure 2.6**. EAN-13 contains an additional digit. This additional digit and the twelfth digit generally represent the country code. EAN-13 is used in the publishing industry to represent ISBN numbers of books. EAN-8 consists of eight digits, in which the first two comprise the country code. The next five digits are used for data, and the last one is used as a check digit.

Figure 2.6 EAN-13 (left), and EAN-8 (right)

Code 128 uses both alphabetic symbols and digits, as presented in **Figure 2.7**. Code 128 can represent the numbers from 00 through 99, as well as uppercase and lowercase alphabets.

a1b2c3

Figure 2.7 - Code 128

Two-Dimensional Barcode Standard

PDF can represent 2525 characters, as shown in **Figure 2.8**. It is a mature symbology, which provides several options, such as data security, compression, error detection, and correction.

Figure 2.8 PDF

Aztec Code can encode 3750 characters, as illustrated in **Figure 2.9**. At the center of this bar code is a square-shaped bulls-eye surrounded by layers of encoded data.

Figure 2.9 Aztec Code

DataMatrix can encode 3116 characters, as presented in **Figure 2.10**. A distinguishing characteristic of this symbology is its perimeter pattern. Apart for this, this type of bar code offers maximum read accuracy.

Figure 2.10 DataMatrix

- **Problems and Limitations of Barcode Technology**

Although the barcode system has already been fully developed, Hunt et al. (2007) illustrate that several problems and limitations of barcode technology still exist, which cannot be solved. The limitations are as follows:

(i) Short read range – The read range of a bar code reader is generally confined to a few meters.

(ii) Need for line of sight – A bar code scanner must need a clear line of sight to scan a bar code.

(iii) Easily damaged – A bar code usually prints on paper. It is easily damaged when used in moist environment.

(iv) Small data capacity – A bar code can store 13-digit characters which is not enough in today's industry.

(v) Not rewritable – A bar code can only store static data which cannot be rewritten.

(vi) Not intelligent – A bar code should be scanned by a human using the reader scanner. Consequently, it is susceptible to human error.

(vii) Not capable of real-time capture – As a bar code cannot keep tracking and tracing continuously and cannot be rewritten, it is not able to perform real-time data capturing.

2.4.2 RFID Technology

According to Landt (2005), the commercial use of RFID technology began in 1980s, primarily in the railroad and trucking industries. It is able to send, process, and store information (Wu et al., 2006). Subsequently, this technology has been widely adopted in different business operations to identify, locate, and track people, as well as animals or assets (Streit et al., 2003; Thevissen et al., 2006; Vijayaraman and Osyk, 2006; Huang et al., 2007).

- **Architecture of RFID System**

RFID technology consists of two sections, i.e., hardware and software. The hardware part is composed of tag, reader, and antenna. The software part is composed of the middleware and the host computer software system.

Hardware Section

(i) Tag

An RFID tag is a device which can store and transmit data to a reader in a contactless manner using radio waves. An RFID tag basically consists of a microchip and antenna. Microchip contains the modulator, which modulates the received reader signal. Likewise, it has a memory for data storage. A tag's antenna is used for drawing energy from the reader's signal to energize the tag, and for sending and receiving data from the reader. This antenna is physically attached to the microchip. The antenna geometry is central to the tag's operations. Lahiri (2006) claims, that the antenna length is directly proportional to the operation wavelength of the tag. A dipole antenna consists of a straight electric conductor (e.g., copper) interrupted at the center. The total length of a dipole antenna is half the wavelength of the required frequency to optimize the energy transfer from the reader antenna signal to the tag. A dual dipole antenna consists of two dipoles, which can greatly reduce the tag's alignment sensitivity. As a result, a reader can read the tag at different tag orientations. A folded dipole consists of two or more straight electric conductors connected in parallel. Each has a dimension that is half of the wavelength. The different designs of the tag's antenna may affect the reading distance, known orientation, and transmitting speed of the tag.

RFID tags can be classified into three: (i) Passive, (ii) Active, and (iii) Semi-Active Tags.

Passive Tag does not have a non-board power source. It uses the power emitted from the reader to energize itself and transmit its stored data to the reader. A passive tag is simple and has no moving parts, as shown in **Figure 2.11**. As a result, the tag has a long lifespan and generally resistant to harsh environmental conditions. It can read ranges starting from less than 2 centimeters to 9 meters. Furthermore, a passive tag is generally cheaper compared with active or semi-active tags.

Figure 2.11 Passive Tag

Active Tag contains an on-board power source, and it is electronically powered for performing specialized tasks. An active tag uses its on-board power for data transmission. **Figure 2.12** illustrates a sample of active tag. The on-board electronics can contain microprocessors, sensors, and input/output ports powered by the on-board power source. The reading distance of an active tag can be up to 30 m or more.

Figure 2.12 Active Tag

Semi-Active Tag contains an on-board power source and electronics for performing specialized tasks. The on-board power supply provides energy to the tag for its operation. However, for transmitting data, a semi-active tag uses the reader's emitted power.

(ii) RFID Reader

An RFID reader or "interrogator" is a device which can read from and write data to compatible RFID tags, as shown in **Figure 2.13**. Thus, a reader also acts as a writer. The main components of the reader are transmitter, receiver, microprocessor, memory, input/output channels for external sensors or actuator, controller, communication interface, and power. The transmitter and receiver are used to send the reader's signal to the surrounding environment and receive tag responses back via the reader antennas. The microprocessor is responsible for implementing the reader protocol to communicate with compatible tags. The RFID reader performs decoding and error checking of the analog signal from the receiver.

Figure 2.13 RFID reader

Generally, there are three types of communication between a reader and a tag. They are the modulated backscatter, transmitter, and transponder types. The reader transmits a continuous-wave (CW) RF signal into the reading environment. When a tag appears in the area, it modulates or breaks up the CW signal into patterns of ones and zeroes, which are defined as the tag's digital data. Since it "speaks" essentially by reflecting the reader's "voice," a backscatter tag is physically incapable of communicating data outside the presence of a reader's signal. A transmitter tag can broadcast a message in the environment even if there is no active reader nearby to "hear" it. This tag acts similarly to the ringing of a telephone even when no one is home to answer it. Another type of tag is the transponder. To conserve power and minimize RF noise pollution, some active/transmitter tags may be configured to "go to sleep" or enter a quiescent or lower-power state when it is not being interrogated. When a reader enters the area, it then transmits a signal to "wake up" all the tags in that area. Therefore, each tag only transmits in response to the reader's command.

(iii) Antenna

Generally, an antenna is physically attached to a reader by a 6 to 25 feet cable, as shown in **Figure 2.14**. A single reader can support up to four antennas. The antenna is also called the reader's coupling element because it creates an electromagnetic field to couple with the tag. The antenna broadcasts the reader transmitter's RF signal in its surroundings and receives tag responses on the reader's behalf.

Software Section

The host and software system is an all-encompassing term for the hardware and software component separated from the RFID hardware. The system is composed of edge interface/system, middleware, enterprise back-end interface, and enterprise back-end.

Figure 2.14 RFID antenna

Hunt et al. (2007) state that middleware is used to route data between the RFID networks and the IT systems within an organization. Middleware merges new RFID systems with legacy IT systems. Middleware is a software tool, which moves data to and from transaction point. For example, in a tag-read process, the middleware moves the data contained in a tag from the reader to the proper enterprise IT system. Conversely, in a tag-write process, middleware moves the data from the enterprise IT system to the proper reader and ultimately to the proper tag. Different companies usually build different middleware themselves to fulfill their special need. Most of the middleware products currently under development are based on EPC global standards.

- **Standard of Radio Frequency**

Different countries have established different ranges of frequency for RFID, as shown in **Table 2.1**.

Table 2.1 International RFID frequency regulations

Country/ Region	Low frequency (LF) (KHz)	High frequency (HF) (MHz)	Ultra high frequency (UHF) (MHz)	Microwave (GHz)
United States	125−134	13.56	902−928	2.400−2.4835, 5.725−5.850
Europe	125−134	13.56	865−868	2.45
Japan	125−134	13.56	950−956	2.45
Singapore	125−134	13.56	923−925	2.45
China	125−134	13.56	840−843, 917−925	2.446−2.454
Hong Kong			865−868, 920−925	

- **Electronic Product Code (EPC)**

EPC is a standard marking system using RFID air interface technology without a fixed air interface framework. The system defines a standard product coding structure for item management application. According to the EPC Global official website (2008), EPC can be classified into the following types:

(i) Class 0 –This is a passive tag which can store 64 or 96 bits of EPC. This is designed for UHF (900 MHz). A class 0 tag consists of a unique serial number, which has already been written by the manufacturer before the tag was shipped to a customer.

(ii) Class 1 – This is a passive tag which can store 64 or 96 bits of EPC data. Class 1 is designed for both UHF (860−930 MHz) and HF (13.56 MHz).

(iii) Class 1 Generation 2 – This is a new generation of EPC WORM tag based on the UHF Generation 2 Foundation Protocol, which will replace Classes 0 and 1 tags. This is designed for UHF (860−930 MHz) and consists of a 128 bits RW tag with 96 bits reserved for EPC data and 32 bits for error correction and kill command.

(iv) Class 2 – This is a passive RW tag, which can store an EPC with user data. The minimum user data capacity of such tag is 224 bits. These tag types are still in the prototypical stage.

(v) Class 3 – This is an RW active tag, which has a large data capacity that is still unspecified at this time. A Class 3 EPC tag supports on-board processing and I/O capability.

(vi) Class 4 – This is an RW active tag with a large user data capacity that is yet to be specified. The minimum read range is 300 feet. These are the most expensive tag types.

- **Operating Principle of RFID**

Figure 2.15 shows the inductive principle of RFID technology. The vast majority of RFID systems operate according to the principle of inductive coupling. A wave is a disturbance, which transports energy from one point to another.

Electromagnetic waves are created by electrons in motion and consist of oscillating electric and magnetic fields. These waves can pass through a number of different material types.

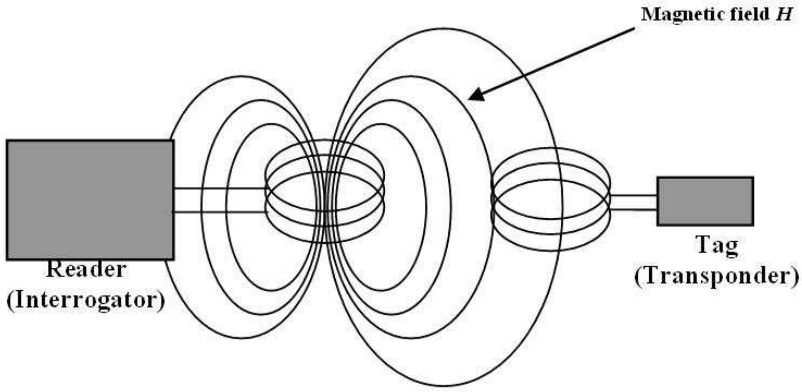


Figure 2.15 Operating principle of RFID technology (Extracted from Finkenzeller, 2003)

RF waves are electromagnetic waves with wavelengths between 0.1 and 1000 km. Radio waves can also be defined in terms of frequency, e.g., electromagnetic waves whose frequencies lie between 30 and 300 GHz. The rest of electromagnetic wave types are infrared, visible light wave, ultraviolet, gamma-ray, x-ray, and cosmic-ray. In general, RFID utilizes radio waves, which are generally between the frequencies of 30 KHz and 5.8 GHz.

The physical connection of RFID can be divided into four types, as shown in **Figure 2.16**.

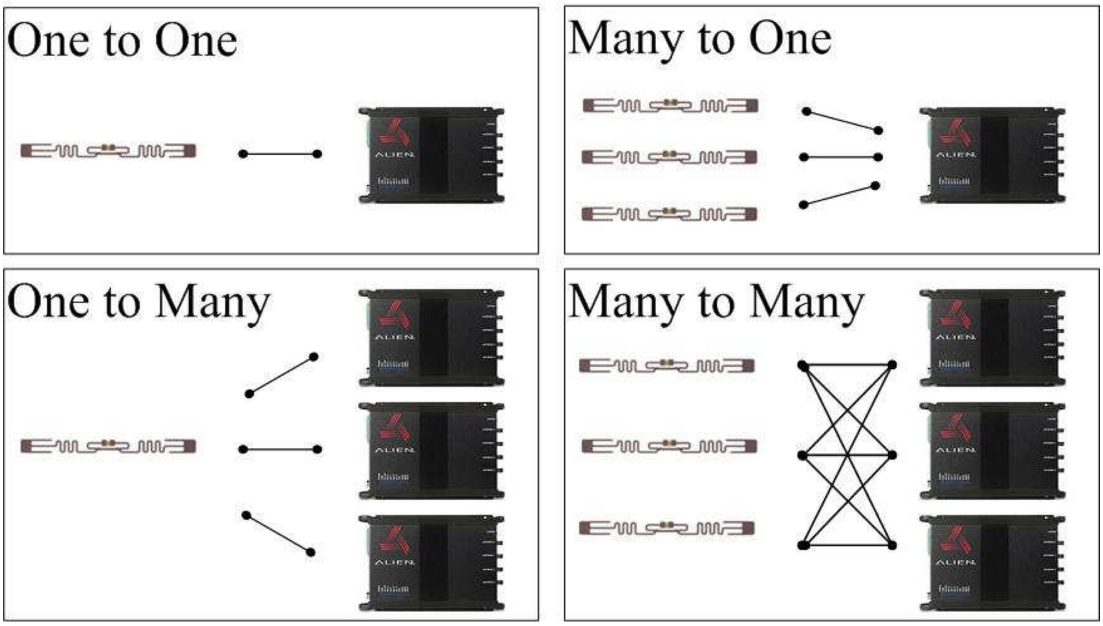


Figure 2.16 Connection between RFID tag and reader

The communication method of “many to one” is commonly adopted in the actual production/warehouse environment. An RFID is usually used to detect multiple tags. This can also be applied in SFCS for tracing the WIP.

- **RF Properties with Various Materials**

According to Lahiri (2006), radio waves can be affected by the material during transmission. A material is called RF-lucent or RF-friendly for a certain frequency if it allows radio waves at this frequency to pass through it without a substantial loss of energy. A material is called RF-opaque if it blocks, reflects, and scatters RF waves. A material which allows the radio waves to propagate through it but with substantial loss of energy is referred to as RF-absorbent. The RF-absorbent or RF-opaque property of a material is relative because it depends on the frequency. Cooney (2006) illustrates that a lower frequency radio wave is used for a longer communication distance because it has less energy loss. On the other hand, a higher frequency radio wave is used for a short communication distance. It loses energy quickly but transmits data faster. **Table 2.2** presents RF properties of various materials.

Table 2.2 RF properties of various materials (Extracted from Scherer, 1998)

Material	LF	HF	UHF	Microwave
Clothing	RF-lucent	RF-lucent	RF-lucent	RF-lucent
Dry-wood	RF-lucent	RF-lucent	RF-lucent	RF-absorbent
Graphite	RF-lucent	RF-lucent	RF-opaque	RF-opaque
Liquid	RF-lucent	RF-lucent	RF-absorbent	RF-absorbent
Metals	RF-lucent	RF-lucent	RF-opaque	RF-opaque
Motor oil	RF-lucent	RF-lucent	RF-lucent	RF-lucent
Paper products	RF-lucent	RF-lucent	RF-lucent	RF-lucent
Plastics	RF-lucent	RF-lucent	RF-lucent	RF-lucent
Shampoo	RF-lucent	RF-lucent	RF-absorbent	RF-absorbent
Water	RF-lucent	RF-lucent	RF-absorbent	RF-absorbent
Wet wood	RF-lucent	RF-lucent	RF-absorbent	RF-absorbent

- **Advantages of RFID over Bar Code**

Although RFID is much more expensive than barcode technology, enterprises are willing to adopt these techniques, if only to improve accuracy of data capture. The advantages of adopting RFID technology are as follows.

(i) **Does not require line of sight –** An RFID reader does not need a line of sight to read a tag's data, unlike a barcode reader.

(ii) **Writable data** – An RFID tag data can be written many times. The data on a barcode is static and cannot be changed.

(iii) **Longer read range –** An RFID tag can have a significantly longer range than a barcode. Generally, a passive RFID tag has a read range of about 9 meters. A barcode reader has a read range of a few meters.

(iv) **Larger data capacity –** A barcode generally has 12 digits. However, an RFID can store much more data than barcode. It has 128 bits equal to 39 digits.

(v) **Multiple reads –** An RFID reader can read several tags within a very short period which a barcode cannot do.

(vi) **Sustainability –** A barcode can be damaged more easily than an RFID tag. An RFID tag is generally resistant to rugged and harsh environments.

(vii) **Read accuracy –** RFID is far more accurate than barcodes.

(viii) **Real-time control –** An RFID tag's data can be monitored in real-time by the connection of RFID reader and the host software system.

RFID technology can remedy the problems of the barcode system in real-time monitoring. Moreover, it has wider access area, larger memory storage, and performs automatic data tracking. The cost of RFID has rapidly decreased in recent years. Thus, it is a technology, which could be adopted in SCFS to increase production efficiency.

- **RFID Applications in the Existing Market**

With RFID technology, the feature of automated data capture is established. RFID technology has been widely adopted in production and warehouse environment (Gu et al., 2007; de Brito and van der Laan, 2009; Sahin and Dallery, 2009; Zhou, 2009). Yin et al. (2009) developed an RFID-based precast production management system for controlling the quality of components during the production stage and managing the storage and transportation issues of finished products. An agent-based collaborative mold production system has been designed for solving the problems of vendor selection and task selection (Trappey et al., 2009). The system utilizes RFID technology to control and monitor outsourcing partners instantly. Poon et al. (2009) propose an RFID case-based logistics resource management system to improve the efficiency and effectiveness of order-picking operations in a warehouse. Martínez-Sala et al. (2009) present the framework of a packing and transport unit for the grocery supply chain. RFID technology is adopted for tracking and tracing the products in the cold chain.

However, the mechanism coordinating the resource management process of analyzing information, decision support, and knowledge sharing is still neglected. This highlights the need to adopt AI techniques integrated with RFID technology to support the management of production-and-warehouse processes.

To conclude, there are independent systems adopted in managing the production and warehouse activities in organizations. However, these systems are either barcode- or manual-based. People mainly rely on their experience, know-how, and knowledge to manage production and warehouse activities, resulting in incapability of acquiring, retrieving, and manipulating various types of production and warehouse information for monitoring and controlling different planning activities and operations. Human error is inevitable, particularly under stressful conditions (Hockey and Sauer, 1996; Sexton et al., 2000). As a result, error and rework frequently occur, resulting in increased operating cost and low accuracy and resource utilization. Enterprises lose their competitive advantages if they cannot satisfy their customers. It is essential to implement a real-time AI-aided system for managing material flow between production and warehouse facilities to provide superior products and services for fulfilling customers' demands.

Chapter 3 Real-time Production Operations Decision Support System

3.1 Introduction

In this chapter, the development of an R-PODSS is discussed to illustrate the process of increasing the visibility of production and warehouse operations status and enhancing the efficiency and effectiveness of decision making when production problems occur. This will enable warehouse resources to be located on a real-time basis and instant material handling solutions will be suggested for automatic handling of customer orders. The feature of real-time and automatic data retrieval in the proposed system is supported by RFID technology, which also facilitates construction of an effective triangular localization scheme to determine the exact locations of warehouse resources. The collected data is then compared with the attributes stored in an embedded case-based engine to determine the appropriate material handling equipment to handle the order-picking operations. Moreover, a material handling solution formulation model is constructed by GA to generate the shortest pickup sequence for the appropriate material handling equipment. Through this, the objectives of maximizing the productivity of warehouse and minimizing the operation costs in a warehouse are achieved. Two construction phases for R-PODSS are required for this process:

Phase 1 – Defining the operating specification of R-PODSS

Phase 2 – Constructing the architecture framework of R-PODSS

The detailed explanation of these phases is provided in the following sections.

3.2 Phase 1 – Defining the Operating Specification of R-PODSS

The objective of this phase is to define the operating specifications of the proposed system. Five stages are involved: (i) warehouse and shop floor layout study, (ii) evaluation of RFID equipment, (iii) RFID reading performance tests, (iv) result analysis, and (v) system design, testing, and evaluation.

Stage 1: Warehouse and shop floor layout study

It is essential to perform a warehouse and shop floor study before the implementation of the proposed system because the layouts of warehouse and shop floor vary among different companies. The physical and environmental factors, such as the size of the warehouse, number of aisles, number of racks, types of racks, types of material handling equipment, types of products stored, number of production lines/workstation, etc., affect the readable range and accuracy of tags (Bhuptani and Moradpour, 2005). By studying the actual environment, the specification of the warehouse and production shop floor is determined for RFID equipment selection.

Stage 2: Evaluation of RFID equipment

As previously mentioned, there are two common types of RFID equipment available on the market, namely, active RFID technology and passive RFID technology. The items of equipment of these technologies vary in size, cost, reading performance, and application domains. The most common RFID equipment used in warehouses and shop floors, are the Active (Alien 2850 Mhz Series) and the Passive (Alien 9800 series) RFID apparatus. Experiments have been conducted for evaluating the reading performance of these types of equipment to select the most appropriate for the actual production shop floor and warehouse environments.

Stage 3: RFID reading performance tests

Seven tests, namely, i) Orientation, ii) Height, iii) Range, iv) Material, v) Power level – distance, (vi) Tag angle, and (vii) Antenna angle tests are proposed to evaluate the performance of the RFID device in the actual production and warehouse environment. In addition, two terminologies, E-plane and H-plane, are adopted in the tests. According to Balanis (1969), E-plane is defined as "the plane containing the electric-field vector and the direction of maximum radiation," whereas the H-plane is "the plane containing the magnetic-field vector and the direction of maximum radiation." Therefore, in this study, the E-plane is regarded as the elevation plane (x-y plane) and H-plane is regarded as the azimuth plane (y-z plane), as illustrated in **Figure 3.1**.

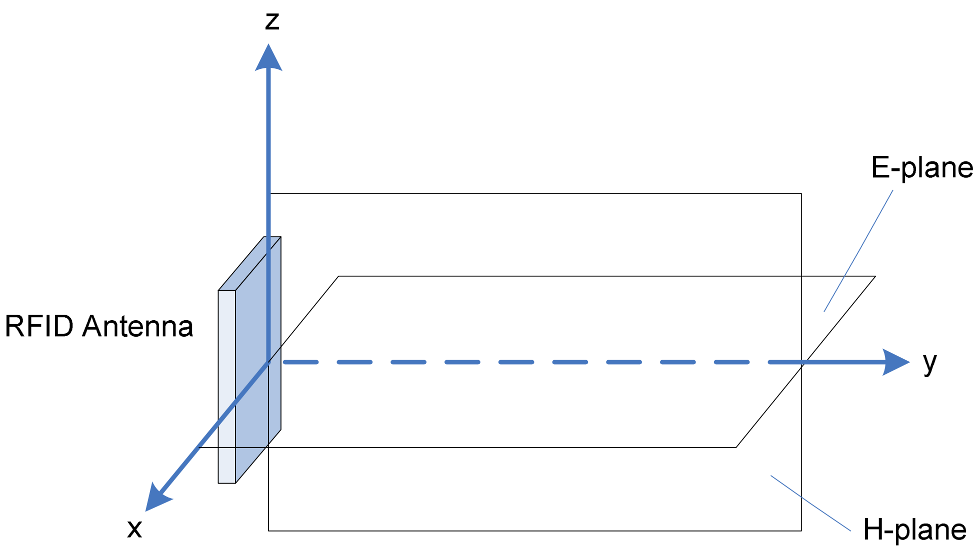


Figure 3.1 E- and H-plane patterns

Before performing the tests, the RFID readers and tags should be appropriately installed so as to obtain reliable experimental results. A pair of antennas is placed at a fixed location and the center of the antennas is placed 1 meter from the ground. Tags are stuck onto objects placed in various locations, facing different directions, and stuck onto various materials. After this, the read rates of the tags (total reads per minute) are taken by performing various tests.

i) Orientation test

The test determines the horizontal effective RF coverage range of the reader. The tags are stuck on the front, top, and side surfaces of the object and corresponding read rates of the tags are measured by horizontally moving the object across different distances. The configuration of the orientation test is shown in **Figure 3.2**.

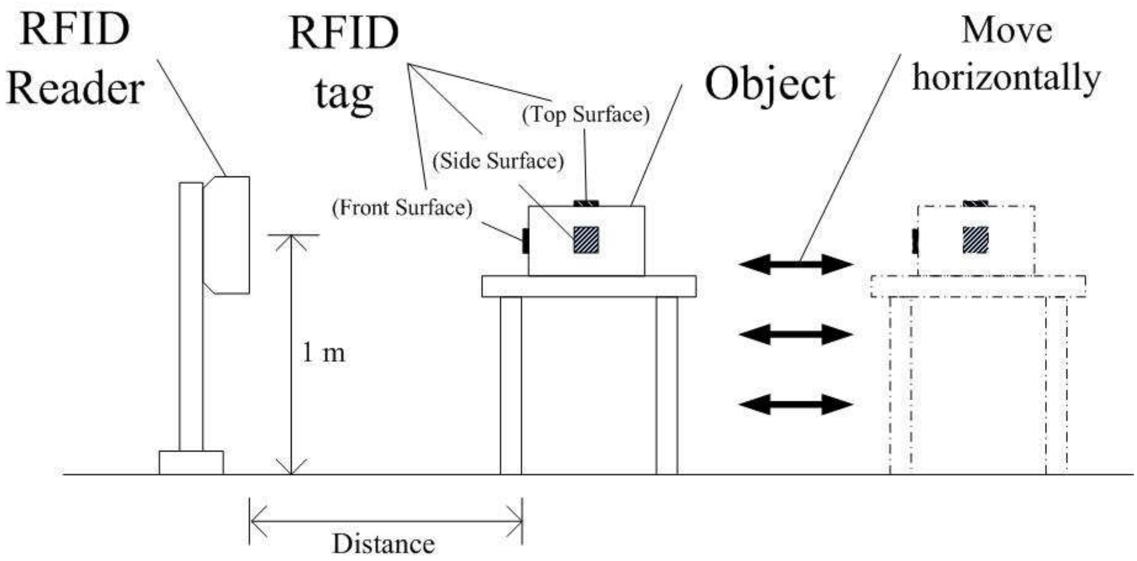


Figure 3.2 Configuration of orientation test

ii) Height test

In this test, the effective vertical RF coverage range of the reader is determined. The tags are stuck on the front surface of the object placed at 1 meter from the reader. Subsequently, the object is vertically moved across different distances and the corresponding read rates of the tags are measured. The configuration of the height test is shown in **Figure 3.3**.

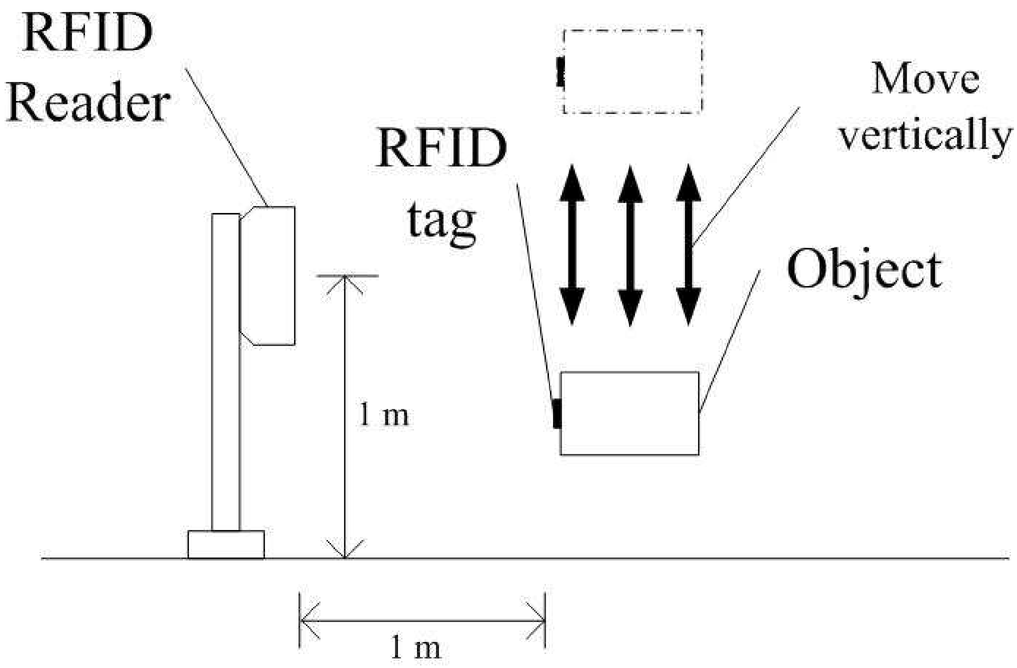


Figure 3.3 Configuration of height test

iii) Range test

The test determines the maximum RF coverage range of the reader in a horizontal direction. As illustrated in **Figure 3.4**, the object is placed 1 meter from the reader and the tags are stuck on the front surface of the object. Read rates of the tags are measured when the object is horizontally moved across different distances.

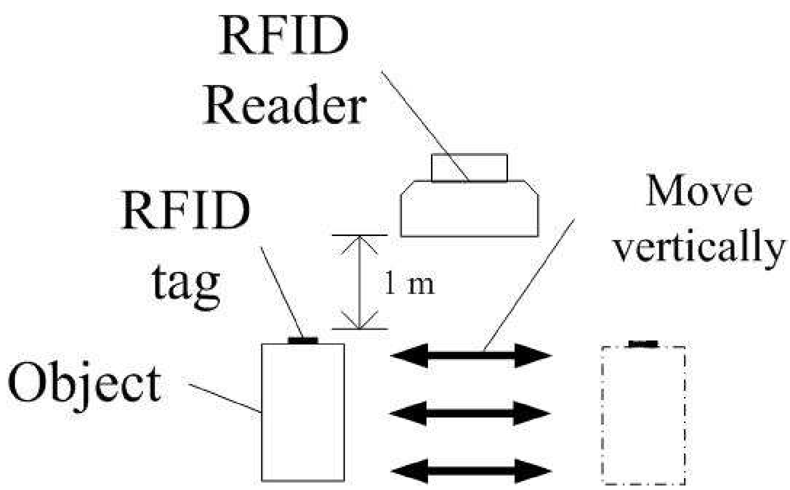


Figure 3.4 Configuration of range test (top view)

iv) Material test

In the material tests, the reading performance of the RFID device is measured when the tags are placed on the front and back surfaces of various types of products in the actual environment. Similar to the orientation test, the tags are stuck on the nearest and farthest surfaces of the object. The object is horizontally moved across different distances and the corresponding read rates of the tags are measured. The configuration of the material test is shown in **Figure 3.5**.

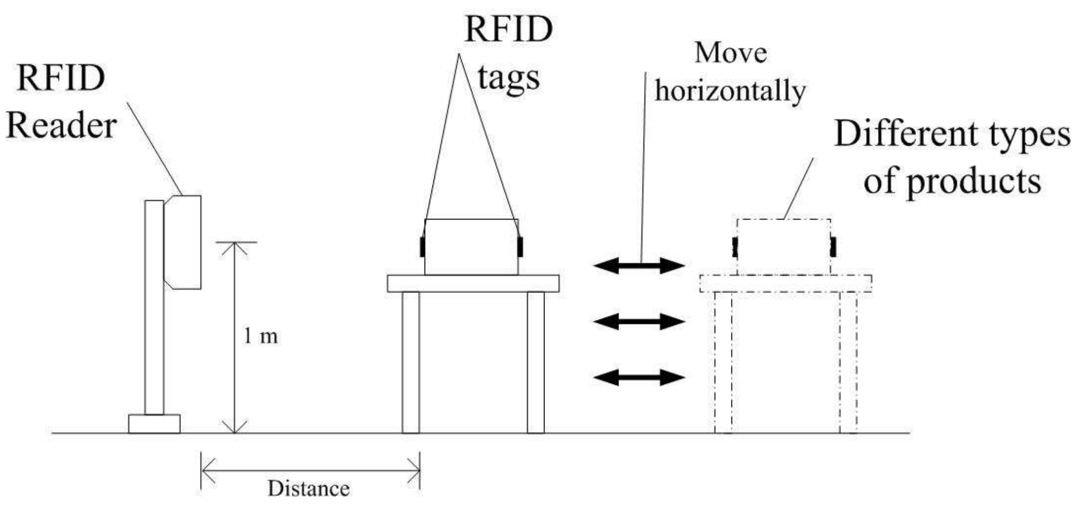


Figure 3.5 Configuration of material test

v) Power level-distance test

In this test, the effective RF coverage range of the reader is determined with an appropriate power level. Two variables are considered in this test: i) distance from the antenna (the center point of the two antennas) to the tag, and ii) energy level. The configuration of this test is shown in **Figure 3.6**.

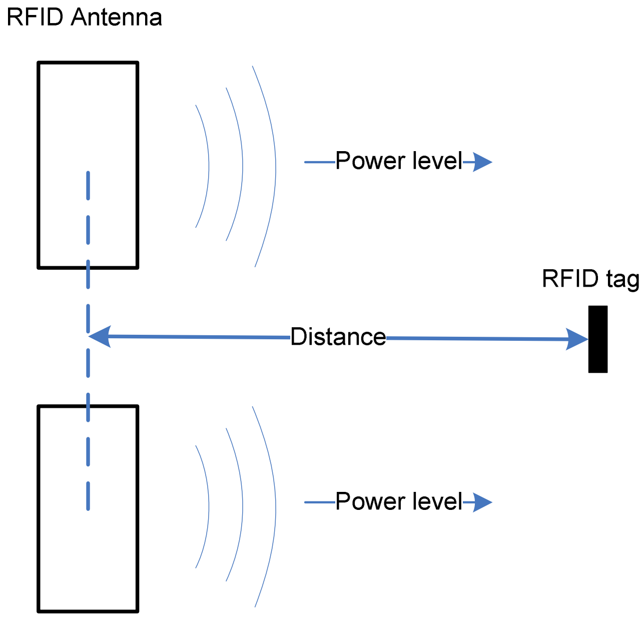


Figure 3.6 Configuration of power level – distance test (side view)

vi) Tag angle test

This test determines the effective RF coverage range of the reader when the tag is placed at a certain angle (α). Two antennas are placed in line parallel to the E- and H-planes, and the tag is placed in different positions in the E-plane. The angle of the tag changes in the H-plane. By doing this, the read range under different tag angles can be plotted. The configuration of the tag angle test is shown in **Figure 3.7**.

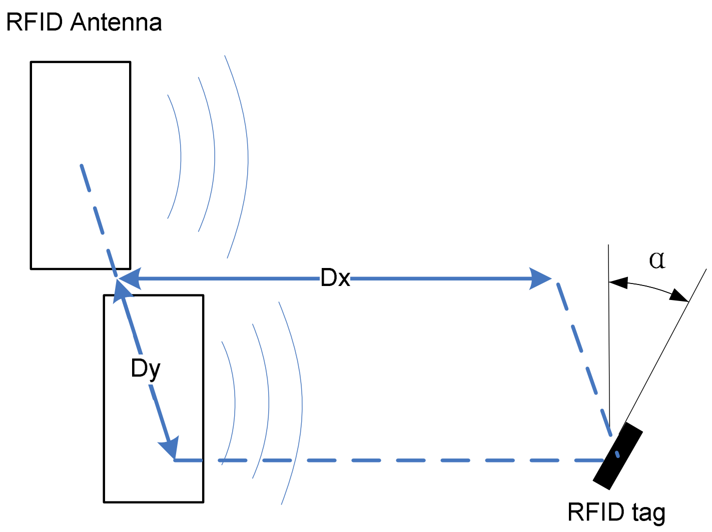


Figure 3.7 Configuration of tag angle test (perspective view)

vii) Antenna angle test

This test determines the effective RF coverage range of the reader when the antennas are placed at a certain angle (β). An object is moved in front of the antennas at different angles and the corresponding read rates of the tags are measured. The configuration of the antenna angle test is shown in **Figure 3.8**.

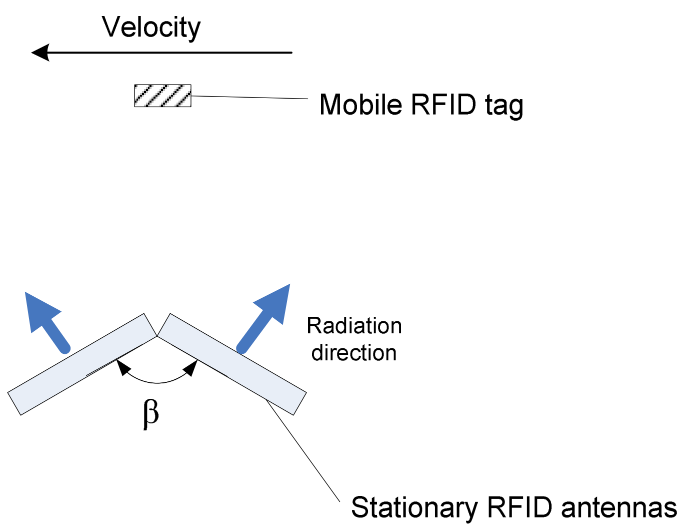


Figure 3.8 Configuration of antenna angle test (top view)

Stage 4: Result analysis

After the tests, three kinds of results are obtained and analyzed, as shown in **Table 3.1**. The first set of results determines the relationship between the power level and the distance between the tags and antennas. The second set shows the relationship between the reading performance and the different reader angles. The third set illustrates the most effective RF coverage range of the reader. Based on the results, the RFID devices are installed in the racks, forklifts, and production materials for real-time data collection, as illustrated in **Figure 3.9**. Through RFID technology, information of material handling equipment is captured when the equipment passes the antennas. The retrieved information is in EPC format, which is a standard product coding structure for item management applications. The retrieved information is then systematically stored in a centralized database for further processing (e.g., location tracking of production materials and optimization of the pick-up routing plan of the forklifts).

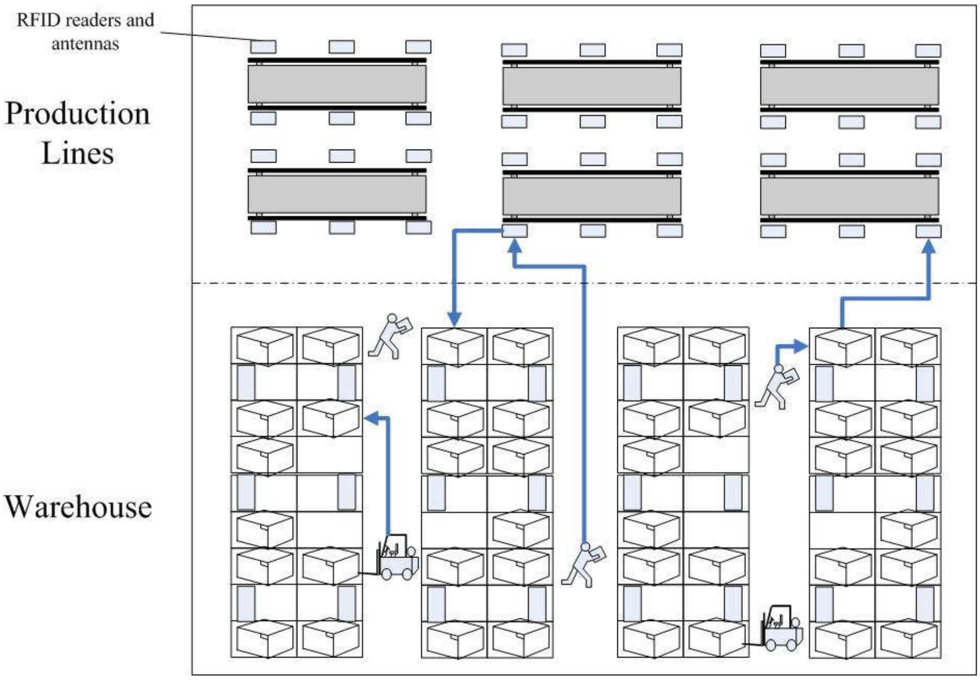


Figure 3.9 Setup of RFID equipment in shop floor and warehouse

Table 3.1 Results of the tests

Test	Expected result	Final result
Orientation Test	Horizontal effective RF coverage range of a reader	The most effective RF coverage range of the reader
Height Test	Vertical effective RF coverage range of a reader	
Range Test	Maximum RF coverage range of a reader in a horizontal level	
Material Test	RF performance effects of handling different materials	
Power Level - Distance Test	RF performance effects of setting different power levels and placing in different locations	
Tag Angle Test	RF performance effects of setting different angles between the tags and antennas	
Reader Angle Test	RF performance effects of setting different angles between the antennas	

Stage 5: System design, testing, and evaluation

After defining all the operating specifications, the architecture of R-PODSS is designed then tested under two case studies to ensure that all the equipment work within the defined specifications.

3.3 Phase 2 –Constructing the Architecture Framework of R- PODSS

After finishing Phase 1, the data capture capability of the RFID is verified. **Figure 3.10** shows the architecture framework of R-PODSS consisting of four main modules.

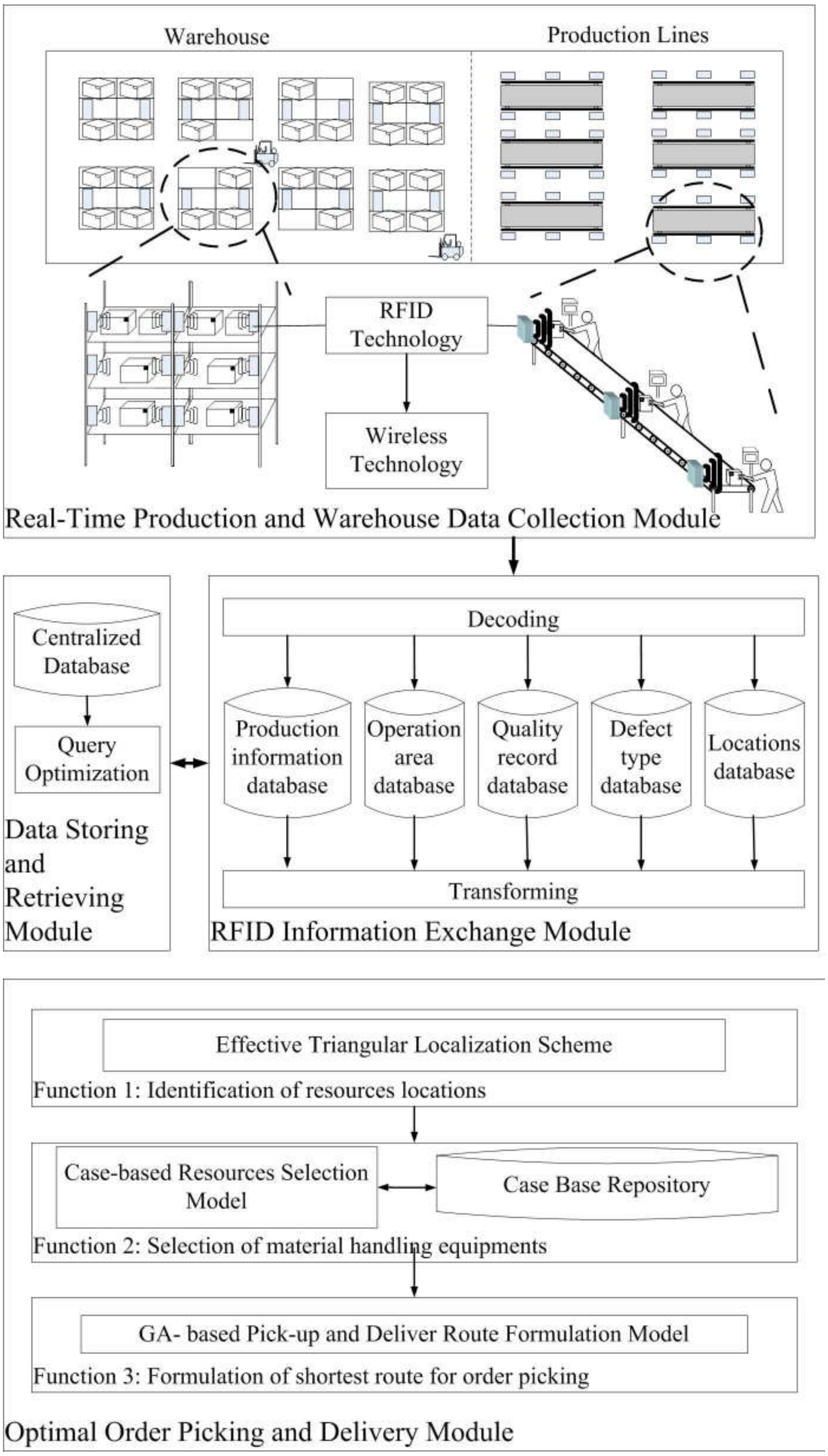


Figure 3.10 Architecture framework of R-PODSS

The first module is the Real-Time Production and Warehouse Data Collection, through which the raw warehouse and production operation information is collected. In the second module, the Data Storing and Retrieving, retrieved information is stored in the centralized database systematically. The third, RFID Information Exchange Module, transforms the EPC code in the RFID tag into meaningful information for further usage. The last module, Optimal Order Picking and Delivery, encompasses the relevant operation components for formulation of the pick-up routes. The detailed description of each module is presented as follows.

3.3.1 Real-Time Production and Warehouse Data Collection Module

In this module, RFID devices are adopted for data collection in the warehouse and production environments. Two types of data, namely, static and dynamic warehouse and production resource data, are captured by the RFID readers to visualize the actual status of warehouse and production operations. Static warehouse and production resource data involve the locations and quantities of production materials stored, types of production materials, available space for incoming products, etc. Dynamic warehouse and production resource data involve the production material demand orders from the production floor, locations of forklifts/warehouse staff members, inventory levels in each rack, status of order picking operations, etc. With the help of wireless network, i.e., 801.11 g WIFI network, the collected warehouse and production resource data are transferred and stored in the centralized database. The general mechanism of Real-Time Production and Warehouse Data Collection Module of R-PODSS is illustrated in **Figure 3.11**.

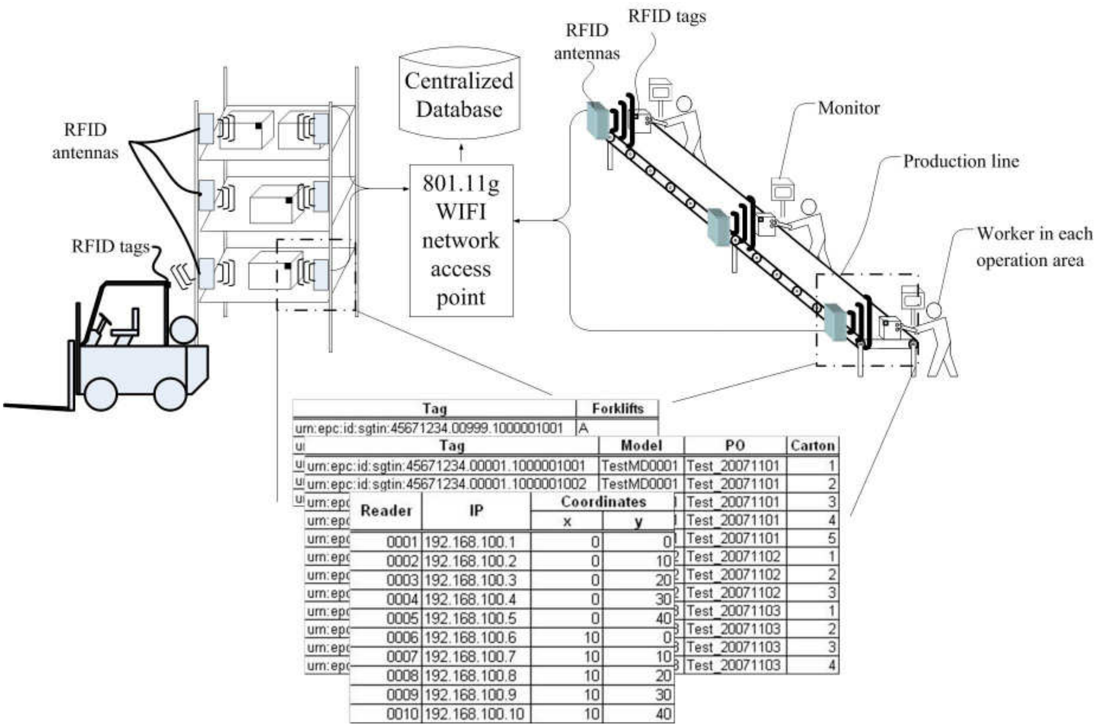


Figure 3.11 Mechanism of Real-Time Production and Warehouse Data Collection Module

3.3.2 Data Storing and Retrieving Module

In this module, the data collected in Real-Time Production and Warehouse Data Collection Module, together with related information extracted from the Enterprise Resource Planning (ERP) database, are stored in a centralized database systematically. As shown in **Figure 3.12**, numerous pre-user-designed data worksheets are constructed in the centralized database. The data are stored in different worksheets according to their nature. This module adopts the Database Management System (DBMS) and Structured Query Language (SQL) statement to provide the function of data retrieval and storage for users. It helps minimize the time used and avoid human mistakes in preparing the program statement for obtaining the required datasets.

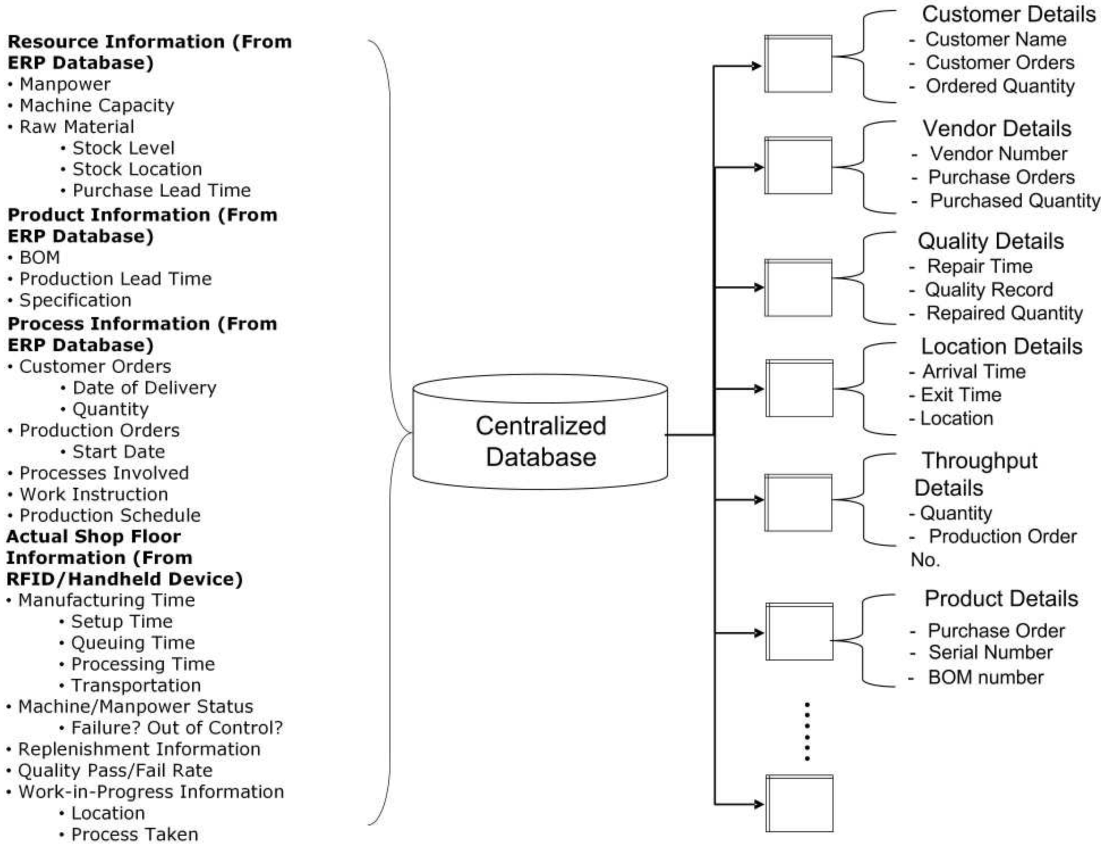
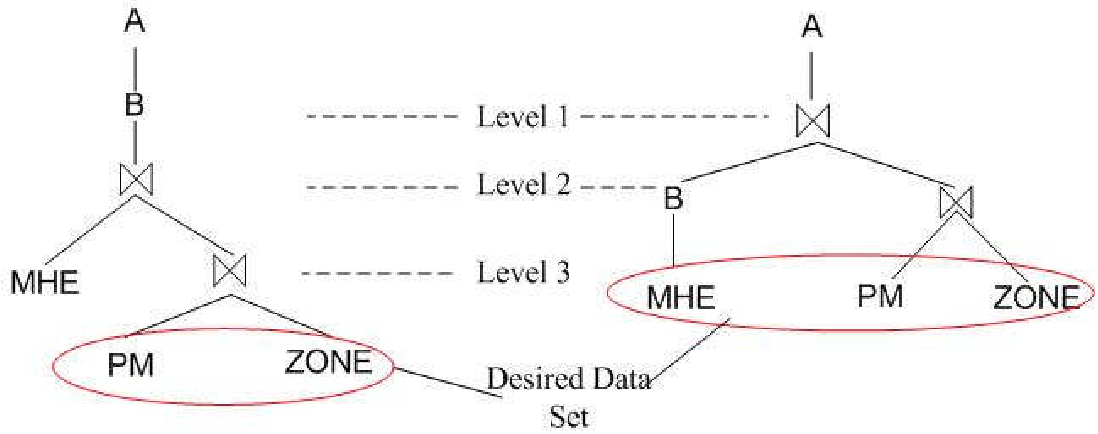


Figure 3.12 –Systematic data storage in the centralized database

To increase the speed of data retrieval in the database, query optimization technique is applied in R-PODSS. Query optimization is the process of minimizing the time used in executing a given query expression (Polat et al., 2001). Its components help determine how queries are performed. With query optimization, the time for information searching is reduced as redundant decision rules are eliminated and restructured (Grant et al., 2000). **Figure 3.13** demonstrates a comparison between traditional and revised tree expressions when the user retrieves the production material information at a time when the production material is assigned a specific material handling equipment. The hierarchy of the tree has been decreased by one level by adopting query optimization (shown on the right hand side). This means that that the corresponding processing time will also be shortened as the search area in the database has also been reduced (Claussen et al., 2000). This helps improve the performance of data retrieval from the centralized database.



where A = $\prod_{PM\_type, PM\_Weight, PM\_Length, PM\_Width, PM\_Height, PM\_Shape}$

B = $\sigma_{MHE\_ID = 'T0123'}$

MHE = Material Handling Equipment

PM = Production Material

Figure 3.13 Comparison between traditional and revised tree expressions

3.3.3 RFID Information Exchange Module

The aim of this module is to facilitate the identification of stochastic production material orders during production processes. A general RFID tag with 24 digits and hexadecimal code is divided in two parts: basic product information and production status. The basic product information is written at the first stage of production. The product status is subsequently updated by the RFID reader at each operation area. The notation of the RFID EPC identification (epcid) is shown in **Table 3.2**.

Table 3.2 Notation of the RFID EPC Code

epcid = a . b . c . d . e . f . g . h . i		
Key	**Size**	**Definition**
a	5 Digits	Product Code
b	4 Digits	Finish Goods Number
c	3 Digits	Part Number
d	2 Digits	Operation Area Code
e	2 Digits	Quality Record
f	2 Digits	Defect Type
g	2 Digits	x-coordinates
h	2 Digits	y-coordinates
i	2 Digits	z-coordinates

The EPC codes collected from the RFID readers are inputted into the module and transformed into meaningful information. **Figure 3.14** shows the mechanism of this module. First, the epcid is sent to a decoding function, which decodes the original epcid into different sections. The sections are then sent to corresponding databases to start the search for related information. All the information retrieved is sent to the transforming function to formulate a meaningful failure report that will be used in the next module.

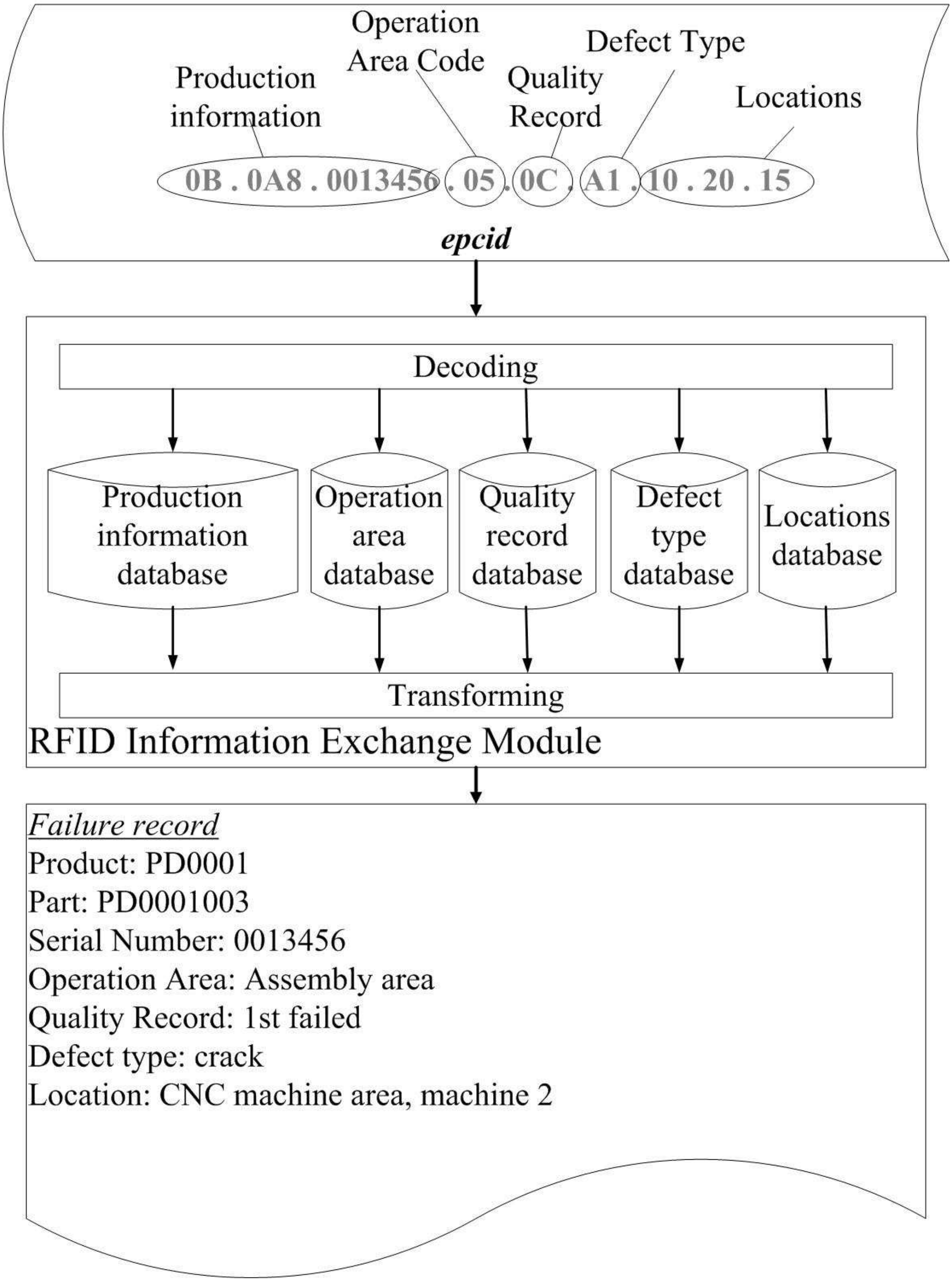


Figure 3.14 Mechanism of RFID Information Exchange Module

3.3.4 Optimal Order Picking and Delivery Module

This module is the core of R-PODSS, which manipulates the data from previous modules effectively and transforms the data into meaningful information for formulating efficient and reliable material handling solutions to address stochastic production material demand problems. There are three functions in this module. They are:

i) Function 1: Identification of the resources locations

ii) Function 2: Selection of material handling equipment

iii) Function 3: Formulation of the shortest route for order picking

Function 1: Identification of locations of resources

Function 1 is designed for identifying the exact locations of the resources in a warehouse to enhance the visibility of warehouse operations. This is illustrated in **Figure 3.15**.

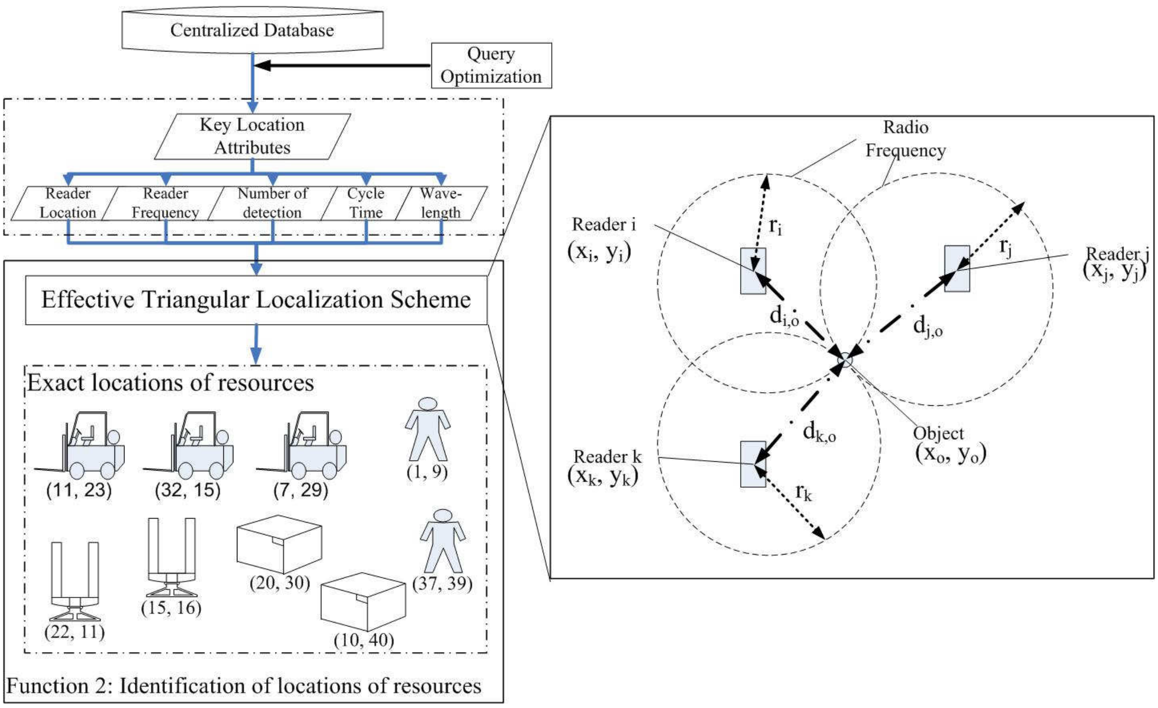


Figure 3.15 Mechanism of Function 1: Identification of resources locations

With the help of the effective triangular localization scheme and the pre-set location information in each reader, the exact locations of the resources are determined. There are two steps involved. Step 1: Calculation of the distance between the reader and the object, and Step 2: Determining the corresponding coordinates of the object, for identifying the exact locations of the resources. The notation of this function is presented in **Table 3.3**.

Table 3.3 Notation of effective triangular localization scheme

f_x	Frequency provided by reader *x*
v_x	Wavelength of frequency provided by reader *x*
(x_x, y_x)	Location of reader *x*
(x_o, y_o)	Location of object (e.g., forklift, production material, etc.)
r_x	Maximum radius of frequency provided by reader *x* can be reached
$d_{x,o}$	Distance between object and reader *x*
p_x	Period of time for tag detection
c_x	Number of tag detection within a period of time

The detailed description of this function is given below.

- *Step 1: Calculate the distance between the reader and the object*

By using the specification of the reader, the distance between the reader *x* and the object is determined. Equation (1) is adopted to calculate the distance between the reader *x* and the object.

$$d_{x,o} = (f_x \times v_x \times p_x)/(2 \times c_x) \quad (1)$$

- *Step 2: Determine the corresponding coordinates of the object*

By using geometrical calculation, the distance between reader *i* and the object is identified, i.e.,

$$d_{i,o} = \sqrt{(x_i - x_o)^2 + (y_i - y_o)^2} \quad \text{where} \quad i = 0, 1, 2, \cdots, n \quad (2)$$

When considering only two readers [(x_i, y_i) and (x_j, y_j)] and the object (x_o, y_o),

$$x_o = \frac{\left(d_{i,o}{}^2 - d_{j,o}{}^2\right) - \left(y_i{}^2 - y_j{}^2\right) - \left(x_i{}^2 - x_j{}^2\right) + 2\left(y_i - y_j\right)y_o}{-2\left(x_i - x_j\right)} \quad (3)$$

Substituting Equation (2) into (3) as formulated by the remaining point (x_k, y_k),

$$y_o{}^2 + \frac{2\left(Ax_k D + CD - A^2 y_k\right)y_o}{\left(A^2 + D^2\right)} + \frac{\left(C^2 + 2Ax_k C - A^2 B\right)}{\left(A^2 + D^2\right)} = 0 \quad (4)$$

where

$A = 2\left(x_i - x_j\right)$

$B = d_{k,o}{}^2 - y_k{}^2 - x_k{}^2$

$C = \left(d_{i,o}{}^2 - d_{j,o}{}^2\right) - \left(y_i{}^2 - y_j{}^2\right) - \left(x_i{}^2 - x_j{}^2\right)$

$D = 2\left(y_i - y_j\right)$

$i = 0, 1, 2, \cdots, n$

$j = 0, 1, 2, \cdots, n$

$k = 0, 1, 2, \cdots, n$

$i \neq j \neq k$

By solving Equations (3) and (4), the exact locations of the objects are identified.

Function 2: Selection of material handling equipment

Function 2 is designed for selecting the appropriate material handling equipment for managing the order picking operations. Function 2 contains a case-based resource selection model for searching for similar cases in the case-based repository and for the proposed reliable solutions for handling the pick-up orders. The three-step process of selecting appropriate material handling equipment using the case-clustering retrieval approach is described below:

- *Step 1: Cluster the case in the case-based repository*

  A list of previous cases is retrieved from the case-based repository and divided into n clusters according to their order specifications. The value of each cluster is calculated by the k-NN method.

- *Step 2: Retrieve the cluster with the potentially highest degree of similarity*

  When a new pick-up order is released, different order attributes, such as SKU type, weight, dimensions, and shape are adopted as problem descriptions. The problem description of the current query is compared with the clusters by the following evaluation function (Sun and Finnie, 1996):

$$\sum_{i=1}^{n} w_i \times sim(f_i^I, f_i^{CR}) \qquad (5)$$

where w_i is the importance of feature f_i, sim is the similarity function, and (f_i^I, f_i^{CR}) are the values for feature f_i in the input and retrieval clusters/cases, respectively.

- *Step 3: Suggest suitable material handling equipment for the order from the potentially useful cases in the retrieved cluster*

  Once the cluster with the highest similarity is discovered, the current query is then compared with the cases in the retrieved cluster by Equation (5). According to the degrees of similarity, a list of order handling solutions on association between material resources equipment and orders is generated. Through this, less time is spent on assigning appropriate resources to different orders, resulting in the best resource utilization and highest productivity.

Function 3: Formulation of shortest route for order picking

As illustrated in **Figure 3.16**, this function consists of two embedded layers. The aim of Layer 1 Algorithm is to solve the optimization of production material demand order constraints for the assignments of material handling equipment. The aim of the Layer 2 Algorithm is to solve the prioritization of the sequence of the items of material handling equipment, so that the different materials are handled according to the sequence in which the orders arrive. The notation of this function is presented in **Table 3.4.**

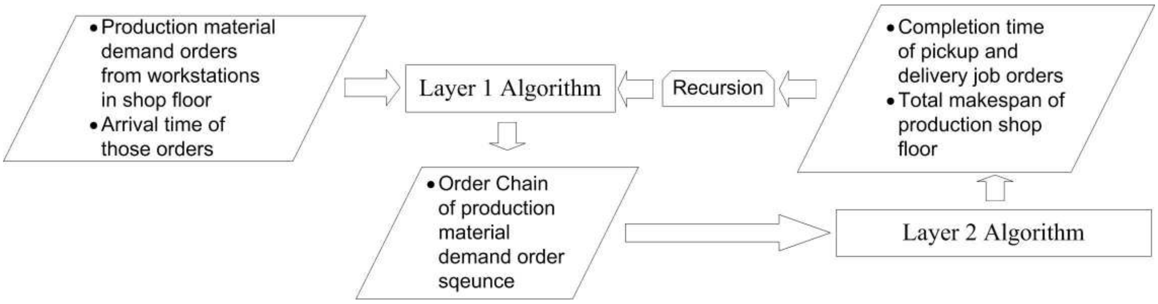


Figure 3.16 Mechanism of two-layered algorithm

Table 3.4 – Notation of GA

a	Number of production workstations
b	Number of racks in the warehouse
c	Number of types of production materials
d	Number of material handling equipment
z, x_{ijk}	Parameter index
$A = \{1, 2, \ldots, a\}$	Set of index of production workstation
$B = \{1, 2, \ldots, b\}$	Set of index of racks in the warehouse
$C = \{1, 2, \ldots, c\}$	Set of index of types of production materials
$D = \{1, 2, \ldots, d\}$	Set of index of material handling equipment
W_i	i-th production workstation located at (x_i, y_i), $\forall i \in A$
R_j	j-th rack located at (x_j, y_j) in the warehouse, $\forall j \in B$

M_k	k-type production material located at (x_k, y_k) in the warehouse, $\forall k \in C$
H_l	l-th material handling equipment located at (x_l, y_l), $\forall l \in D$
$N_{i,k}(t)$	Quantity of k-type production material requested by W_i at time t, $\forall k \in C$
$CH_l(t)$	Capacity of H_l at time t, $\forall l \in D$
O_i	Production material demand order from i-th production workstation
T^0, T^1, T^2	Time Record Set
e	Quantity of production material demand orders requested by workstations
C_i	Completion time of production material demand order O_i to workstation W_i
R_i	Requesting time of production material order i from workstation W_i
S_{ij}	Starting time to pick production material j of order i in the warehouse
P_{ij}	Processing time of production material j of order i in the warehouse

(i) The Layer 1 algorithm

Layer 1 is designed to optimize the job sequence of material handling equipment, (i.e., forklifts), for a production material demand order to minimize the completion time of each order. In this algorithm, the failure records generated by the real-time data transformation engine are first reformed into a number of order chains. Each chain represents a sequence of incomplete production material demand orders, as shown in **Figure 3.17**.

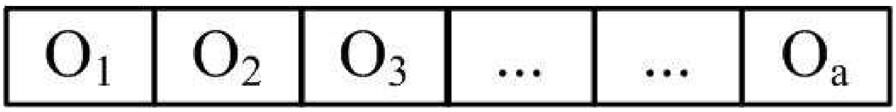


Figure 3.17 Structure of an order chain

For each order chain, an originating time record set for each forklift, T^0, exists which represents the time when each forklift can start to process the top ranking order of that order chain. An initial order chain is created using the first-come-first-served strategy, such that the incomplete orders in set ∂^1 are scheduled first according to the requesting time from the corresponding workstation. The set of time records, T^1 and the order identity are passed to Layer 2 algorithm for the calculation of the value of completion time of each order, as well as its time records, set T^2. Hence, the completion time of the orders and set of time records T^2 for following the order chain are evaluated iteratively using Layer 2 algorithm until all the completion times of the grouped orders in the orders chain, as well as set of time records, T^2, are both solved. The detailed description of pseudo-codes for solving an order chain is illustrated as follows.

For i = 1 to number of grouped orders in the proposed orders chain

If (i == 1)   // the first element of orders chain

$T^1 = T^0$

[Completion time of that order, $T^2(i)$ *] =Interrupt call Layer 2 algorithm (set of time records* T^1*, order identity)*

Else

$T^1 = T^2(i-1)$

[Completion time of that order, $T^2(i)$ *] =Interrupt call Layer 2 algorithm (set of time records* T^1*, order identity)*

End;

End;

Based on the results of estimated completion time of the orders, the makespan value (i.e., $C_i - R_i$) is determined. Layer 1 algorithm minimizes the makespan on the production floor. This facilitates the calculation of the average makespan minimization by swapping around the precedence order constraints within the orders chain. A transition process for the order chain is created by using a swap mutation operator. In this swap mutation operator, two starting cut-point sites are randomly chosen and the lengths of the two swapping bands are randomly determined with their constraints. However, the chosen swapping bands must not overlap nor should they be identical. After the swapping process, a new order chain, called a transition order chain, is formed. The average makespan is then evaluated by iteratively interrupting the call Layer 2 algorithm. Subsequently, the transition order chain replaces the original one. Therefore, the steps of looping used in approaching the minimum value of the average makespan are repeated until the number of iterations for that particular transition order chain meets the termination condition. After the transition order chain with the optimum order sequence is settled, the value of the earliest completion time of a production material demand order is also determined.

(ii) The Layer 2 algorithm

Layer 2 algorithm, used to solve the assignment of forklift at the production material level for a particular order for workstation α, is embedded in Layer 1 algorithm. In Layer 2 algorithm, an interrupt call and the set of time records are first received from the Layer 1 algorithm. The set of time records from Layer 1 algorithm is a time vector, which represents the time that the forklifts are available. In this algorithm, a row vector is constructed to represent the forklift assignment for that particular order. As there are *k* number of forklifts, the order of availability $\{FA\}$ for accessing them from set of time records, is defined as

$\{FA\} = \{FA_1, FA_2, ..., FA_k\}$.

The initialization of a row vector is intended to fill the identities of forklifts according to their availability in recursive accessing order.

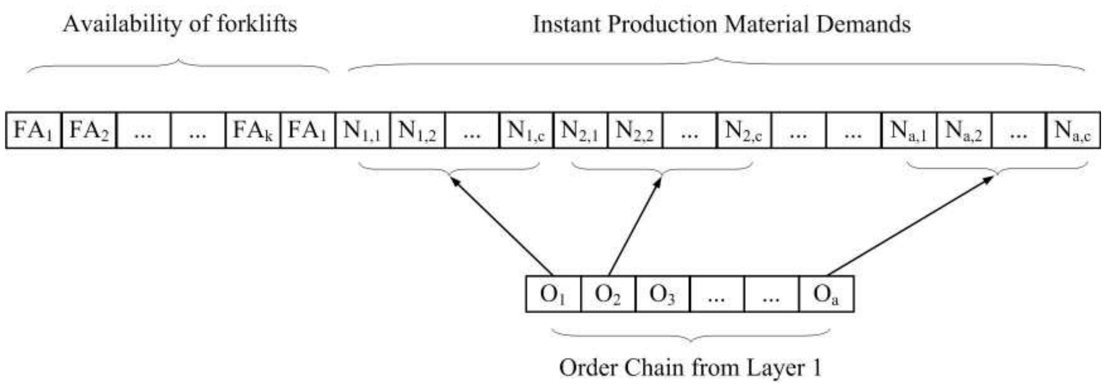


Figure 3.18 Structure of a row vector

As shown in **Figure 3.18**, the original row vector is divided into two areas: the availability of forklift area and the instant production material demands area. In each chromosome, the encoding schemes for the two areas are different. In the availability of forklift area, the value of each gene is binary, whereas the value is a real number in the instant production material demands area. The correlation between the two areas is illustrated in **Figure 3.19**.

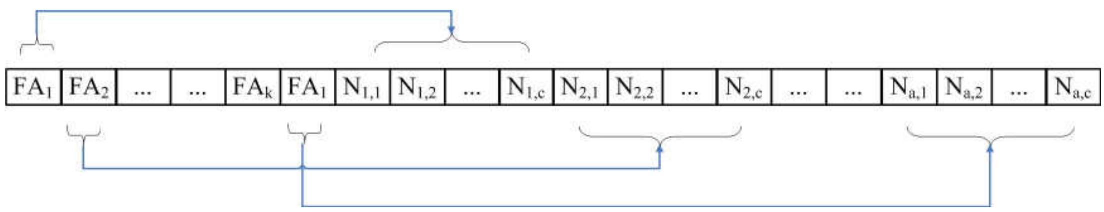


Figure 3.19 Correlation within the chromosome

Based on real-time information collected from the shop floor, the value of a gene is 1 in the availability of forklift area, if the corresponding forklift is available at that moment. The requested quantities of specific production materials from the particular production demand order in the order chain from Layer 1 are stored in the correlated genes in the instant demand of production materials area. For example, if demand order O_1 is present, the requested quantities of specific production materials are stored in the correlated genes $N_{1,k}$, $\forall k \in C$.

- *Fitness evaluation*

To determine the fittest chromosome in the population, a fitness function is adopted to evaluate every chromosome. In this layer, the objective function is to minimize the total makespan on the shop floor by minimizing the time spent in waiting for production materials requested from workstations, due to production failure

i.e., $Min\left\{\sum_{i} C_i - R_i\right\}$ where $\forall i \in A$, (6)

subject to the following constraints:

(i) Assignments of material handling equipment – production material of each order is assigned to only one forklift.

$$x_{ijk} = \begin{cases} 1 & \text{if production material j of order i is assigned to material handling equipment k in the warehouse} \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

(ii) The starting and processing times for handling the production material of each order must be greater than 0;

$S_{ij} \geq 0$ and $P_{ij} \geq 0$. (8)

(iii) The requesting time must be greater than the completion time of each order;

$R_i \geq C_i$. (9)

(iv) The total quantity of production materials stored in the warehouse must be able to fulfill the total quantity of production materials requested by all the production workstations;

$$\sum_{j=1}^{b} M_{j,k} \geq \sum_{i=1}^{a} N_{i,k} \quad . \quad (10)$$

(v) The total capacity of all items of material handling equipment must be able to satisfy the total quantity of production materials requested by all the production workstations;

$$\sum_{l=a}^{d} CH_l \geq \sum_{i=1}^{a}\sum_{k=1}^{c} N_{i,k} \ . \qquad (11)$$

- Uniform Crossover

A crossover operator is applied to combine the selected parents for generating new offspring. However, only a couple of parents take part in the crossover operation, with a probability of crossover p_{cross}. A crossover probability index s_i, randomly generated in the range of 0 – 1, is assigned to the chromosomes and compared with the probability of crossover p_{cross}. If $s_i < p_{cross}$, then i-th chromosome is selected from the mating pool to perform the crossover operation. Otherwise, no crossover occurs. In the proposed system, a uniform crossover is applied. A mask is generated before performing crossover, using a random number generator with a binomial distribution, i.e., either 0 or 1. Through the mask, the offsprings are generated from portions of the selected parents. For example, if $bit_{i,mask} = 1$, $bit_{i,chrom1}$ and $bit_{i,chrom2}$ are exchanged, where $chrom_1$ and $chrom_2$ are the selected parents. On the other hand, $bit_{i,mask} = 0$, thus no action is taken.

- Mutation with probability between 0.0015 and 0.03

A mutation operator is applied to transform the chromosome by randomly changing chromosome of genes. This is a critical operation because it diversifies the search directions and avoids convergence to a local optima. Only several offsprings take part in the mutation operation with a probability of mutation p_{mut}. The typical value of p_{mut} is between 0.0015 and 0.03 (Guo et al., 2008).

- Repairing

Violations, including the destruction of consistency between the two areas, may occur after the crossover and mutation operations in the chromosome. It is therefore essential to repair the chromosome before the next iteration. According to Ho *et al*. (2008), repairing is divided into three stages: forward, backward, and limit repairing.

1. Forward repairing

In forward repairing, checking starts from the genes in the availability of forklift area. If a gene contains a value of 1 in the availability of forklift area, but all of its related genes contain a value of 0 in the instant production material demands area, random numbers are generated and assigned to the corresponding zero-valued genes in the instant production material demands area. This is demonstrated in **Figure 3.20**.

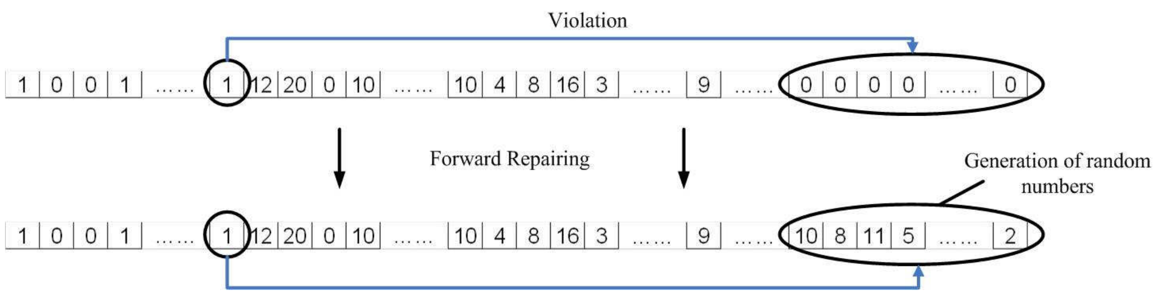


Figure 3.20 Forward repairing of a rhromosome

2. Backward repairing

In backward repairing, checking starts from the genes in the instant production material demands area. If the genes contain non-zero values in the instant production material demands area, and their related genes contain a value of 0 in the availability of forklift area, the values of those genes are changed from 0 to 1 accordingly. This is illustrated in **Figure 3.21**.

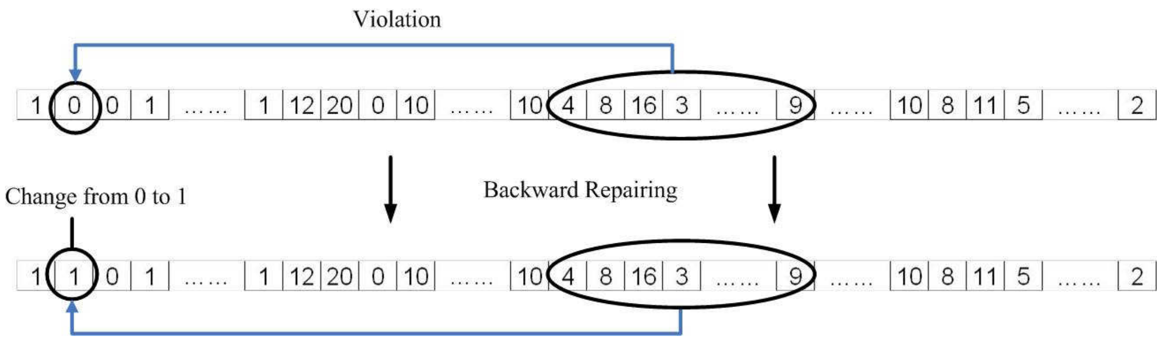


Figure 3.21 Backward repairing of a chromosome

3. Limit repairing

In limit repairing, only the values of genes in the instant production material demands area are checked. Since only one item of material handling equipment is assigned to one chromosome, the total quantity of requested production material in a chromosome may exceed the capacity of the assigned material handling equipment after the crossover and mutation operations, i.e. $\sum N > \sum CH_l$, where *l*-th material handling equipment is assigned to handle the overloaded demand order. Therefore, it is essential to conduct limit repairing to assign a value of 0 to the gene with the largest value in a chromosome, i.e., newly repaired value $N_{i,k}^{'} = \max(N_{i,k}) \longrightarrow 0$. **Figure 3.22** shows the limit repairing process.

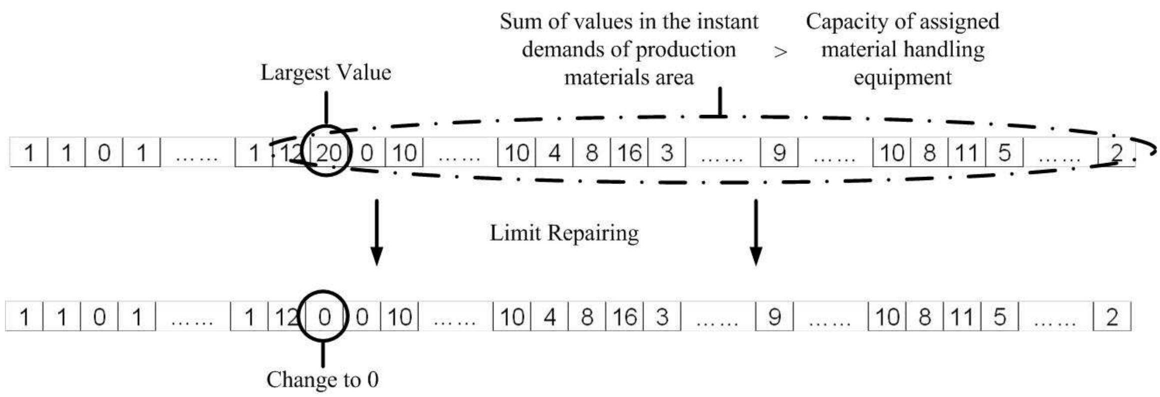


Figure 3.22 Limit repairing of a chromosome

The transition row vector is accepted if and only if the order’s completion time of the transition row vector is less than that of the parent row vector. The row vector is replaced by the transition row vector if the transition row vector is successfully accepted.

Chapter 4 The Implementation Procedures of the system

4.1 Introduction

In this chapter, the design and implementation procedures of R-PODSS in real working practice are described. The system development in this research is divided into six phases: (i) Identification of Problems and Objectives, (ii) Structural Formulation of Real-Time Production and Warehouse Data Collection Module, (iii) Structural Formulation of Data Storing and Retrieving Module, (iv) Structural Formulation of RFID Information Exchange Module, (v) Structural Formulation of Optimal Order Picking and Delivery Module, and, (vi) System Implementation and Evaluation, as shown in **Figure 4.1**.

4.2 Phase 1 – Identification of Problems and Objectives

The aim of this phase is to identify the problems and objectives in an actual manufacturing company. This phase consists of two steps: 1) company operation analysis, and, 2) preparation of system development.

- *Step 1: Company operation analysis*

  This step involves the study of existing production operation flows in the company. Activities, such as interviews with the company staff and investigation of production operation flows, are conducted to gain a fundamental understanding of the company. Interviewees involved in this phase include production managers, Information Technology (IT) managers, warehouse managers, and workers. Through the interviews and the investigation of production operation flows, problems are identified. Thus, the scope of the project and the duration of system implementation are defined.

1) Company operation analysis
2) Preparation of system development

Phase 1 – Identification of Problems and Objectives

↓

1) Definition of data types of production and warehouse operations
2) Physical testing and set up of RFID equipment
3) Construction of data capturing mechanism

Phase 2 – Structural Formulation of Real-Time Production and Warehouse Data Collection Module

↓

1) Construction of datasheets with different natures
2) Construction of statement of query optimization

Phase 3 – Structural Formulation of Structural formulation of Data Storing and Retrieving Module

↓

1) Construction of sub-databases for decoding purpose
2) Construction of decoding and transforming mechanisms

Phase 4 – Structural Formulation of RFID Information Exchange Module

↓

1) Construction of effective triangular localization scheme
2) Construction of case-based resource selection model
3) Construction of two layers algorithm

Phase 5 – Structural Formulation of Optimal Order Picking and Delivery Module

↓

1) Prototyping
2) Implementation
3) System performance monitoring

Phase 6 – System Implementation and Evaluation

Figure 4.1 The implementation procedures of R-PODSS

- *Step 2: Preparation of system development*

This step entails the preparation of specifications for system development. In this step, the requirement of production and warehouse operations are defined by production and warehouse managers, respectively. The requirements of production and warehouse operations include data input, operation processes, and output in a structural graphic form. With the help of the structural graphic form, IT managers are able to construct the R-PODSS.

4.3 Phase 2 – Structural Formulation of Real-Time Production and Warehouse Data Collection Module

The aim of this phase is to formulate the Real-Time Production and Warehouse Data Collection Module of R-PODSS. This phase consists of two steps: 1) definition of data types of production and warehouse operations, and 2) physical testing and set up of RFID equipment.

- *Step 1: Definition of data types of production and warehouse operations*

In this step, different types of information within the production and warehouse operations are studied. The information includes production and warehouse operations data, resource data, data of production material demand orders, and related attributes. To visualize the actual production and warehouse operation and obtain real-time production material demand orders, sets of RFID equipment are tested and implemented in the production shop floor and warehouse environments. The raw warehouse and production operation information is collected by the RFID equipment and transmitted to RFID Information Exchange Module by the wireless technology for further processes.

- *Step 2: Physical testing and set up of RFID equipment*

This step comprises different experiments for evaluating the reading performance of active and passive RFID equipment to select the most appropriate one for the implementation in the production shop floor and warehouse environments. By using the results from the experiments, the effective RF coverage ranges of the RFID equipment are identified, so as to determine the best locations for installing RFID readers and antennas. The setup of RFID equipment within the manufacturing companies varies according to the reading performance of RFID equipment, layouts, operation flows, and throughput of the production shop floors and warehouses.

- *Step 3: Construction of data capturing mechanism*

This step is concerned with the construction of the data capturing mechanism of R-PODSS. The program language of the mechanism is Java Script, as illustrated in **Figure 4.2**. With the help of the script, the data stored in the tags are scanned and captured by the RFID readers and antennas. The captured data are transmitted to the centralized database for further use.

4.4Phase 3 – Structural Formulation of Data Storing and Retrieving Module

The aim of this phase is to formulate the Data Storing and Retrieving Module of R-PODSS. This phase consists of two steps: 1) construction of datasheets with different natures, and 2) construction of statement of query optimization.

```
Void DataCapture() {
   Do {
      int RFID_DEVICES_NO = RFID_DEVICES.LENGTH;
    FOR (int counter=0; RFID_DEVICES_NO > counter; counter ++)
    {
      String TAG_DATA = RFID_DEVICES[counter].readTag();
      StoreToDB(String TAG_DATA, CurrentDateTime);
    }
  } While (IsSystemRunning == True);
}
```

Figure 4.2 Script of data capturing mechanism

- *Step 1: Construction of datasheets with different natures*

In this step, the systematic construction of different datasheets in the centralized database is performed to facilitate access to the data by users within a short period of time. As shown in **Figure 4.3**, the data structure inside the centralized database is constructed by a well-defined Entity Relationship Diagram (ERD). Data from different sources, such as ERP database and Real-Time Production and Warehouse Data Collection Module, are stored in different tables in the database according to their nature.

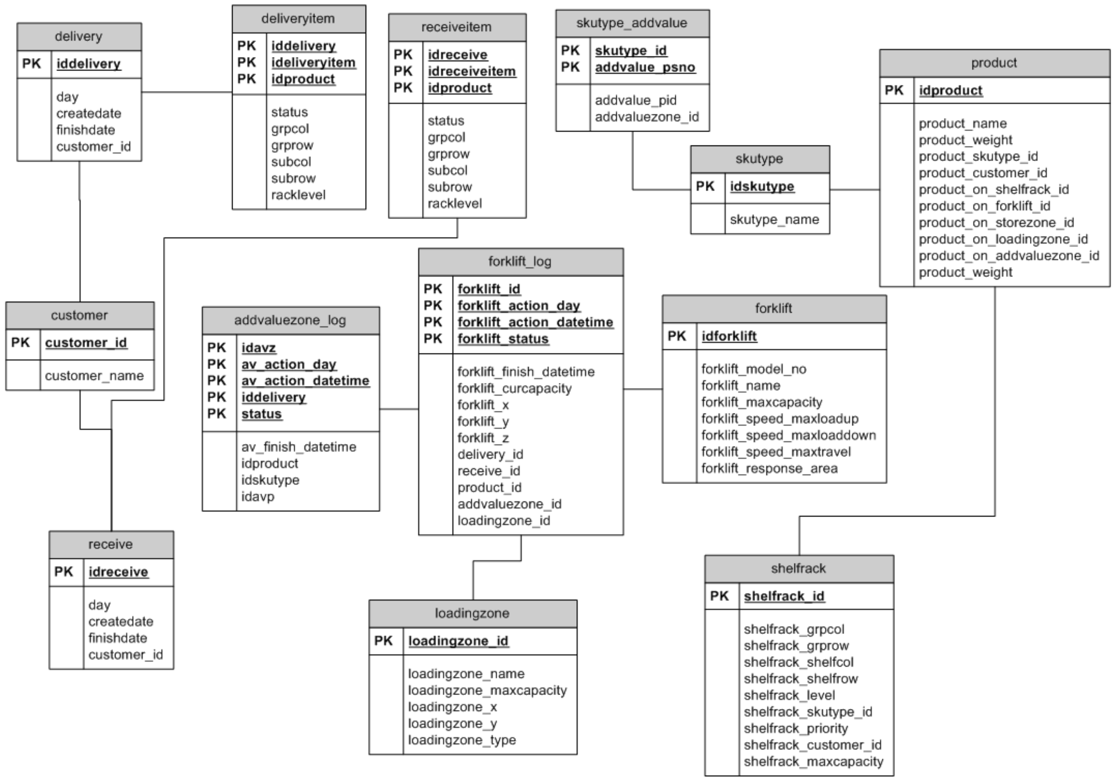


Figure 4.3 ERD of Data Storing and Retrieving Module

- *Step 2: Construction of statement of query optimization*

Conduct of the statements for query optimization is the focus of this step. This improves the performance of data retrieval from the centralized database. The query optimization is formulated by SQL statements. An example of query optimization is shown as follows:

CREATE VIEW TA AS

    SELECT SID, TrdDate, ItemName

        FROM (TRADE NATURAL FULL OUTER JOIN ASSET)

            WHERE TrdDate **BETWEEN** #4/1/2008# **AND** #4/30/2008#

                AND TrdType = 'ORDER'

SELECT SID, SName, TrdDate, ItemName

    FROM (SUPPLIER NATURAL INNER JOIN TA)

        WHERE SID = 'S1032'

4.5 Phase 4 – Structural Formulation of RFID Information Exchange Module

The aim of this phase is to formulate the RFID Information Exchange Module of R-PODSS. This phase consists of two steps: 1) construction of sub-databases for decoding purpose, and 2) construction of decoding and transforming mechanisms.

- *Step 1: Construction of datasheets with different natures*

  Different sub-databases are constructed in the RFID Information Exchange Module for decoding and transforming mechanisms. The sub-databases include production information, operation area, quality record, defect type, and locations databases. When an EPC code is sent to the RFID Information Exchange Module, data stored in the sub-databases will be utilized for decoding and transforming the EPC code into meaningful information.

- *Step 2: Construction of decoding and transforming mechanisms*

  Decoding and transforming mechanisms are formulated to transform EPC codes collected from the RFID readers into meaningful information. The epcid is sent to a decoding function, which breaks the original epcid into different sections, such as production information, operation area, quality record, defect type, and locations. Each section is then sent to the corresponding sub-databases to search for related information, as shown in **Figure 4.4**.

```
String[] DecodeTranform(String EPC_id) {
    int DecodingPattern[] = {12, 2, 2, 2, 6};
    //Production information = 12 digits
    //Operation Area Code = 2 digits
    //Quality Record = 2 digits
    //Defect Type = 2 digits
    //Location = 6 digits, 2 for x-co, 2 for y-co, 2 for z-co
    String Transformed_Info [] = DecodeFromDB(EPC_id, DecodingPattern);
    return Transformed_Info; // send out the meaningful information to screen
}
```

Figure 4.4 Script of decoding and transforming mechanism

An example of searching process is shown as follows.

SELECT operation_area

FROM OPERATION_AREA_DATABASE

WHERE operation_ID = '05'.

Once the searching process is completed, a meaningful failure report will be constructed by the transforming mechanism. The report is then sent to the warehouse staff for production material order picking.

4.6 Phase 5 – Structural Formulation of Optimal Order Picking and Delivery Module

The aim of this phase is to formulate the Optimal Order Picking and Delivery Module of R-PODSS. This is the most important phase in the roadmap because this module manipulates the data from previous modules for formulating efficient and reliable material handling solutions to address stochastic production material demand problems. This phase consists of three steps: 1) construction of effective triangular localization scheme, 2) construction of case-based resource selection model, and 3) construction of two-layered algorithm.

```
Void  LocationTracing()
{
   Do {
      int RFID_DEVICES_NO = RFID_DEVICES.LENGTH;
      int TAG_READCOUNT[] = new int[RFID_DEVICES_NO];
      double ObjDistance []= new double[RFID_DEVICES_NO];
    FOR (int counter=0; RFID_DEVICES_NO > counter; counter ++)
    {
      TAG_READCOUNT[counter] = _
      RFID_DEVICES[counter].readCount();
      ObjDistance[counter] = _
      CalculateDistance(RFID_DEVICES[counter].location, _
      TAG_READCOUNT[counter]);
      CalculateObjXY(ObjDistance);
    }
  } While (IsSystemRunning == True);
}
```

Figure 4.5 Script of effective triangular localization scheme

- *<u>Step 1: Construction of effective triangular localization scheme</u>*

Effective triangular localization scheme is formulated in this step to identify the exact locations of the resources, such as forklifts, manpower, raw materials, etc., in a warehouse. Through this, the visibility of warehouse operations is enhanced and the order picking process is hastened. The programming language, Java Script, is adopted to formulate the scheme, as illustrated in **Figure 4.5**.

In the scheme, three or more sets of RFID antennas and readers are adopted for locating the exact locations of the objects. One set of RFID antenna and reader can identify the object but its exact location cannot be captured, as shown in **Figure 4.6**.

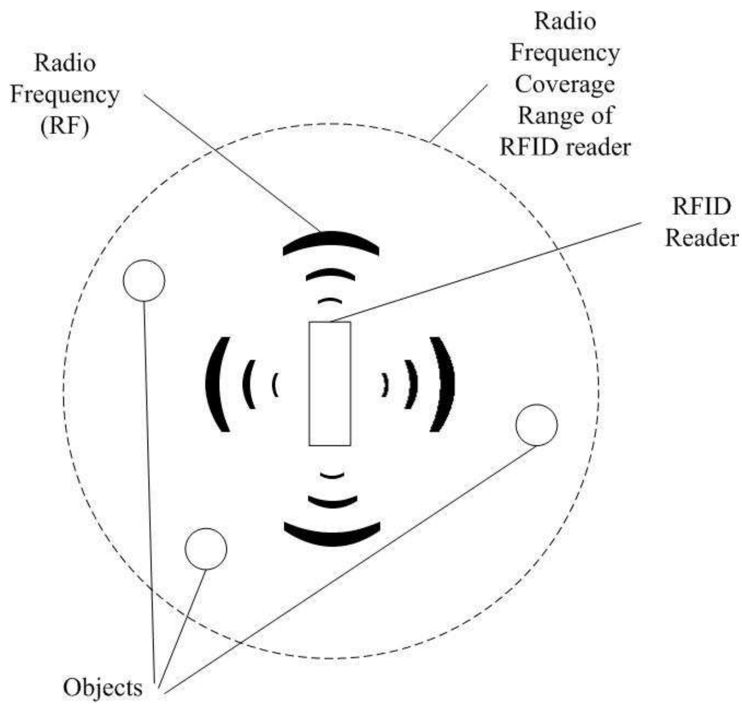


Figure 4.6 One set of RFID equipment for locating object

Similarly, when using two sets of RFID antennas and readers, two points of the object are determined, as illustrated in **Figure 4.7**.

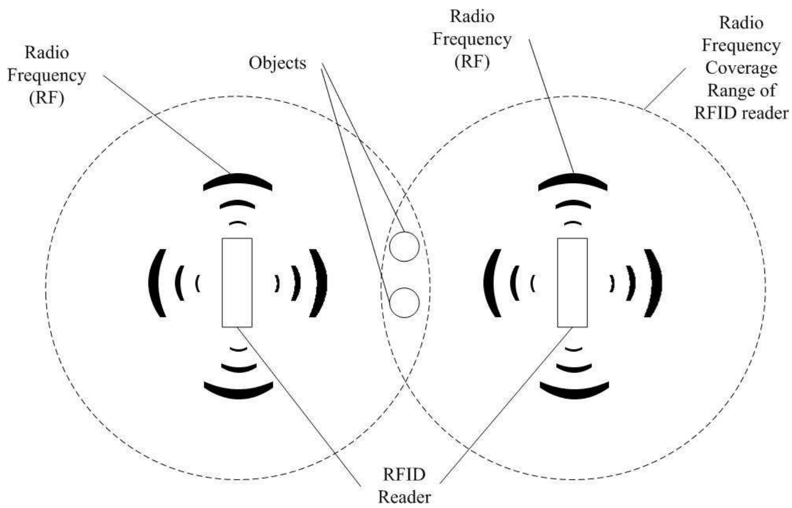


Figure 4.7 Two sets of RFID equipment for locating object

It is impossible to reflect the actual location of the object accurately. To retrieve a higher confidence level of the locations of the object, additional data are required and one more set of RFID antenna and reader is needed, as shown in **Figure 4.8**.

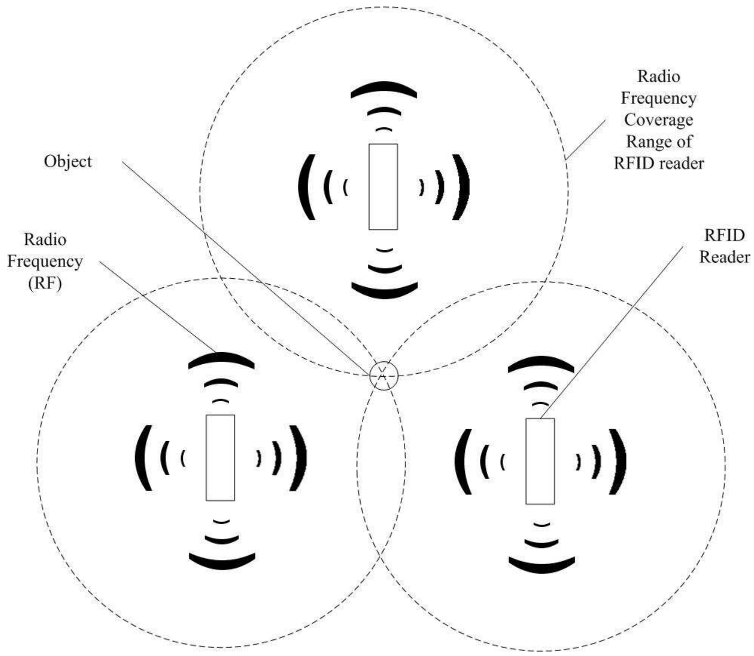


Figure 4.8 Three sets of RFID equipment for locating object

- *Step 2: Construction of case-based resource selection model*

Case-based resource selection model for selecting the appropriate material handling equipment is developed to manage order picking operations. The software tools for developing the model are JavaScript and MATLAB. During the model formulation, warehouse information within companies is provided, validated, and constructed in machine-readable format by warehouse managers. The information includes standard operating procedure (SOP), skills and experiences of staff members, solutions of previous production material demand problems, order-picking sequence, etc., within the company. The warehouse information is presented in a case-format to support the case-based resource selection model. Through CBR, warehouse information is retrieved and an appropriate material handling equipment is provided to system users for handling the production material demand orders. **Figure 4.9** demonstrates the mechanism of case-based resource selection model.

```
Void CBR_Process() {
 String RankingList[] = ReadFromCriteria();
 String InputRankingList []= ReadFromInputRanking();
 String InputValues []= ReadFromInputValues();
 String Cases[][] = CasesFromDB();
 String ranking_weighting[] = CalculateWeighting(InputRankingList, RankingList);
 double sim_value[] = Cases[0].length();
 for (int cases_no=0; cases_no <= Cases[0].length(); cases_no++)
   for (int attr_no = 0 ; attrno <=RankingList.length() ; attr_no++)
   {
     simvalue[cases_no] = ranking_weighting *
     CompareDiff(InputValues[attr_no], Cases[cases_no][attr_no]);
   }
  Sorting(Cases, sim_value);
}
```

Figure 4.9 Mechanism of case-based resource selection model

- *Step 3: Construction of two-layered algorithm*

In this step, the two-layered algorithm is formulated to provide a comprehensive solution for stochastic production material demand problems. The algorithm comprises two activities: (i) optimization of production material demand orders and (ii) optimization of the sequence of the items and material handling equipment. The mechanism of two-layered algorithm is presented in **Appendix D.**

4.7 Phase 6 – System Implementation and Evaluation

System implementation and evaluation is the last phase of the R-PODSS in manufacturing companies. In this phase, three steps, i.e., prototyping, implementation, and system performance monitoring are involved. In the first step, a prototype is designed and developed by the system developers according to the design methodologies from previous sections. JavaScript and MATLAB are utilized for developing the prototype of R-PODSS, whereas Microsoft SQL Server is adopted for constructing the centralized database and the sub-databases. In the second step, the developed prototype is implemented and tested in the manufacturing companies to evaluate its feasibility and reliability in actual manufacturing environments. In the last step, comparisons between traditional and proposed approaches for addressing stochastic production material demand problems are conducted to determine the performance of the proposed R-PODSS. The relevant experimental results are discussed in Chapter 6.

Chapter 5 Case Studies

5.1 Introduction

In this chapter, two application case studies have been conduct ed to validate the feasibility of adopting R-PODSS in providing sophisticated decision support for manufacturing companies in dealing with stochastic production material demand problems. The case studies were carried out in two manufacturing companies: i) Group Sense Limited (GSL), one of the world's leading manufacturers of electronic dictionaries and other handheld information devices, and ii) Jing Chi Engineering Company Limited (JCE), a mold manufacturing company. This chapter provides the profiles of the case companies, the existing practices of each company, and the implementation of R-PODSS.

5.2 Case Study 1 – Electronic Devices Manufacturing Company

GSL was founded in June 1988. It launched the first English/Chinese electronic dictionary in Hong Kong in 1989. The company has become a leading consumer brand in the Greater China market. In 1996, GSL launched the world's first Personal Digital Assistant (PDA), which operated on a Chinese language platform, together with the functions of inputting Chinese characters in handwriting, and built-in electronic dictionaries. GSL manufactures a number of hi-tech Original Design Manufacturing (ODM) electronic products for major customers in Japan and Europe. Over the years, GSL has been granted numerous awards, such as Consumer Product Design (1995), Technological Achievement (1997), Productivity (1999), Quality (1999) by the Hong Kong Awards for Industry and more than 10 other awards in different categories.

5.2.1 Problem definition of GSL

Since GSL is an international electronic device provider, it is required to handle large numbers of production orders everyday. Thus, production failures occur frequently and production materials are required to be delivered from warehouse to production shop floor to ensure the throughput of the company. Currently, GSL adopts a manual-based order pickup and delivery mechanism in its warehouse and manually records the documents of warehouse inventory status and the location of production materials. Owing to this, several problems have occurred, as shown in **Figure 5.1**.

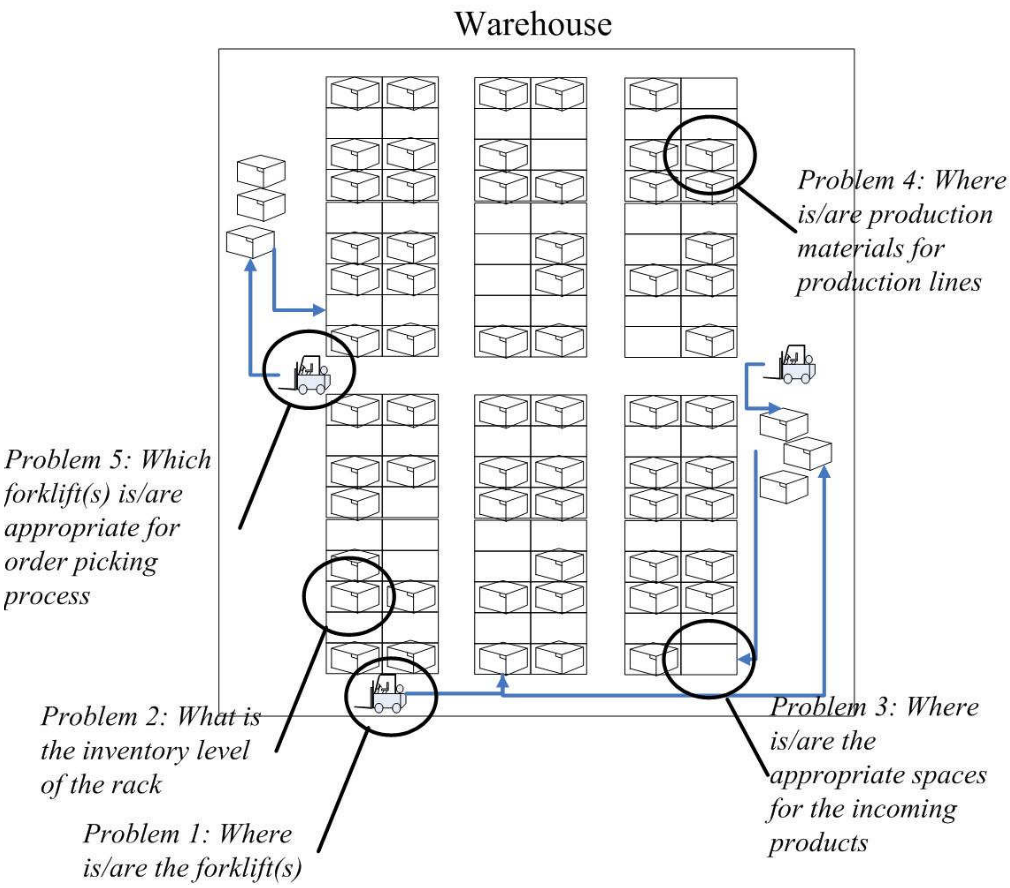


Figure 5.1 Problem definition of GSL

There are five problems found in GSL: i) Problem 1: Where is/are the forklift(s), ii) Problem 2: What is the inventory level of the rack, iii) Problem 3: Where is/are the appropriate space(s) for the incoming products, iv) Problem 4: Where is/are production material(s) for production lines, and v) Problem 5: Which forklift(s) is/are appropriate for order picking process. To solve these problems, GSL adopts R-PODSS for tracking production materials and forklifts in the warehouse.

5.2.2 Deployment of R-PODSS for Supporting Decisions on Order Picking in GSL

To facilitate the decision-making process of order picking operations, GSL implements R-PODSS in the warehouse in Dongguan, China. The proposed R-PODSS is constructed using JavaScript computer language. Through RFID technology, the resources, such as forklifts and production materials, are tracked and traced in a real-time manner. Thus, RFID is able to facilitate the order picking process in the warehouse. As shown in **Figure 5.2**, there are five operating steps in the R-PODSS.

- *Step 1: Study the actual warehouse environment in GSL*

  In this step, a clear picture of the actual warehouse environment in GSL is essential for adopting appropriate RFID equipment with the most suitable specifications. Finished products, such as PDAs, electronic dictionaries, and corresponding electronic parts are stored in the GSL warehouse. The warehouse consists of six aisles and 24 two-level racks. The height of each rack is about four meters and the width of the aisle is 6 feet. There are three means of handling material: forklifts, manual trucks, and warehouse staff manpower. These are all used for handling the pickup orders in GSL. The warehouse attributes previously mentioned are the selection criteria for RFID equipment.

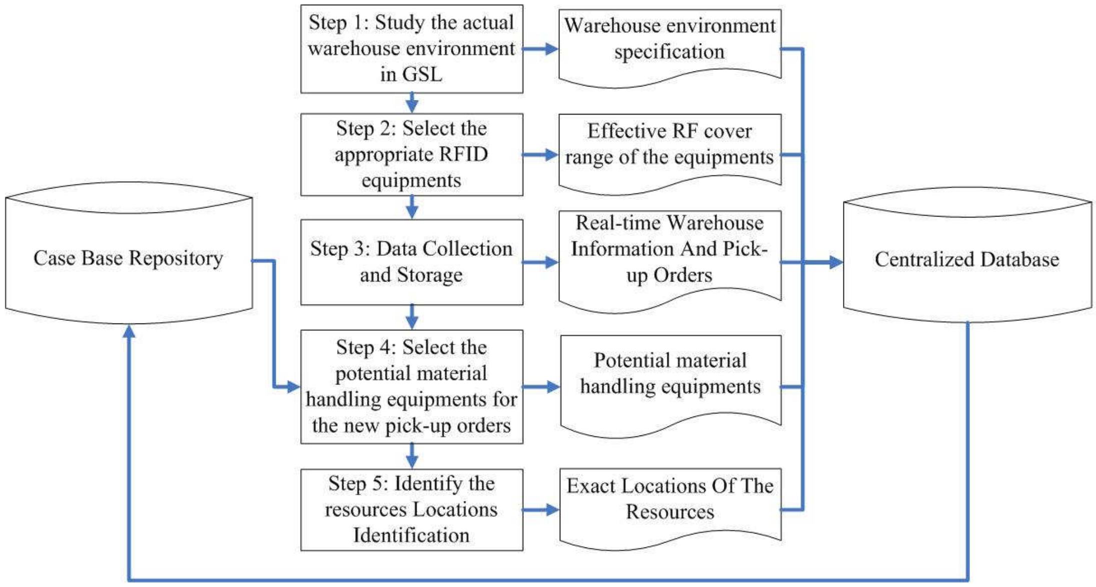


Figure 5.2 Five operating steps in the R-PODSS

- *Step 2: Select the appropriate RFID equipment*

In this step, four tests, i.e., i) Orientation, ii) Height, iii) Range, and, iv) Material Tests, have been conducted for evaluating the reading performance of these types of equipment to select the most appropriate for the actual production shop floor and warehouse environments.

1) Orientation Test

Figures 5.3 – 5.5 demonstrate the hardware setting of this test. Both the tag and antennas are perpendicular to the E-plane. In this test, the tag is placed on the front, at the top, and on the side surfaces of the object and moved along the intersection line of the E-plane and the H-plane. Thus, the read counts per second can be measured.

Figure 5.3 – 5.5 Orientation Test

2) Height Test

Figures 5.6 – 5.8 demonstrate the hardware settings for the height test. The tag is placed at a distance of 1.2 meters and at a height with increments of 20 centimeters from floor level up to 180 centimeters. The read counts per second are measured with different heights of the tags.

Figures 5.6 – 5.8 Height Test

3) Range Test

Figure 5.9 shows the hardware setting of the range test. The tag is placed 1 meter from the reader. The read counts per second are measured when the object is horizontally moved across different distances.

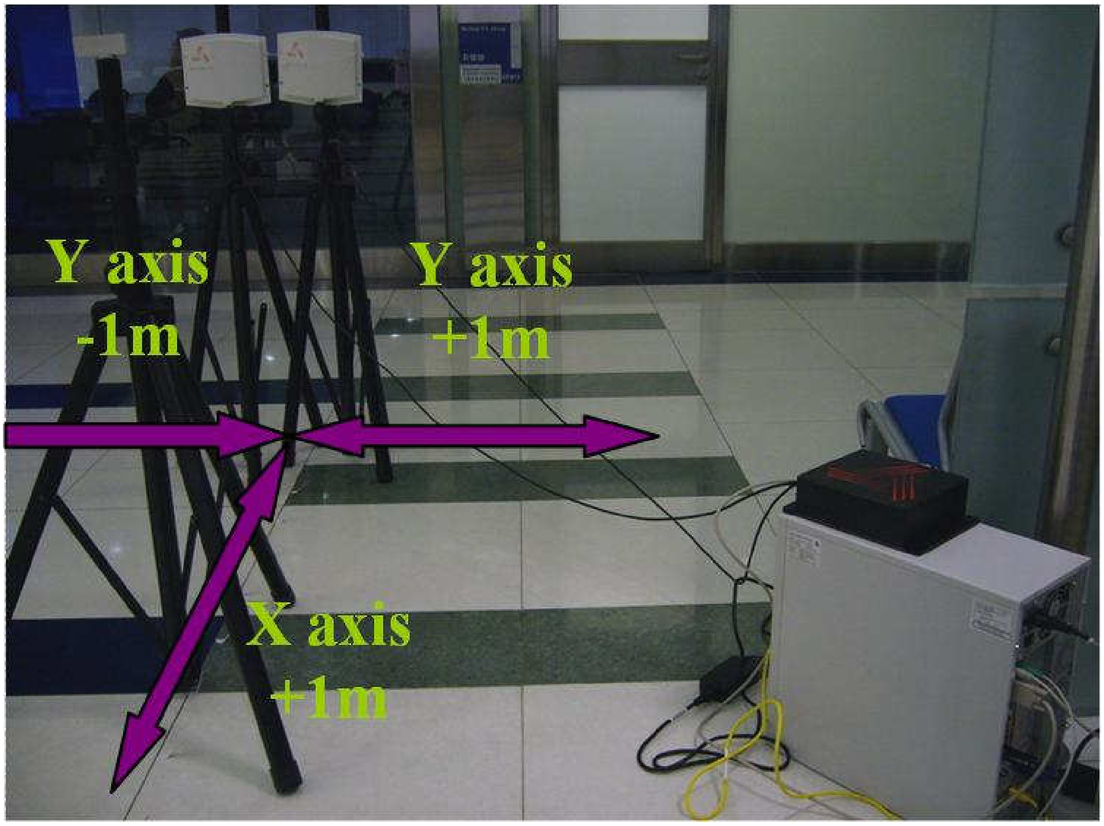


Figure 5.9 Range Test

4) Material Test

The tag is placed on the front and back surfaces of various types of products, such as metal, water, and carton. The read counts per second are measured when the object is moved horizontally across different distances.

After performing the tests**,** the reading performance comparison between active and passive RFID equipment is conducted, as shown in **Table 5.1**. The reading performance of active RFID technology is better than that of passive RFID technology.

Table 5.1 Reading performance comparison between active and passive RFID equipment

Test	Active RFID equipment	Passive RFID equipment
	Average Results (total counts/second)	
Orientation Test	1157	349
Tags stuck on the front surface of the product	1482	447
Tags stuck on the top surface of the product	1474	313
Tags stuck on the top surface of the product	516	287
Height Test	2465	436
Range Test	646	95
Material Test	1117	202
Tags placed in front of the product	1492	389
Tags placed behind the product	1486	375
Tags placed in front of the metal	1826	5

Tags placed behind the metal	157	166
Tags placed in front of the water	1541	166
Tags placed behind the water	199	108

However, the costs of active RFID readers and related equipment are relatively high (between US$2,000 and US$3,000 for readers and US$20−30 for tags), compared to the costs of passive RFID devices (between US$1,000 and US$2,500 for readers and US$0.07−1.00 for tags) (Speakman and Sweeney, 2006). It is difficult to implement the active RFID devices for item-level RFID tagging in the warehouse environment due to high implementation cost. To overcome this problem, a full passive RFID implementation plan is suggested for implementation in GSL.

According to **Table 5.2**, the reading performance of the passive large-sized tag is the best among the three passive tags. However, it is not suitable in tracking material handling equipment, such as forklifts because the reader is unable to detect the tags stuck on the metal. Thus, passive middle-sized tags are adopted in this case study.

In **Appendix B,** the effective RF coverage range of the reader is about 2 meters when middle-sized tags are selected.

Table 5.2 Reading performance comparison among passive RFID equipment

Test	Large-sized tag	Middle-sized tag	Small-sized tag
	Average Results (total counts/second)		
Orientation Test	611	357	80
Tags stuck on the front surface of the product	716	527	99
Tags stuck on the top surface of the product	396	544	0
Tags stuck on the top surface of the product	720	0	142
Height Test	532	595	182
Range Test	200	84	0
Material Test	266	339	0
Tags placed in front of the product	556	611	0
Tags placed behind the product	590	535	0
Tags placed in front of the metal	0	14	0
Tags placed behind the metal	194	305	0
Tags placed in front of the water	195	304	0
Tags placed behind the water	60	265	0

Therefore, one set of reader and antenna is installed in each level of the rack, which is fully covered by the RF from the RFID reader and antenna, as illustrated in **Figure 5.10**. The middle-sized passive RFID tags are stuck onto the surfaces of forklifts and products directly facing the RFID readers and antennae. A unique Internet Protocol (IP) (in terms of x-, y-, and z- coordinates) is set in each reader (antenna) to represent exact locations of the reading points.

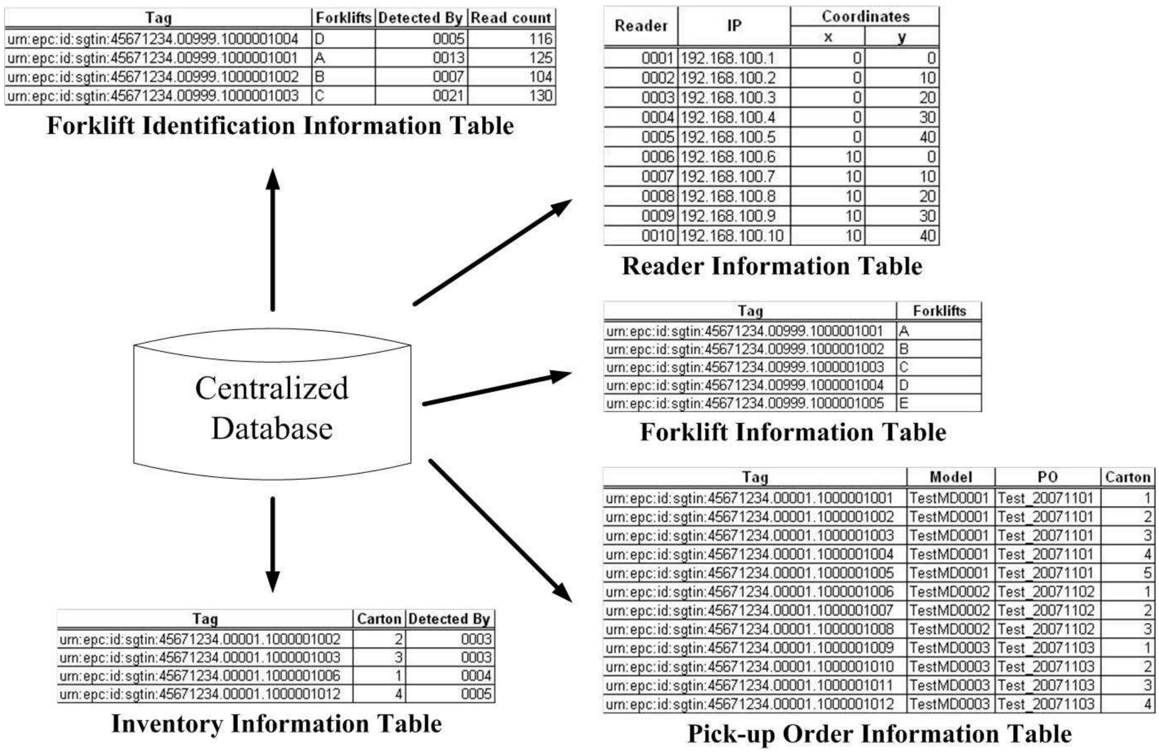
Figure 5.10 RFID technology implementation in a warehouse environment

- *Step 3: Collect and store the data*

In this step, instant warehouse resource data are captured by the RFID device and stored in the centralized database, as shown in **Figure 5.11**. By utilizing RFID technology, information about forklifts is captured when the forklifts pass the antennas. The retrieved information is then stored systematically in the centralized database for further processing, such as location tracking of resources.

- *<u>Step 4: Select the potential material handling equipment for new pick-up orders</u>*

Before performing the selection of material handling equipment, 501 pick-up orders performed in GSL are transformed as cases and stored into a case-based repository. A decision tree is formulated for categorizing the cases and problems in the repository, as shown in **Figure 5.12**.



Tag	Forklifts	Detected By	Read count
urn:epc:id:sgtin:45671234.00999.1000001004	D	0005	116
urn:epc:id:sgtin:45671234.00999.1000001001	A	0013	125
urn:epc:id:sgtin:45671234.00999.1000001002	B	0007	104
urn:epc:id:sgtin:45671234.00999.1000001003	C	0021	130

Forklift Identification Information Table

Reader	IP	Coordinates	
		x	y
0001	192.168.100.1	0	0
0002	192.168.100.2	0	10
0003	192.168.100.3	0	20
0004	192.168.100.4	0	30
0005	192.168.100.5	0	40
0006	192.168.100.6	10	0
0007	192.168.100.7	10	10
0008	192.168.100.8	10	20
0009	192.168.100.9	10	30
0010	192.168.100.10	10	40

Reader Information Table

Tag	Forklifts
urn:epc:id:sgtin:45671234.00999.1000001001	A
urn:epc:id:sgtin:45671234.00999.1000001002	B
urn:epc:id:sgtin:45671234.00999.1000001003	C
urn:epc:id:sgtin:45671234.00999.1000001004	D
urn:epc:id:sgtin:45671234.00999.1000001005	E

Forklift Information Table

Tag	Carton	Detected By
urn:epc:id:sgtin:45671234.00001.1000001002	2	0003
urn:epc:id:sgtin:45671234.00001.1000001003	3	0003
urn:epc:id:sgtin:45671234.00001.1000001006	1	0004
urn:epc:id:sgtin:45671234.00001.1000001012	4	0005

Inventory Information Table

Tag	Model	PO	Carton
urn:epc:id:sgtin:45671234.00001.1000001001	TestMD0001	Test_20071101	1
urn:epc:id:sgtin:45671234.00001.1000001002	TestMD0001	Test_20071101	2
urn:epc:id:sgtin:45671234.00001.1000001003	TestMD0001	Test_20071101	3
urn:epc:id:sgtin:45671234.00001.1000001004	TestMD0001	Test_20071101	4
urn:epc:id:sgtin:45671234.00001.1000001005	TestMD0001	Test_20071101	5
urn:epc:id:sgtin:45671234.00001.1000001006	TestMD0002	Test_20071102	1
urn:epc:id:sgtin:45671234.00001.1000001007	TestMD0002	Test_20071102	2
urn:epc:id:sgtin:45671234.00001.1000001008	TestMD0002	Test_20071102	3
urn:epc:id:sgtin:45671234.00001.1000001009	TestMD0003	Test_20071103	1
urn:epc:id:sgtin:45671234.00001.1000001010	TestMD0003	Test_20071103	2
urn:epc:id:sgtin:45671234.00001.1000001011	TestMD0003	Test_20071103	3
urn:epc:id:sgtin:45671234.00001.1000001012	TestMD0003	Test_20071103	4

Pick-up Order Information Table

Figure 5.11 Data collection and storage

By adopting a case clustering method, the cases are divided into ten clusters based on four key attributes: order size, product dimension, product weight, and product shape. The clusters are then indexed by the k-NN method. Once the new pick-up order is released, the order is compared with the clusters using Equation (5) for selecting the clusters with a potentially high degree of similarity. By using a similar approach, these potentially useful cases are retrieved from the selected clusters as reference cases, and the corresponding material handling equipment is suggested as the equipment for handling the current query.

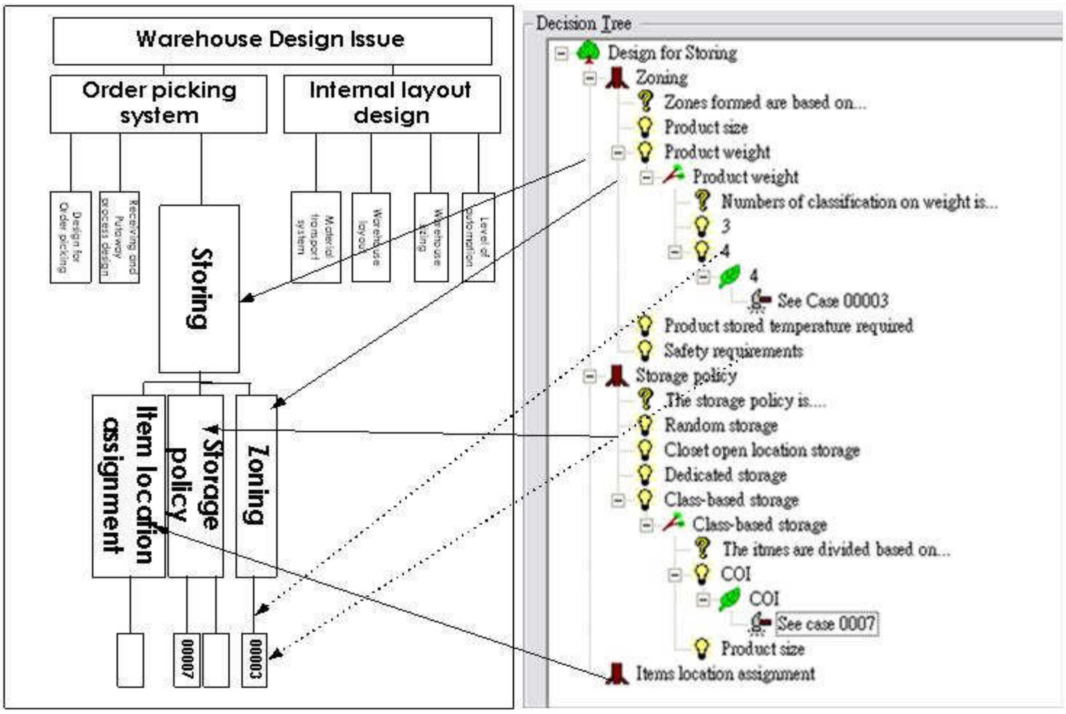


Figure 5.12 Decision tree formulation

As illustrated in **Figure 5.13**, Cluster B is the first choice for solving new pick-up order "PL001" because its similarity value to Cluster B is 99%, which is the highest among the ten clusters. By using a similar approach in case "PA231," the 95% similarity value ranks as the first resource choice for handling "PL001."

- *Step 5: Identify the locations of the resources*

With Equation (1), the warehouse operation data are used as the input parameters for calculating the distance between the forklifts and RFID readers. The result of the calculation is used to determine the exact location of the resources.

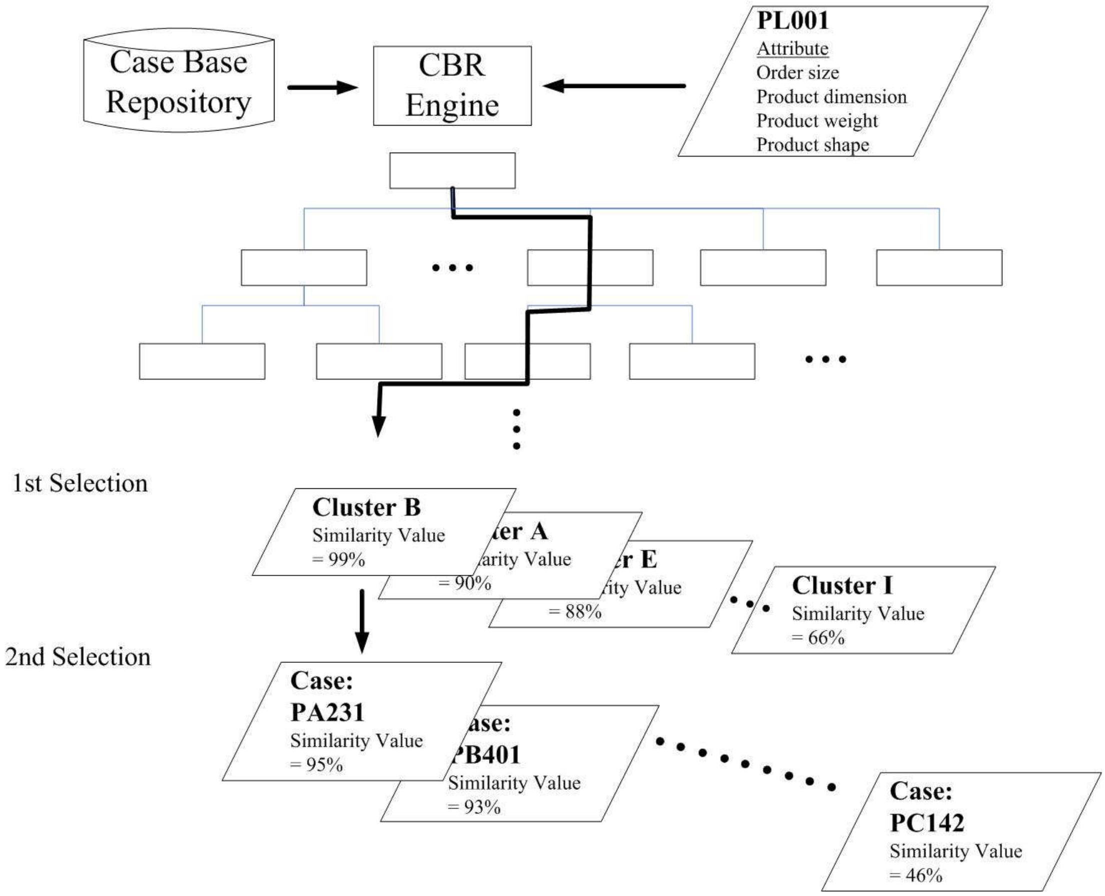


Figure 5.13 Selection of the potentially useful material handling equipment for new pick-up orders

Let the RF of the RFID reader 0013 be 915 MHz and the corresponding wavelength be 33 cm. When forklift A, with an embedded RFID tag, passes through RFID reader 0013, it is detected and the corresponding read out within a fixed period of 5 seconds by reader 0013 is identified and stored in the centralized database. Then, using Equation (1), the distance between the forklift A and reader 0013 can be obtained by:

$d_{0013,\,A} = (915MHz \times 33cm \times 5s)/(2 \times 250)$ = 301.95 cm ≈ 3 m.

After calculating the distances between the readers and the objects, the exact locations of the objects in term of x- and y- coordinates, are determined by applying Equations (3) and (4), respectively.

Using forklift A as an example, substitute the distances among readers 0013, 0014, 0018, and corresponding locations of the readers into Equation (4).

$$y_A{}^2 + \frac{2\left(Ax_{0018}D + CD - A^2 y_{0018}\right)y_A}{\left(A^2 + D^2\right)} + \frac{\left(C^2 + 2Ax_{0018}C - A^2 B\right)}{\left(A^2 + D^2\right)} = 0$$

where

$$A = 2\left(x_{0013} - x_{0014}\right) = 2(20 - 20) = 0$$

$$B = d_{0018,\,A}{}^2 - y_{0018}{}^2 - x_{0018}{}^2 = 1 - 400 - 400 = -799$$

$$C = \left(d_{0013,\,A}{}^2 - d_{0014,\,A}{}^2\right) - \left(y_{0013}{}^2 - y_{0014}{}^2\right) - \left(x_{0013}{}^2 - x_{0014}{}^2\right)$$

$$= 9 - 25 - 400 + 900 - 400 + 400 = 484$$

$$D = 2\left(y_{0013} - y_{0014}\right) = 2(20 - 30) = -20 \; .$$

Thus, the equation becomes

$$y_A{}^2 + \frac{2\left[484 * (-20)\right]y_A}{(400)} + \frac{\left(484^2\right)}{(400)} = 0$$

$$y_A{}^2 - 48.4y_A + 585.64 = 0$$

$$\therefore\; y_A = 24.2$$

Sub. $y_A = 24.2$ into (3),

$x_A = 17.06$.

As a result of using the effective triangular localization scheme, the exact location of forklift A is (17, 24).

Through R-PODSS, all the exact locations of the material handling equipment can be identified in the warehouse and shown in the Java-based platform, as illustrated in **Figure 5.14**.

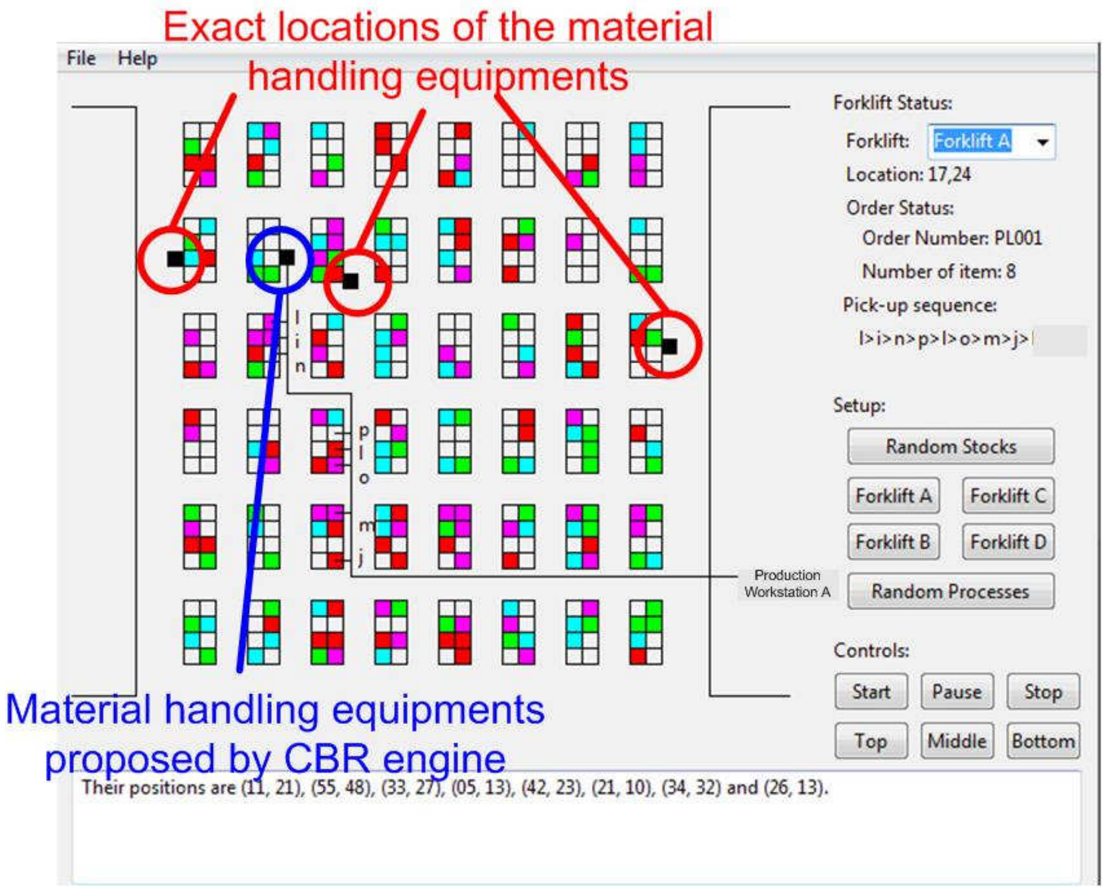


Figure 5.14 Java-based platform of R-PODSS

Thus, GSL solves the problem of selecting the material handling equipment to perform the pick-up order. As a result, the productivity of GSL is enhanced through selecting the right equipment for the order-picking process.

In the following case study, the function of R-PODSS in manipulating the exact locations of the resources to support the decision-making process of order picking routes formulation is illustrated.

5.3 Case Study 2 – Mold Manufacturing Company

Mold manufacturing can be divided into two categories: producing standard molds and unique molds. Standard molds enable the streamlining of the production cycle for specific products. This kind of mold is manufactured in the Make-to-Stock (MTS) mode of production, in which the production processes and specifications of each product are standardized. In contrast, the unique mold is operated in the Make-to-Order (MTO) mode, in which products are manufactured according to customers' unique requirements.

Jing Chi Engineering Company Limited (JCE), a mold manufacturing company, was established in 1968. It is a vertically integrated surface finishing organization, and mainly focuses on producing molds of automotive parts, bathroom, and kitchen equipment. To provide high quality and customized service to customers, they produce in the MTO mode so that the products can be easily customized.

5.3.1 Problem definition of JCE

Due to the economic down-turn and low-sale seasons, the company found that the capacity of the shop floor is excessive. A hybrid business mode of producing standardized and unique molds is adopted in the company. In shifting to this production model, the company faced difficulties in preparing a suitable production schedule. Due to the confusing production schedule, material requirement planners found difficulty in preparing the materials for the products in the two different production modes. In addition, the scrap in production increases due to the frequent re-calibration of the machines. This makes the replenishment of material more difficult. Therefore, JCE is determined to further improve the performance of shop floor so as to enhance its manufacturing capacity and improve its customer service along four initiatives: i) to be alert, in real-time, to the need to replenish any materials or to the necessity for setting up a new production line, ii) to enhance customer service by acquiring the production status of customer orders and the activities being performed by the equipment in real-time, iii) to allocate the forklift and manpower effectively and efficiently in order to fulfil stochastic production demand, and iv) to define the actual inventory level and locate the exact position of material handling equipment and SKUs in the warehouse.

5.3.2 Deployment of R-PODSS in JCE in Support of the Decisions on Warehouse Operations Planning

To achieve these goals, JCE adopts R-PODSS for solving the stochastic production material demand problem. The seven operating steps in R-PODSS are shown in **Figure 5.15**.

- *Step 1: RFID performance evaluation*

  In this step, three more tests are conducted to evaluate the RFID reading performance, as illustrated in **Figures 5.16 and 5.17**. The tests are 1) Power level-distance, 2) tag angle, and, 3) antenna angle tests

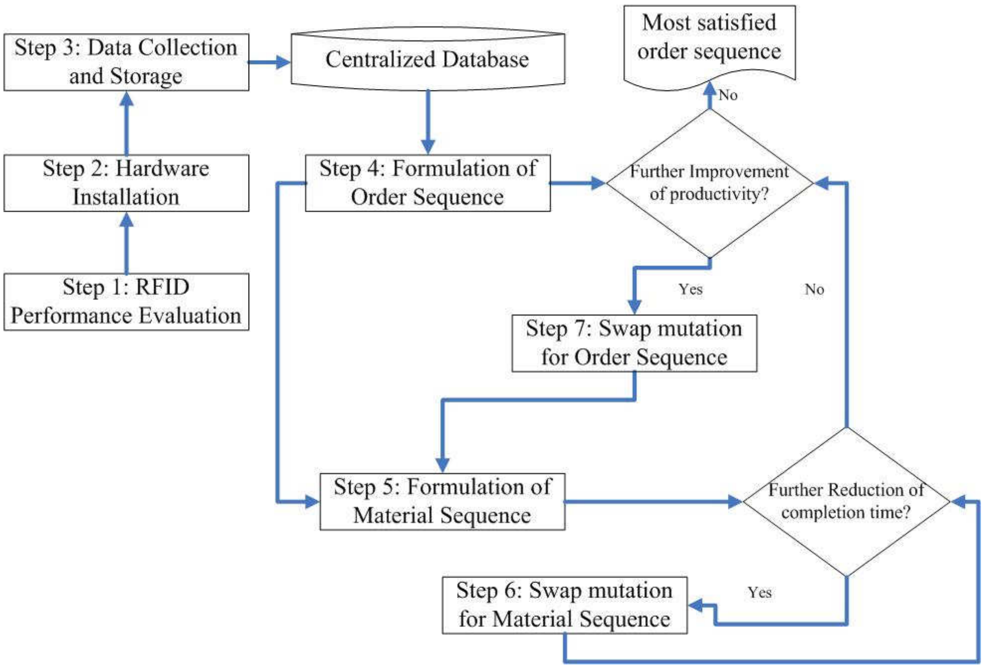
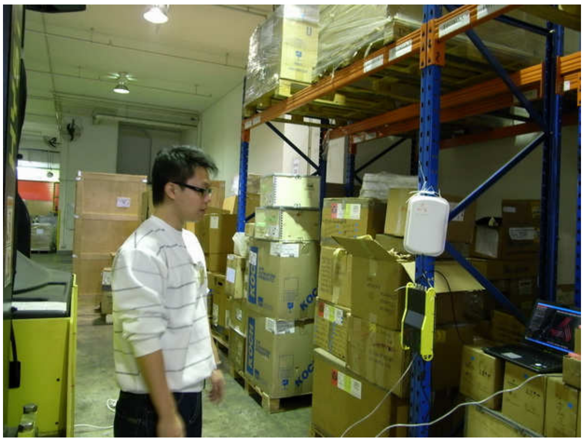


Figure 5.15 Seven operation steps of R-PODSS



Figures 5.16 – 5.17 On site tests in JCE

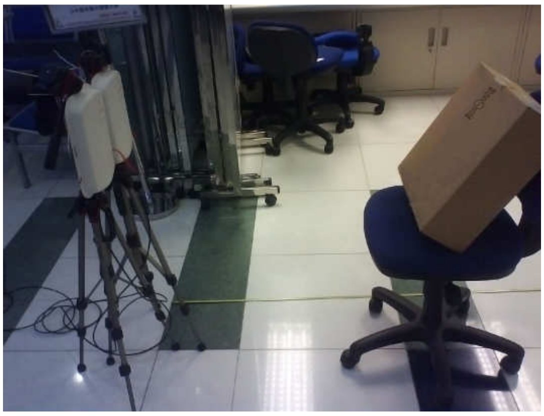
1) Power level – distance test

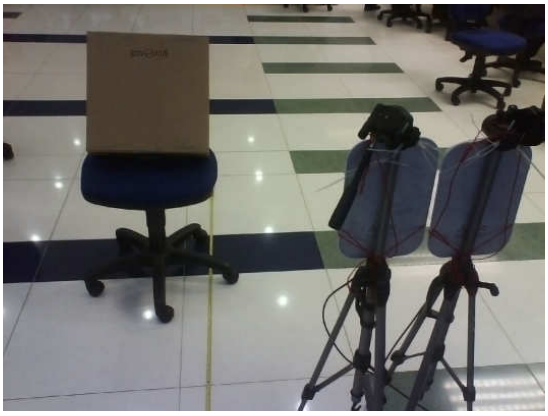
Figure 5.18 illustrates the hardware setting of this test. Both the tag and antennas are perpendicular to the E-plane. In power-level test, the tag is moved along the intersection line of the E-plane and the H-plane. In doing so, the read counts per second can be measured with different combinations of distances and power levels.

Figure 5.18 Power level-distance test

2) Tag angle test

Figures 5.19 and 5.20 demonstrate the hardware settings for the tag angle test. The radiation directions of both antennas are parallel to each other. Both the RFID antennas and the RFID tag are fixed at a height of 100.0 centimeters. The distance between the geometrical centers of the two antennas is 30.0 centimeters. In this test, the tag is rotated at a unit interval of 15-degree steps along the H-plane, and the angles vary from 0 to 180 degrees. The read counts per second are measured with different combinations of distances and angles.





Figures 5.19 and 5.20 Tag angle test

3) Antenna angle test

Figures 5.21 and 5.22 show the hardware setting of the antenna angle test. The antenna angle being tested varies from 0 to 150 degrees at the unit interval of 30 degrees, and the object is moving at the speed of 1.5 m/s in front of the antennas. The read counts per second are measured with different antenna angles.

Figures 5.21 and 5.22 Antenna angle test

- *Step 2: Hardware installation*

After evaluating the RFID reading performance, the most effective hardware setting is identified. By performing the three proposed tests, RFID performance is evaluated. **Figure 5.23** shows the relationship between the power level and distance between the tags and antennas. The minimum RF power level required to detect a tag is 7 dB, and the maximum distance is 200 centimeters. The maximum average read count is around 8.6 times per second. The read count is relatively stable at the maximum level. However, the readability between the tag and the reader significantly drops with an increase in distance or a decrease in power level. Therefore, using a higher power level can provide a better and larger coverage range.

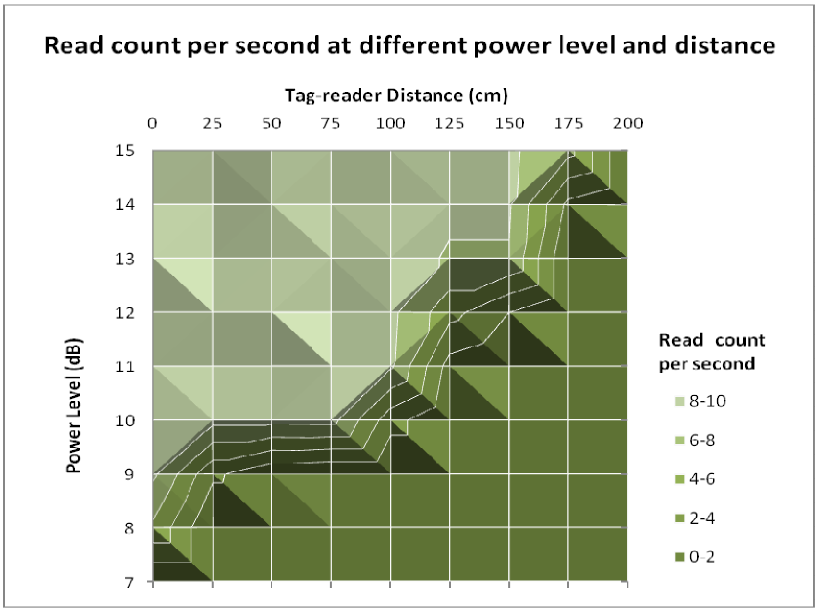


Figure 5.23 Different power levels and distances

Figure 5.24 illustrates the relationship between the reading performance in the form of read count per second and different tag angles. The performance of angles between 0 – 30 degrees is slightly lower than that between 135 – 180 degrees. The reading performance becomes stable when the angle is between 45 – 120 degrees. Thus, it is not necessary to place the tag parallel to the surface of the reader.

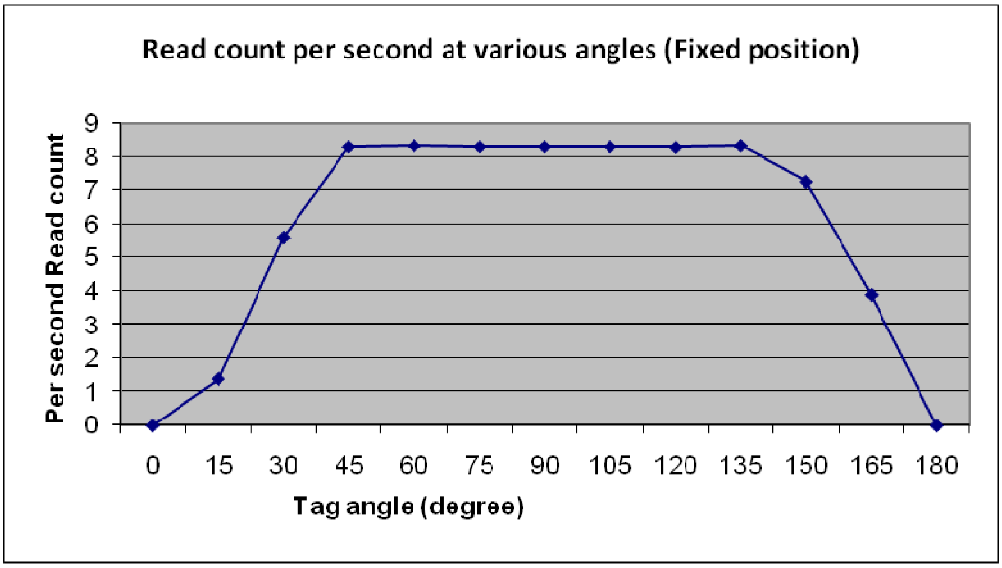


Figure 5.24 Result of tag angle test

Figure 5.25 explains the relationship between the reading performance in the form of read count per second and different reader angles. The result indicates that the readability of the antennas increases when the angle between the two antennas increases. The optimum readability of the reader is achieved at reader angle of 120 degrees.

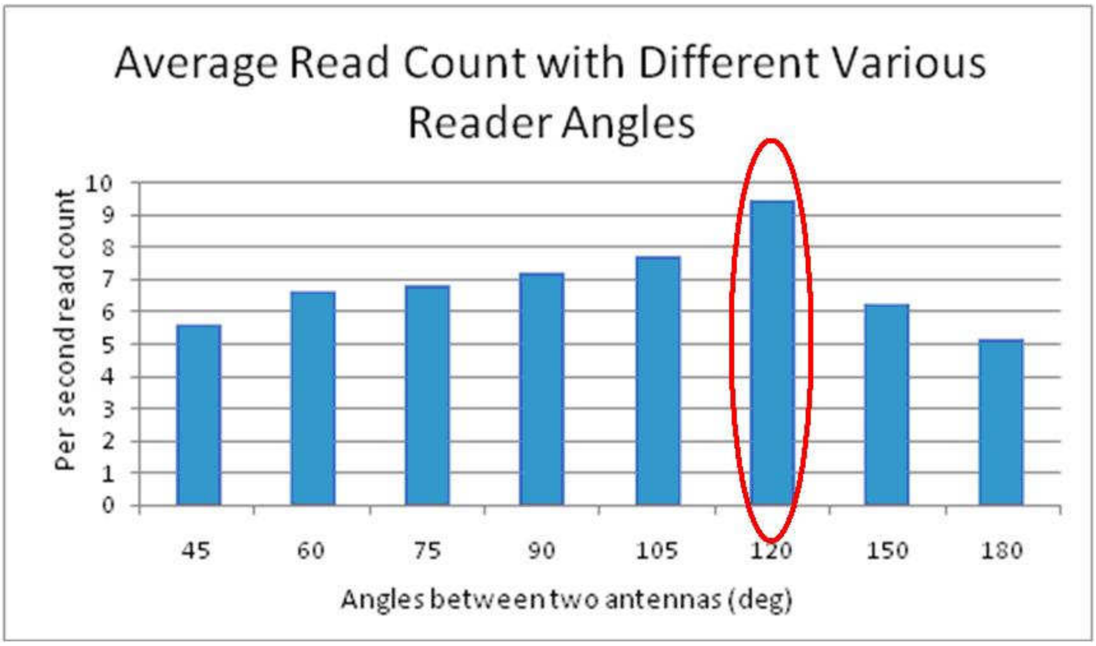


Figure 5.25 Result of reader angle test

By using the results of the tests, two sets of readers and antennas are installed at the entrance of each operation area, as illustrated in **Figure 5.26**. Thus, the operation area is fully covered by the RF from the RFID readers and antennas.

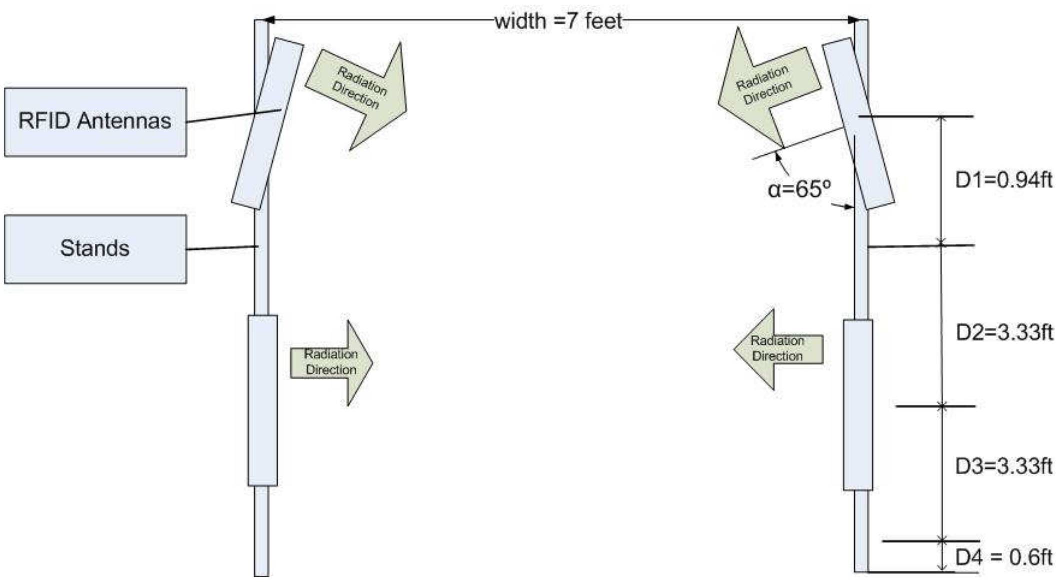


Figure 5.26 Hardware installation

- *Step 3: Data collection and storage*

In this step, the production data is captured by the RFID equipment, and then transferred and stored in the centralized database for further analysis. If production failure occurs, a sign will be sent through RFID technology and transmitted to the order sequence in the GA engine.

- *Step 4: Formulation of order sequence*

Once the signs are obtained from the RFID technology, the order sequence is formulated, as shown in **Figure 5.27**. For example, if production failure occurs in Operation Area 1, the corresponding gene will be marked 1 in the order sequence. Otherwise, it will be marked 0.

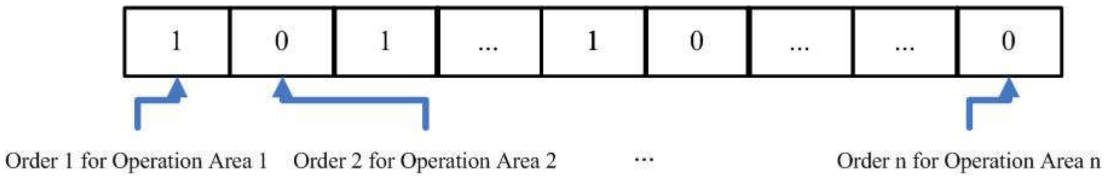


Figure 5.27 Order sequence

- *Step 5: Formulation of material sequence*

Once the order sequence is formulated, the production material demand of each operation area is identified. With the integration of the availability chromosome of the material handling equipment, the corresponding material sequence is constructed, as shown in **Figure 5.28**. The size of the population is 100. The chromosomes are evaluated by fitness Function (6), and the probability of selection of each chromosome is $p(chrom_i) = f_i \Big/ \sum_{x=1}^{100} f_x$, where $i \in [1\ 100]$.

Availability of forklifts | Instant Production Material Demands | Fitness values

Parents																											Distance
chrom1	=	1	0	0	1	……	1	12	20	0	10	……	10	0	0	0	0	……	0	……	5	8	14	6	……	7	243
chrom2	=	0	1	0	0	……	0	0	0	0	0	……	0	4	8	16	3	……	9	……	0	0	0	0	……	0	251
chrom3	=	1	1	0	0	……	1	7	8	2	0	……	5	7	11	9	4	……	1	……	10	8	11	5	……	2	237
chrom4	=	0	0	1	1	……	0	0	0	0	0	……	0	0	0	0	0	……	0	……	0	0	0	0	……	0	224
chrom5	=	0	0	0	1	……	1	0	0	0	0	……	0	0	0	0	0	……	0	……	6	7	10	9	……	5	245
chrom6	=	1	1	1	1	……	1	10	11	3	7	……	2	5	9	11	4	……	8	……	6	2	5	8	……	1	241
chrom7	=	…	…	…	…	……	…	…	…	…	…	……	…	…	…	…	…	……	…	……	…	…	…	…	……	…	…

Figure 5.28 Population of material sequence

A random number *r* is generated for selecting the parents. If the value of *r* is between 0 and $p(chrom_1)$, $chrom_1$ is selected. Similarly, if the value of *r* is between $p(chrom_1)$ and $p(chrom_2)$, $chrom_2$ is selected. The selected chromosomes are then transferred to the mating pool for crossover and mutation.

Before performing uniform crossover, a crossover probability index s_i, randomly generated in the range of 0 – 1, is assigned to the chromosomes and compared with the probability of crossover p_{cross}. If the value of s_i is smaller than the value of p_{cross}, the *i*-th chromosome is selected from the mating pool to perform the crossover operation. Otherwise, no crossover occurs. Assuming that p_{cross} is 0.8, the process of crossover is executed if $s_i < 0.8$. After that, a mask is created by a random number generator through MATLAB script, as illustrated in **Figure 5.29**.

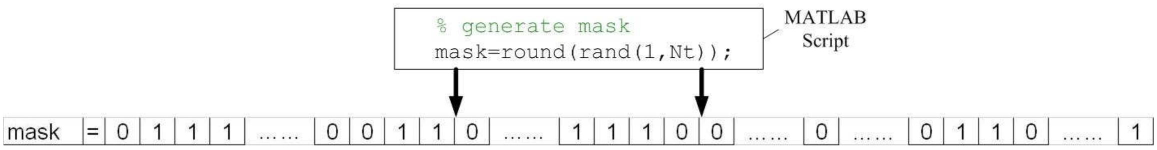


Figure 5.29 Mask generation through MATLAB

Through the mask and the MATLAB script, parents $chrom_1$ and $chrom_2$ are combined and offsprings $offspri_1$ and $offspri_2$ are generated. As illustrated in **Figure 5.30**, $bit_{3,chrom1}$ and $bit_{4,chrom1}$ are exchanged with $bit_{3,chrom2}$ and $bit_{4,chrom2}$ when $bit_{3,mask}$ and $bit_{4,mask}$ are equal to 1. On the other hand, if $bit_{i,mask}$ = 0, no action is taken.

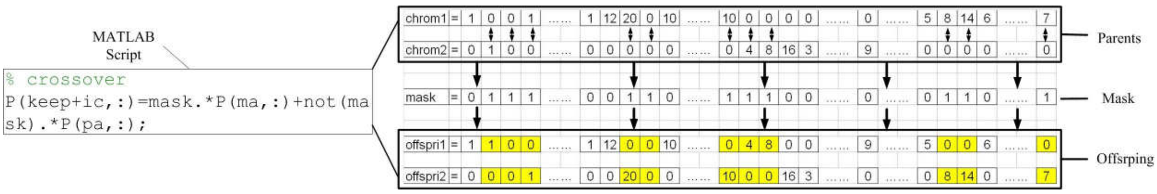


Figure 5.30 Offspring generation by crossover

After crossover, mutation starts with the probability of mutation p_{mut}. Repair operations will take place if there is any violation between the production workstation area and the instant demand of production materials. The generated offspring are then passed to Equation (6) for evaluation, as shown in **Figure 5.31**. The total travel distance for fulfilling each chromosome is re-calculated.

Parents																											Distance
chrom1	=	1	0	0	1	......	1	12	20	0	10	......	10	0	0	0	0	......	0	......	5	8	14	6	......	7	243
chrom2	=	0	1	0	0	......	0	0	0	0	0	......	0	4	8	16	3	......	9	......	0	0	0	0	......	0	251
chrom3	=	1	1	0	0	......	1	7	8	2	0	......	5	7	11	9	4	......	1	......	10	8	11	5	......	2	237
chrom4	=	0	0	1	1	......	0	0	0	0	0	......	0	0	0	0	0	......	0	......	0	0	0	0	......	0	224
chrom5	=	0	0	0	1	......	1	0	0	0	0	......	0	0	0	0	0	......	0	......	6	7	10	9	......	5	245
chrom6	=	1	1	1	1	......	1	10	11	3	7	......	2	5	9	11	4	......	8	......	6	2	5	8	......	1	241
chrom7	=	...	...	...	...	......	...	...	...	...	...	......	...	...	...	...	...	......	...	......	...	...	...	...	......	...	...
1st Generation																											Distance
offspri1	=	1	1	0	0	......	1	12	0	0	10	......	0	4	8	0	0	......	9	......	5	0	0	6	......	0	232
offspri2	=	0	0	0	1	......	0	0	20	0	0	......	10	0	0	16	3	......	0	......	0	8	14	0	......	7	238
offspri3	=	1	1	1	1	......	1	7	0	2	0	......	0	7	0	0	4	......	1	......	10	0	11	0	......	2	245
offspri4	=	1	1	0	0	......	1	0	8	0	0	......	5	0	11	9	0	......	0	......	0	8	0	5	......	0	229
offspri5	=	1	0	0	1	......	1	10	0	3	0	......	0	0	0	0	0	......	0	......	6	2	5	8	......	1	240
offspri6	=	1	1	1	1	......	1	0	11	0	7	......	2	5	9	11	4	......	8	......	6	7	19	9	......	5	240
offspri7	=	...	...	...	...	......	...	...	...	...	...	......	...	...	...	...	...	......	...	......	...	...	...	...	......	...	...

Figure 5.31 Fitness evaluation

The optimized replenishment routes are then formulated with the shortest distance after several crossovers and mutations. Through JavaScript, the optimized and suggested pick-up routes are suggested and shown as user interfaces for handling the replenishment operations in coordinate form, as shown in **Figure 5.32** and **Table 5.3,** respectively.

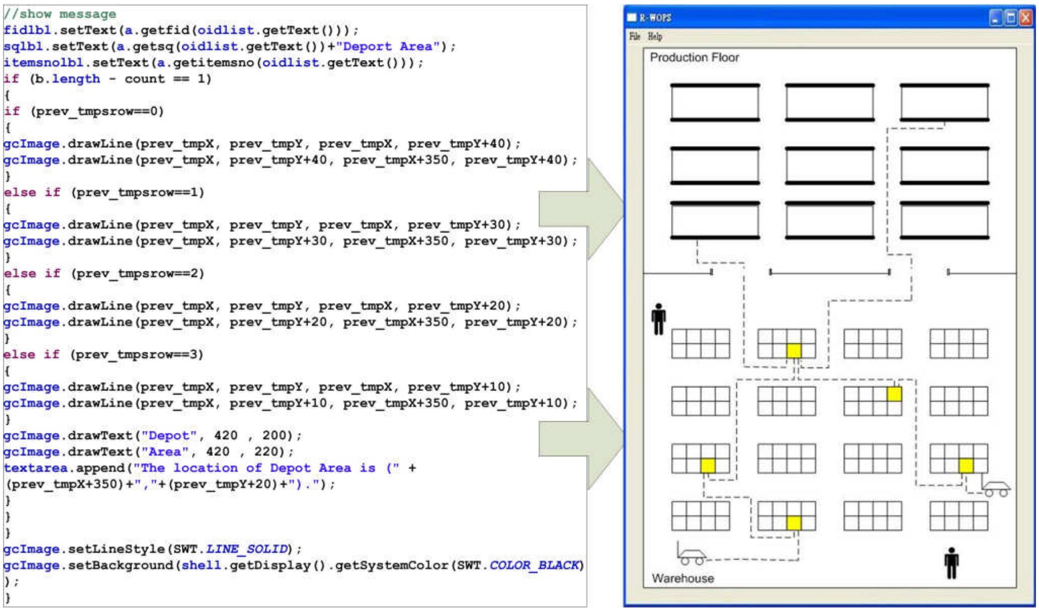


Figure 5.32 Formulation of optimized pick-up route

Table 5.3 Suggested pick-up route

Route 1					
Sequence of route	1	2	3	4	5
Node	l	i	n	p	o
Coordinates	11, 21	55, 48	33, 27	05, 13	26, 13

Chapter 6 Results and Discussion

6.1 Introduction

In this research, an R-PODSS is proposed for facilitating inbound operations to increase the visibility of production and warehouse operations status and enhance the efficiency and effectiveness of decision making when production problems occur. R-PODSS adopts RFID technology, CBR, and GA techniques for optimizing the pick-up and delivery routes of production materials between shop floor and warehouse environments to minimize the effect of stochastic production material demand problems. In this chapter, the results and discussion on two areas are presented in Sections 6.2 and 6.3.

Through the experiments and case studies, the benefits of the proposed R-PODSS are examined and described. These insights can serve as references for enterprises interested in adopting the RFID solution.

6.2 Experimental Results and Discussion of System Performance in the Production-warehouse Operation Decision Support

In this section, two experiments are conducted to examine the system performance of R-PODSS in the production-warehouse operation decision support. Experiment 1 is the comparison of transaction errors before and after the implementation of the RFID system, whereas Experiment 2 is the comparison of processing time for stochastic production material demand problem. The aim of the first experiment is to evaluate the transaction errors of a warehouse system before and after implementation of the RFID system. The objective of the second experiment is to determine the contribution of R-PODSS in the efficiency and effectiveness of tackling the stochastic production material demand problem.

6.2.1 Experiment 1: Comparison of Transaction Errors Before and After Implementation of the RFID System

To determine the performance of the RFID system, a mathematical model is proposed for evaluating the transaction errors of a warehouse system before and after implementation of the RFID system. Assume that a transaction error in the warehouse system due to the unreliability of the constructed RFID system for product j is denoted as e_{1j} for reading process, $\forall j \in J$. The characteristics of reliability of the constructed RFID system, before implementation of RFID system (nRFIDs) and after implementation of RFID system (RFIDs), are shown in **Table 6.1**.

Table 6.1 Characteristics of reliability of the RFIDs and nRFIDs

	Probability of miscounting	**Probability of exact counting**	**Probability of repeated counting**
(RFIDs)/ for 1 tagged item unit	p_0	p_1	p_2
(nRFIDs)/ for 1 item unit	φ_0	φ_1	φ_2

The probability of repeated counting is time-independent and follows a geometric distribution. Based on this, the mathematical expressions of Equation (12) are constructed:

$$p_0 + p_1 + \sum_{n=1}^{\infty} p_2^n = 1, \; p_2 = \frac{1 - p_0 - p_1}{2 - p_0 - p_1}; \quad \varphi_0 + \varphi_1 + \sum_{n=1}^{\infty} \varphi_2^n = 1, \; \varphi_2 = \frac{1 - \varphi_0 - \varphi_1}{2 - \varphi_0 - \varphi_1}. \tag{12}$$

Thus, the expectation of the counting result for 1 item unit is denoted as $\hat{n}$,

$$\hat{n} = \begin{cases} \hat{n}_1 = p_0(0) + p_1(1) + \sum_{n=1}^{\infty} p_2^n (n+1) = p_1 + (3 - p_0 - p_1)(1 - p_0 - p_1) & for \quad RFIDs \\ \hat{n}_2 = \varphi_1 + (3 - \varphi_0 - \varphi_1)(1 - \varphi_0 - \varphi_1) & for \quad nRFIDs \end{cases} \tag{13}$$

The time-independent transaction error for product size M_j is e_{1j}, which shows the difference between the actual amount and expectations of the counting result;

$$e_{1j} = M_j - \hat{n} M_j = (1 - \hat{n}) M_j \quad . \tag{14}$$

Through the above mathematical models, the degree of improvement of transaction errors before and after the implementation of RFID system is derived and shown in **Table 6.2**. The results show the average transaction error per order is greatly reduced, i.e., 75%, after the implementation of RFID system.

Table 6.2 Degree of improvement of transaction errors before and after the implementation of the RFID system

	Average transaction error/order
nRFID	0.20
RFID	0.05
Degree of improvement	75%

6.2.2 Experiment 2: Comparison of Processing Time for Stochastic Production Material Demand Problem

In this section, all the results are generated using MATLAB 2006b on an Intel Core 2 Duo 2.00 GHz PC with 2G MB memory. Three cases are analyzed, namely, i) small production material demand order size, ii) medium production material demand order size, and, iii) large production material demand order size tests, to evaluate the performance of the proposed algorithm. Five problem sets are solved within each case, and the number of workstations and the type of production materials are the same in each problem set. Each problem set is simulated ten times to find the worst, average, and best total makespan of the R-PODSS for solving the problem. The total makespan comparison between the first-come-first-served (FCFS) strategy and R-PODSS is also recorded.

i) Small-sized production material demand order test

Five problem sets with a number of production material demand orders from 10 to 90 under two production environments are generated. The results are shown in **Table 6.3**. In these problem set results, both FCFS strategy and proposed R-PODSS result in a longer makespan when the number of production material demand orders and the number of production material requested are increased. However, the proposed R-PODSS provides better results for the total makespan than the FCFS strategy. The average makespan generated by the R-PODSS is 30.29% shorter than that generated by the FCFS strategy in a heavy production environment, and 23.73% shorter than a normal one. The results prove the capability of the proposed R-PODSS in minimizing the total makespan for producing goods when handling small sized incoming and outgoing orders, within a reasonable computational runtime.

ii) Medium-sized production material demand order test

Five sets of medium-sized production material demand order problems ranging from 110 to 190 incoming order sizes are used. The results are recorded in **Table 6.4**. Results similar to those of the small size incoming order test are obtained. The total makespan generated by the proposed R-PODSS outperforms the FCFS strategy. However, the average percentage deviation of total makespan between the two approaches has dropped by nearly 20% compared with the small size production material demand order test.

iii) Large-sized production material demand order test

Five large production material demand order problem sets ranging from 210 to 270 are tested. The results can be found in **Table 6.5**. The average percentage deviations of makespan generated by the two approaches are 14.91% and 5.31% in heavy and normal situations, respectively.

Table 6.3 Results of FCFS strategy and R-PODSS on random instances of small-sized production material demand orders

Scenario	Trial Run	Number of orders		Total Number of raw material requested	Total makespan (FCFS)(seconds)	Total makespan (R-PODSS)(seconds)			Comparing two cases of total makespan		Computation time of R-PODSS (seconds)
		Incoming / outgoing	Ratio of Incoming / outgoing			Worst	Average	Best	(seconds)	(%)	
Heavy	1	10 / 30	0.33	156	843	501	407	345	436	51.72	664
	2	30 / 30	1	331	2364	1511	1399	1326	965	40.82	3210
	3	50 / 30	1.67	505	5095	4652	4111	4054	984	19.31	3225
	4	70 / 30	2.33	664	11949	10875	9811	9513	2138	17.89	4761
	5	90 / 30	3	841	10918	11507	8545	8106	2373	21.73	5016
	Average				***6233.8***	***5809.2***	***4854.6***	***4668.8***	***1379.2***	***30.29***	***3375.2***
Normal	1	10 / 30	0.33	160	248	232	220	214	28	11.29	412
	2	30 / 30	1	325	608	421	342	281	266	43.75	524
	3	50 / 30	1.67	497	813	661	523	506	290	35.67	602
	4	70 / 30	2.33	668	1039	912	898	791	141	13.57	579
	5	90 / 30	3	825	1589	1484	1361	1284	228	14.35	557
	Average				***859.4***	***742***	***668.8***	***615.2***	***190.6***	***23.73***	***534.8***

Table 6.4 Results of FCFS strategy and R-PODSS on random instances with medium-sized incoming orders

Scenario	Trial Run	Number of orders		Total number of raw material requested	Total makespan (FCFS)(seconds)	Total makespan (R-PODSS)(seconds)			Comparing two cases of total makespan		Computation time of R-PODSS (seconds)
		Incoming / outgoing	Ratio of Incoming / outgoing			Worst	Average	Best	(seconds)	(%)	
Heavy	1	110 / 30	3.67	1010	14564	14212	13857	13151	707	4.85	2371
	2	130 / 30	4.33	1170	19178	17511	15689	14209	3489	18.19	1890
	3	150 / 30	5	1336	27435	26917	24970	23411	2465	8.98	2545
	4	170 / 30	5.67	1530	35816	34542	33355	31547	2461	6.87	2973
	5	190 / 30	6.33	1698	46861	44526	41346	40987	5515	11.77	3101
	Average				***28770.8***	***27541.6***	***25843.4***	***24661***	***2927.4***	***10.13***	***2576***
Normal	1	110 / 30	3.67	921	2491	2491	2387	2262	104	4.18	390
	2	130 / 30	4.33	1196	4214	4268	4095	3945	119	2.82	568
	3	150 / 30	5	1391	6996	6855	6591	5249	405	5.79	989
	4	170 / 30	5.67	1554	7991	7991	7746	7521	245	3.07	438
	5	190 / 30	6.33	1704	11897	13521	11510	10974	387	3.25	512
	Average				***6717.8***	***7025.2***	***6465.8***	***5990.2***	***252***	***3.82***	***579.4***

Table 6.5 Results of FCFS strategy and R-PODSS on random instances with large-sized incoming orders

Scenario	Trial Run	Number of orders		Total number of raw material requested	Total makespan (FCFS)(seconds)	Total makespan (R-PODSS)(seconds)			Comparing two cases of total makespan		Computation time of R-PODSS (seconds)
		Incoming / outgoing	Ratio of Incoming / outgoing			Worst	Average	Best	(seconds)	(%)	
Heavy	1	210 / 30	7	1848	53584	48211	45514	39983	8070	15.06	2434
	2	230 / 30	7.67	2034	63002	55144	51069	48182	11933	18.94	2364
	3	250 / 30	8.33	2195	68478	62592	57009	55417	11469	16.75	3055
	4	270 / 30	9	2363	84402	75218	66015	64624	18387	21.79	4821
	5	290 / 30	9.67	2464	76712	76712	75151	75059	1561	2	2915
	Average				***69235.6***	***63575.4***	***58951.6***	***56653***	***10284***	***14.91***	***3117.8***
Normal	1	210 / 30	7	1791	20076	19451	18507	13159	1569	7.82	598
	2	230 / 30	7.67	1948	28771	28156	27721	26854	1050	3.65	682
	3	250 / 30	8.33	2078	32691	32691	31854	30749	837	2.56	570
	4	270 / 30	9	2395	32787	32187	31606	30174	1181	3.6	586
	5	290 / 30	9.67	2485	47177	43528	42958	38474	4219	8.94	1098
	Average				***32300.4***	***31202.6***	***30529.2***	***27882***	***1771.2***	***5.31***	***706.8***

Based on the three tests results, the proposed R-PODSS is capable of minimizing the makespan in the shop floor environment. **Table 6.6** are the results of improvement of total makespan among different quantities of orders with different optimization approaches. For the small size orders, the improvement of total makespan is from 17.89% to 51.72% in the heavy production scenario. In the normal production scenario, there is similar improvement of total makespan, from 14.35% to 43.75%. For the medium size orders, the improvement of total makespan is smaller than that in small size orders. A similar improvement range of total makespan between medium and large size orders in the heavy production scenario is shown, i.e., around 15% improvement of total makespan. For the normal scenario, the total makespan is increased by 5% when using the FCFS strategy and the R-PODSS.

Table 6.6 Results of improvement of total makespan between different numbers of orders and different optimization approaches

Three Scenarios								
Small number of orders			**Medium number of orders**			**Large number of orders**		
Total number of orders	*Efficiency (Heavy)*	*Efficiency (Normal)*	*Total number of orders*	*Efficiency (Heavy)*	*Efficiency (Normal)*	*Total number of orders*	*Efficiency (Heavy)*	*Efficiency (Normal)*
40	51.72%	41.29%	140	16.85%	4.18%	240	15.06%	7.82%
60	40.82%	43.75%	160	18.19%	2.82%	260	18.94%	3.65%
80	19.31%	35.67%	180	12.98%	5.79%	280	16.75%	2.56%
100	17.89%	13.57%	200	14.87%	3.07%	300	21.79%	3.60%
120	21.73%	14.35%	220	11.77%	3.25%	320	3.03%	4.94%

The proposed R-PODSS provides good solution results and reasonable computational run time when addressing the problem of random arrival of incoming orders in both heavy and normal production environments. In the heavy production scenario, a 15% to 20% maximum improvement within 2500 to 3000 seconds (40 to 60 minutes) is observed. Thus, the most optimal and realistic results are generated in that period, as illustrated in **Figure 6.1**.

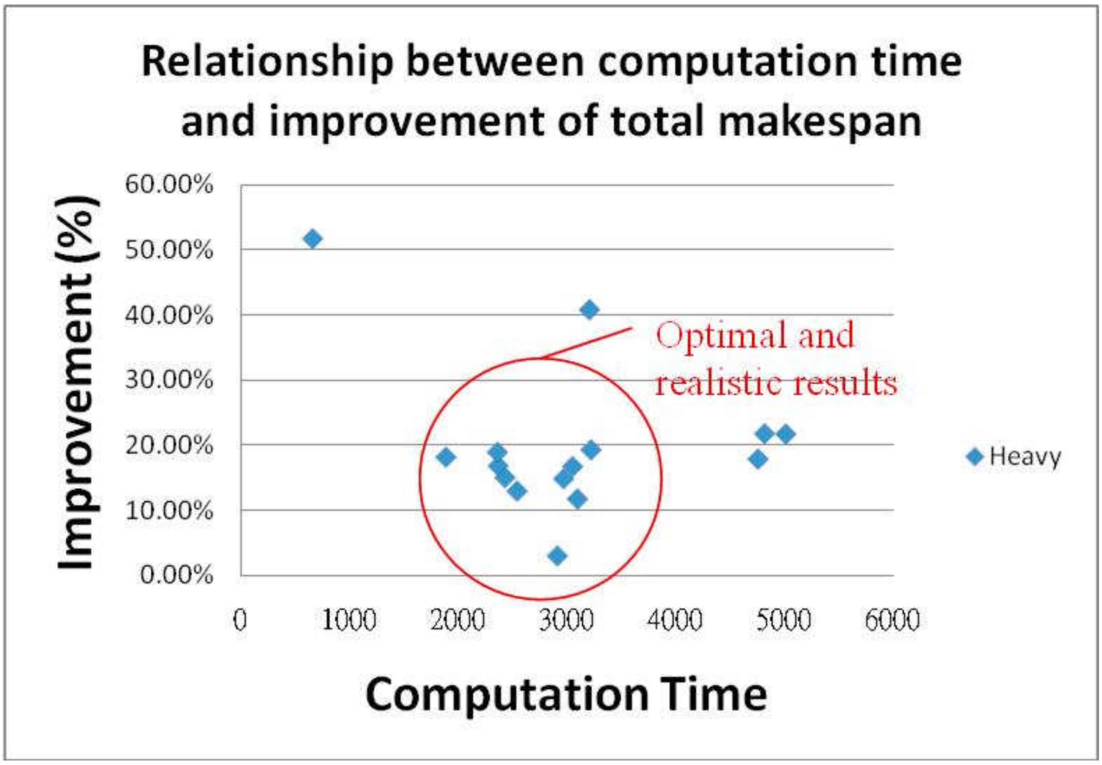


Figure 6.1 Relationship between computation time and improvement of total makespan in the heavy production scenario

In a normal production scenario, there is at most a 10% to 15% improvement within 500 seconds (about 8 minutes). Thus, the most optimal and realistic results are generated in that period, as shown in **Figure 6.2**.

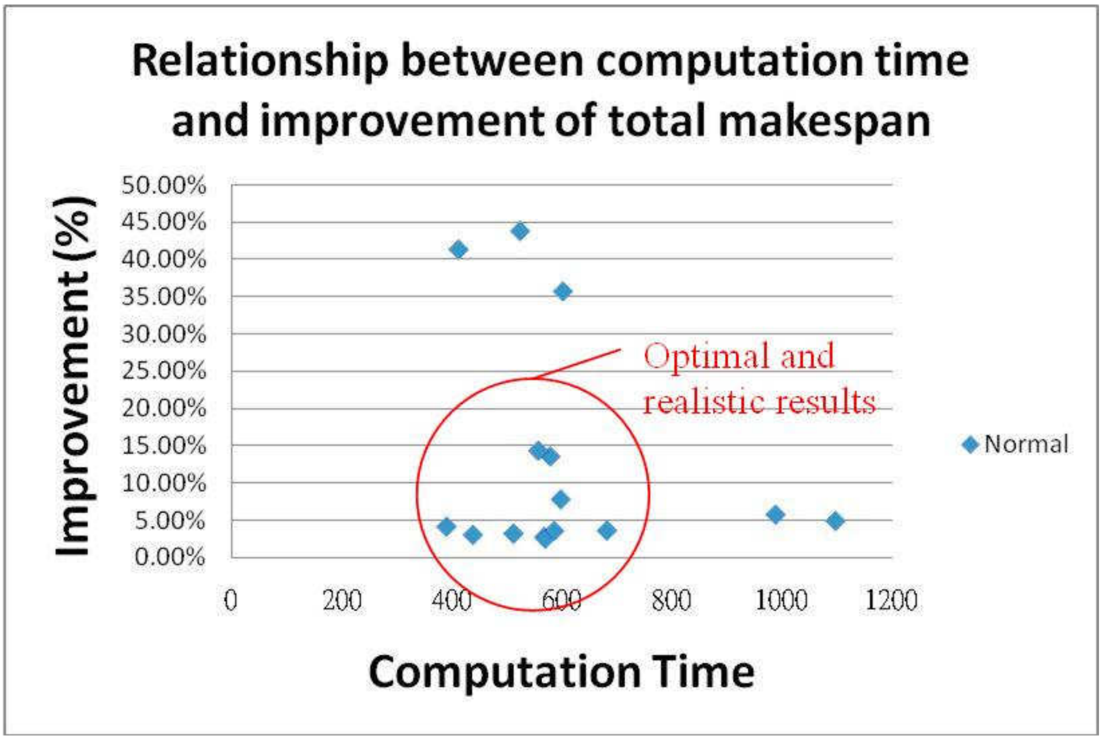


Figure 6.2 Relationship between computation time and improvement of total makespan in a normal production scenario

By comparing the relationship between computation time and improvement of total makespan, the improvement of total makespan is limited to a fixed range, whether the computation time is short or long.

In the next section, the performance of R-PODSS in supporting the decision making on production-warehouse operations in two case studies is recorded and discussed.

6.3 Discussion of the Use of R-PODSS in Two Case Studies

In the previous sections, the development of prototypes in two case studies was described to evaluate the feasibility and adoptability of the proposed R-PODSS. In this section, quantitative measurements of the R-PODSS are carried out and evaluated to verify system performance in actual manufacturing companies. Within the quantitative measurements, comparisons of performance assessment criteria, before and after system implementation, are conducted. The performance results in the two case studies are positive after implementing R-PODSS.

6.3.1 Results and Discussion of R-PODSS in GSL Company

In this section, the contributions of R-PODSS to the GSL Company are examined and described. R-PODSS enhances the warehousing operating performance of GSL in three categories: i) RFID adoption procedure simplification, ii) improvement of accuracy of retrieved information, and, iii) enhancement of productivity of the warehouse.

i) RFID adoption procedure simplification

Through the proposed reading performance tests, the performances of active and passive RFID devices are determined in different scenarios, such as in different locations, with different materials being handled. According to the results in **Appendix B**, the distance at which an active tag is able to receive a signal is about 10 meters, but a passive tag cannot receive a signal beyond a distance of approximately 2 meters. The reading performance of an active RFID device is better than that of a passive RFID device. Results reveal that all of the tags achieve their best performance when placed at the same level as the antennas. Based on the results, the procedures for the RFID equipment selection are simplified. This facilitates determination of the locations suitable for the installation of RFID devices in the GSL warehouse.

ii) Improvement of accuracy of retrieved information

Once the RFID equipment is installed effectively, the accuracy of retrieved warehouse information is significantly improved. In **Table 6.7**, the inventory level recorded by R-PODSS is exactly the same as the actual level, which is better than using manually recording this information. R-PODSS provides the exact location of the material handling equipment. The visibility of warehouse is significantly increased.

Table 6.7 Improvement in the accuracy of retrieved information

	Previous Situation (Manual Document/Barcode)	*R-PODSS (RFID)*	*Actual*
Inventory in warehouse	1547 Units	1574 Units	1574 Units
Inventory in specific locations (Level 2 of Rack 6)	No Record	43 Units	43 Units
Location of material handling equipment (Forklift A)	Zone A	(17, 24)	(18, 23)

iii) Enhancement of productivity of the warehouse

Owing to the adoption of RFID technology and query optimization technique in R-PODSS, the performance of retrieving and storing information are significantly enhanced. The lengths of time for retrieving and storing specific warehouse information are reduced from one minute and ten seconds to five seconds and two seconds respectively, as shown in **Table 6.8**.

Table 6.8 Time reduction in retrieving and storing information

	Previous Situation (Manual Document/Barcode)	*R-PODSS (RFID/query optimization)*
Time for retrieving warehouse information		
Inventory in warehouse	30 s	2 s
Inventory of specific type of product	1 min	5 s
Time for recording warehouse information (weight of SKU A)	10s	2s

Moreover, the job assignment process is changed from manual-based to automatic. The speed of assigning pick-up jobs and formulating material handling solutions for fulfilling customers' demands is significantly enhanced. Previously, the average time for formulating one material handling solution is about two minutes. Time is greatly reduced to 15 seconds when R-PODSS is implemented, as illustrated in **Table 6.9**. This enhances the productivity of the warehouse.

Table 6.9 Time reduction in formulating the material handling solutions

	Previous Situation	*R-PODSS*
Time for formulating one material handling solution		
Determine the appropriate material handling equipment	15 s	15 s
Determine the shortest pick-up route	45 s	
Modify the solution if not feasible	1 min	
Total	2 mins	

6.3.2 Results and Discussion of R-PODSS in JCE Company

In this section, the contributions of R-PODSS to the JCE Company are examined and described. R-PODSS enhances production operation performance of JCE in two categories: i) time reduction in identifying the stochastic production demand orders, and ii) time reduction in formulating solutions for the stochastic production material demand orders.

i) Time reduction in identifying the stochastic production demand orders

Table 6.10 shows the different lengths of time for identifying the stochastic production demand orders. When the number of operation areas and material demand orders increase, identification time of production failure also increases under a manual approach. The efficiency of information collection is significantly enhanced after implementing the RFID equipment.

Table 6.10 Identification time of production failure

Number of operation areas	*Number of material demands*	*Manual Approach (Sec)*	*R-PODSS (Sec)*
1	1	10	2
	2	12	2
	3	11	2
	4	13	2
2	1	31	2
	2	27	2
	3	25	2
	4	34	2
3	1	75	2
	2	68	2
	3	89	2
	4	90	2
4	1	80	2
	2	100	2
	3	111	2
	4	130	2

ii) Time reduction in formulating solutions for the stochastic production material demand orders

Two different probabilities of crossover, 0.8 and 0.9, and two different probabilities of mutation, 0.0015 and 0.03, are tested and evaluated in this case study. Using different combinations of GA parameters, such as probability of crossover, probability of mutation, population size, and number of iteration, the average fitness value, standard deviation, and best fitness value are recorded (refer to **Appendix C**).

Based on the results, the fitness values are reduced from generation to generation until there no improvement is observed in the best fitness value, up to 2000 iterations. With reference to the results, the combination of GA parameters, probability of crossover p_{cross} = 0.9, and probability of mutation p_{mut} = 0.0015, achieves lower fitness values. Thus, the shortest routes are formulated by adopting this combination. By adopting the probability of crossover p_{cross} = 0.9 and the probability of mutation p_{mut} = 0.0015, the traditional manual-based approach and the proposed R-PODSS for solving the stochastic production material demand problem are compared.

Generally, three steps are involved for formulating routes for stochastic production material demand orders: i) determine the appropriate material handling equipment, ii) determine the shortest route, and iii) modify if the solution is not feasible. **Table 6.11** presents the lengths of time for formulating routes for stochastic production material demand orders for both manual approach and R-PODSS. Using a manual approach to formulate a feasible pick-up route is time-consuming if only one item of material handling equipment and a few pick-up requests are considered. When the number of items of material handling equipment is considered and the number of production workstations requesting production materials is increased, the time for formulating a feasible route is greatly increased when using the manual approach. On the other hand, no significant difference is observed when R-PODSS is adopted to generate the routes. For example, if there are 4 items of material handling equipment assigned to handle production materials replenishment orders from 80 production workstations, it is necessary to spend 8545 seconds for formulating small batch replenishment routes for those orders, whereas only 20 seconds are spent for the same purpose with R-PODSS. This illustrates that the GA approach facilitates a faster search and generates a better solution for large-sized problems.

Table 6.11 Time for formulating routes for stochastic production material demand orders

Number of material handling equipments	Number of production workstations requesting production materials	Manual approach (second)	R-PODSS (second)	Improvement (%)
1	5	60	15	300.00
	10	123	15	720.00
	20	257	15	1613.33
	40	558	16	3387.50
	80	1201	17	6964.71
2	5	118	16	637.50
	10	234	17	1276.47
	20	466	16	2812.50
	40	972	16	5975.00
	80	1840	17	10723.53
3	5	241	18	1238.89
	10	508	18	2722.22
	20	1019	19	5263.16
	40	2164	19	11289.47
	80	4321	19	22642.11
4	5	513	18	2750.00
	10	1108	19	5731.58
	20	2097	20	10385.00
	40	4299	20	21395.00
	80	**8545**	**20**	**42625.00**

Chapter 7 Conclusion and Future Work

7.1 Summary of Research Work

In today's trend of increasing mass customization, smaller lot size and short delivery time have caused frequent changes in manufacturing operations. Due to the changes, problems such as workers' absenteeism, machine breakdowns, and loss of materials frequently occur in real-life dynamic production environments. Small batches of production materials have to be delivered frequently from warehouse to production shop floors within a short period of time. Warehouse operations are no longer confined to inventory storage and protection of goods, but include different operations ranging from receiving, packaging of goods, and after sales services to light assembly and inspection. Organizing available and appropriate resources to cope with the daily demand, has become a complex task.

The aim of this research is to propose and develop an R-PODSS to aid in managing production and warehouse activities to fulfil customers' demand. R-PODSS makes use of RFID technology and AI techniques, such as CBR and GA, to increase the visibility of production and warehouse operations status and enhance the efficiency and effectiveness of decision making when production problems occur. The principle and structure of R-PODSS have been developed and demonstrated in Chapters 3 and 5.

7.2 Contributions of the Research

This research provides a methodology for the development of a production operation decision support system for the manufacturing industry to facilitate inbound operations. The contributions of this research are summarized below.

(i) In this research, RFID technology is adopted to capture real-time information in the production shop floor and warehouse environments. This enhances information flow, visualizes the actual production and warehouse operations better, and facilitates production and warehouse operation decision making in a real-time manner. In addition, the use of the proposed RFID reading performance tests determined the reading performances of RFID equipments in different scenarios. This simplifies the RFID adoption procedure in the companies used as case studies. Moreover, with the help of proposed effective triangular localization scheme, the exact locations of resources are easily identified. This facilitates the resource allocation process effectively and efficiently.

(ii) DBMS and SQL statements are adopted to provide the function of data retrieval and storage for users. These help prevent human mistakes in preparing the program statement for obtaining the required datasets. Through query optimization, the speed of data retrieval from the database is enhanced.

(iii) The RFID Information Exchange Module has been developed for converting the EPC codes collected from the RFID readers to meaningful and readable information. The unique feature of this module facilitates identification of stochastic production material orders during production processes and resource allocation for the orders.

(iv) Through Optimal Order Picking and Delivery Module, the RFID data are manipulated efficiently and effectively which facilitated the formulation of reliable material handling solutions to address stochastic production material demand problems. The embedded CBR and GA facilitate the selection of resources and the route formulation for order picking process, respectively. Thus, the time for solving stochastic production material demand problems is significantly reduced.

(v) In R-PODSS, RFID technology and AI technique including CBR and GA are adopted to deal with stochastic production material demand problems. From the literature review, the research area related to integration of these technologies in monitoring production status in real-time to provide instant solution to solve daily shop floor problems is limited. Therefore, an opportunity to study the adoption of several technologies to improve the performance of the existing system exists.

(vi) The successful implementation of R-PODSS in actual manufacturing companies is demonstrated in two cases studies. After launching the R-PODSS in the companies, overall efficiency of production and warehouse operations is significantly improved. Thus, the case studies prove the feasibility of R-PODSS in actual working practice.

7.3 Limitations of the proposed system

Although R-PODSS is proposed to solve the stochastic production material demand problem, it is necessary to address the following limitations of the proposed system.

(i) The CBR-based module manipulates historical information as cases for facilitating order picking activities. In order to ensure the accuracy of the solutions provided by the module, it is essential to renew the cases in the case-based repository frequently and validate the appropriateness of the cases to deal with the new problems. If the enterprise does not renew and validate the cases regularly, the reliability of the case-based module may be reduced.

(ii) Two case studies have been conducted in an electronic manufacturer and a mold manufacturer, so as to validate the proposed system. However, other manufacturing sectors have similar production material demand problems. It is necessary to determine the feasibility and adoptability of the proposed system in different manufacturing sectors in the future.

(iii) The proposed system solely consider the response time for fulfilling customers' orders as a key performance indicator. It is suggested to consider more attributes, e.g. cost or quality, in determining the system performance in the manufacturing industry.

7.4 Suggestions for Future Work

Although R-PODSS has improved the operation performance in the companies studied, there is still room for improvement. Three areas should be considered in future research toward improving the capabilities of the proposed system.

(i) Another type of RFID tag has not been examined in this research. It is a semi-passive tag, which is battery-assisted, with greater sensitivity than passive tags, and cheaper than active tags. It is essential to evaluate the reading performance of this tag in production shop floor and warehouse environments to provide a comprehensive RFID performance comparison for formulating an efficient RFID solution.

(ii) In this research, the effective triangular localization scheme is developed for locating moving objects. However, it is only applied by the passive RFID technology. Therefore, it is essential to modify the effective triangular localization scheme for application in active RFID equipment.

(iii) A GA mechanism is adopted in formulating replenishment routes. However, it is important to handle different warehouse operations with a limited amount of material handling equipment. Therefore, further investigation has to be done to enhance the efficiency of the GA mechanism in determining the priority of warehouse operations.

(iv) Nowadays, people are more conscious of their partners in the entire supply chain performance. A generic R-PODSS is necessary to manage the logistics resources for improving the operation performance in such a supply chain. Therefore, studies on different parties, such as retail, distribution, etc., should be considered to determine the requirements for modifying the current architectural framework of the R-PODSS toward fitting with the whole supply chain network.

This thesis provides an overview of the development of R-PODSS in the production shop floor and warehouse environments to solve stochastic production material demand problems. It is hoped that this research inspires exploration from both researchers and enterprises with regard the future application of RFID and AI techniques in the manufacturing industry.

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Appendix A - Basic description of the testing equipment

(Source: http://www.alientechnology.com)

Reader specification	**Active RFID Reader** 	**Passive RFID Reader** 
Brand	Alien Technology	Alien Technology
Name	Nanoscanner Reader	Alien Multi-Port General Purpose RFID Reader
Model Number	B2450R01-A	ALR 9800
Frequency	2410 MHz – 2471.64 MHz	902.75 MHz – 927.25 MHz
Antenna Polarization	Circular	Linear

Antenna	**Active** 	**Passive** 
Frequency	2410 MHz – 2471.64 MHz	902-928 MHz
Polarization	Circular	Linear

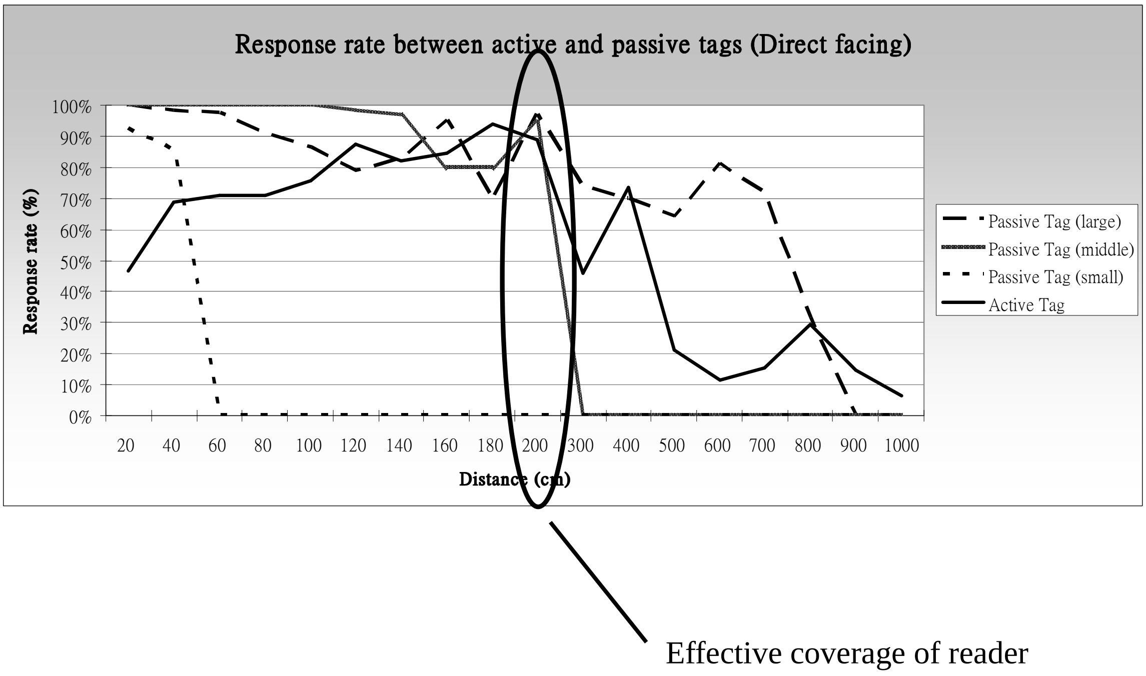
Tag				
Nature	Active	Passive (large)	Passive (middle)	Passive (small)
Dimension (cm)	8 x 2.5 x 1.2	9 x 4.5	9.5 x 3	4 x 2.5

Appendix B - Results from the RFID tests

B1 Orientation test

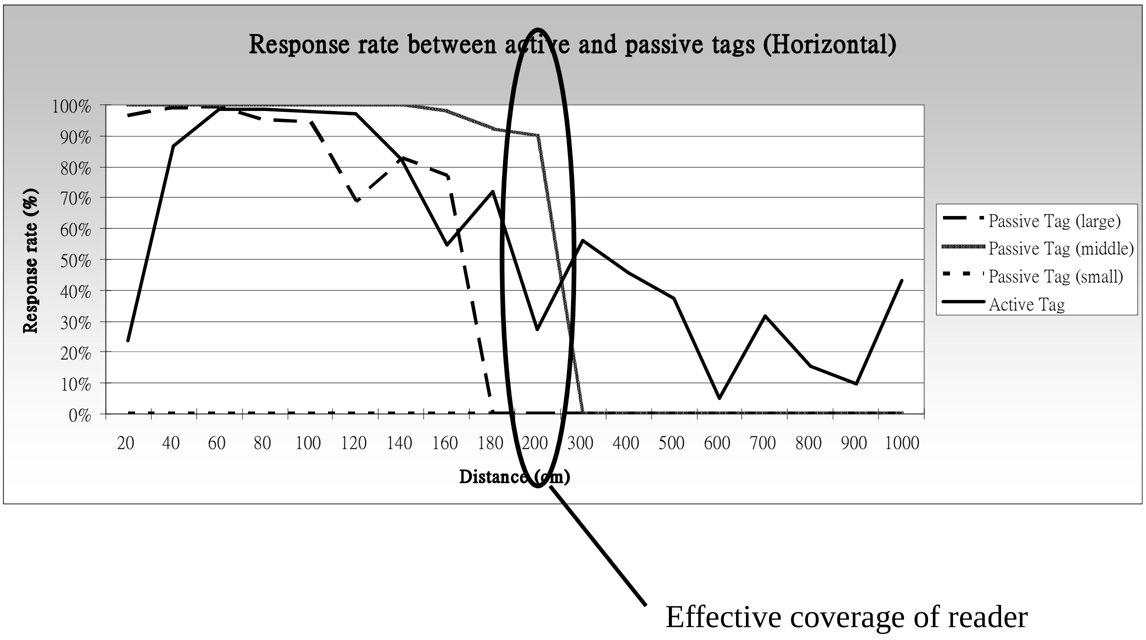
B1.1 Tags stuck on the front surface of SKU

	Total Read in 1 Min (Active)						Total Read in 1 Min (Passive large)						Total Read in 1 Min (Passive middle)						Total Read in 1 Min (Passive small)					
Distance (cm)	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
20	1100	1100	1700	1500	900	1260	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	900	900	928	950	946	924.8
40	2000	2100	2000	2100	1100	1860	988	985	982	978	976	981.8	1000	1000	1000	1000	1000	1000	850	878	856	850	854	857.6
60	2000	1900	1600	2100	2000	1920	975	970	978	968	975	973.2	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
80	1900	2000	2000	2100	1600	1920	907	910	908	905	910	908	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
100	1900	2000	2000	2400	1900	2040	850	866	856	865	880	863.4	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
120	2500	2200	2400	2300	2400	2360	760	790	780	800	805	787	980	980	982	980	980	980.4	0	0	0	0	0	0
140	2200	2000	2000	2300	2600	2220	831	850	770	840	854	829	960	965	966	980	960	966.2	0	0	0	0	0	0
160	2200	2200	2200	2400	2400	2280	970	953	936	940	960	951.8	800	800	800	800	800	800	0	0	0	0	0	0
180	2500	2500	2900	2500	2300	2540	710	668	680	714	705	695.4	800	800	800	800	802	800.4	0	0	0	0	0	0
200	2500	2500	2600	2400	2000	2400	970	970	975	975	972	972.4	978	920	890	970	965	944.6	0	0	0	0	0	0
300	1100	1100	1100	1900	1000	1240	734	730	730	746	750	738	0	0	0	0	0	0	0	0	0	0	0	0
400	1800	2000	2000	2200	1900	1980	700	690	698	702	700	698	0	0	0	0	0	0	0	0	0	0	0	0
500	380	420	360	900	800	572	660	655	664	620	610	641.8	0	0	0	0	0	0	0	0	0	0	0	0
600	200	260	230	300	550	308	830	790	799	825	823	813.4	0	0	0	0	0	0	0	0	0	0	0	0
700	390	480	440	490	270	414	715	720	717	740	699	718.2	0	0	0	0	0	0	0	0	0	0	0	0
800	1000	700	770	800	700	794	300	298	314	340	317	313.8	0	0	0	0	0	0	0	0	0	0	0	0
900	450	480	400	250	380	392	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	170	130	180	150	220	170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



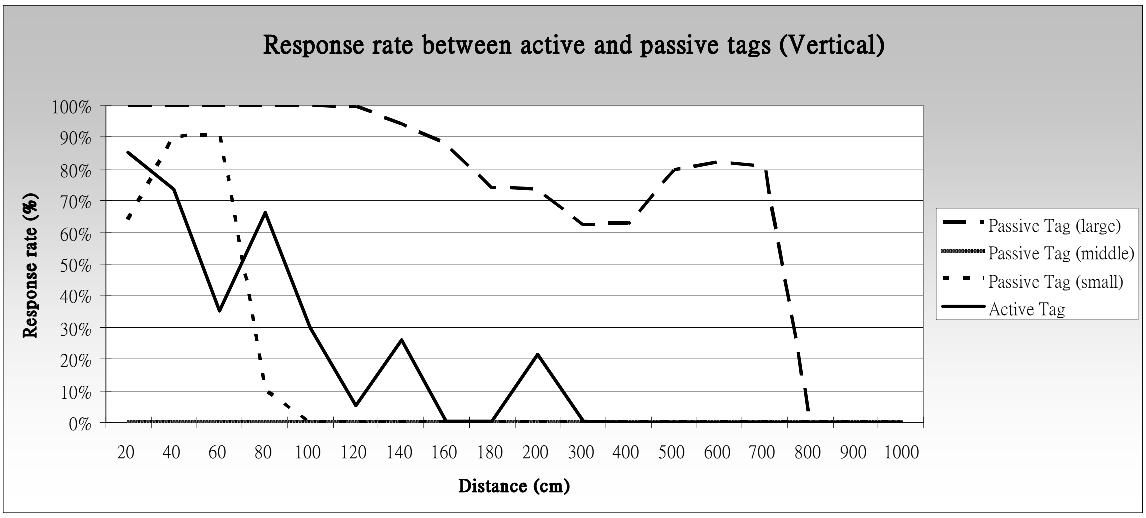
B1.2 Tag stuck on the top surface of SKU

	Total Read in 1 Min (Active)						Total Read in 1 Min (Passive large)						Total Read in 1 Min (Passive middle)						Total Read in 1 Min (Passive small)					
Distance (cm)	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
20	900	750	500	450	600	640	960	966	967	959	966	963.6	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
40	2400	2300	2400	2300	2300	2340	974	995	996	978	998	988.2	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
60	2600	2700	2600	2600	2800	2660	992	994	998	978	995	991.4	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
80	2800	2600	2700	2500	2700	2660	914	990	995	920	924	948.6	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
100	2800	2500	2700	2600	2600	2640	996	956	940	921	924	947.4	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
120	2600	2500	2700	2600	2700	2620	833	877	20	850	854	686.8	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
140	2300	2300	2200	2200	2100	2220	820	819	825	830	836	826	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
160	1500	1500	1600	1500	1300	1480	772	780	750	756	790	769.6	980	984	978	975	982	979.8	0	0	0	0	0	0
180	2100	1800	2000	1900	1900	1940	0	0	0	0	0	0	906	925	926	926	921	920.8	0	0	0	0	0	0
200	700	700	770	797	712	735.8	0	0	0	0	0	0	900	890	899	880	924	898.6	0	0	0	0	0	0
300	1712	1674	1200	1700	1300	1517.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
400	1175	1322	1271	1210	1188	1233.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
500	914	910	974	1026	1246	1014	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
600	162	154	160	100	100	135.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
700	787	922	925	945	700	855.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
800	374	413	490	429	366	414.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
900	271	332	282	251	180	263.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	1234	1065	1204	1076	1235	1162.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



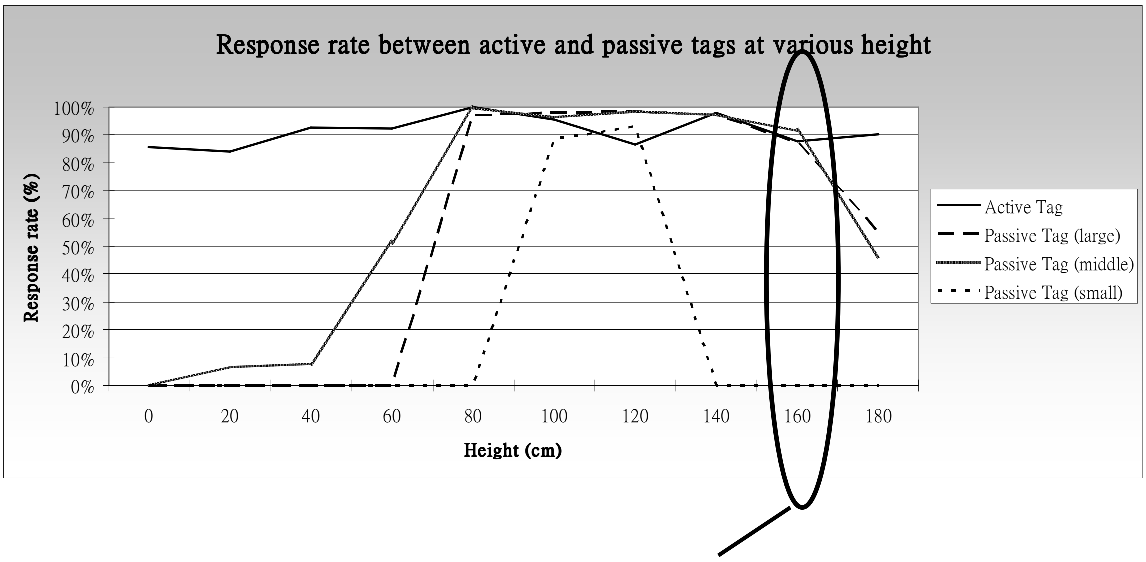
B1.3 Tags stuck on the side surface of SKU

	Total Read in 1 Min (Active)						Total Read in 1 Min (Passive large)						Total Read in 1 Min (Passive middle)						Total Read in 1 Min (Passive small)					
Distance (cm)	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
20	2300	2366	2346	2180	2309	2300.2	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0	600	904	599	550	554	641.4
40	2000	1978	2000	2100	1862	1988	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0	900	900	900	900	900	900
60	942	915	948	1035	908	949.6	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0	900	905	921	921	900	909.4
80	2030	1700	1700	1830	1700	1792	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0	100	100	100	104	102	101.2
100	800	760	850	900	750	812	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0	0	0	0	0	0	0
120	124	216	160	100	100	140	990	998	990	1000	998	995.2	0	0	0	0	0	0	0	0	0	0	0	0
140	550	680	800	700	780	702	950	956	954	920	925	941	0	0	0	0	0	0	0	0	0	0	0	0
160	20	10	15	14	10	13.8	882	889	890	854	873	877.6	0	0	0	0	0	0	0	0	0	0	0	0
180	6	10	7	15	12	10	721	745	756	755	720	739.4	0	0	0	0	0	0	0	0	0	0	0	0
200	500	500	650	600	640	578	750	721	750	724	728	734.6	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	600	635	625	641	620	624.2	0	0	0	0	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	600	603	666	667	600	627.2	0	0	0	0	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	820	825	799	780	754	795.6	0	0	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	820	750	898	854	787	821.8	0	0	0	0	0	0	0	0	0	0	0	0
700	0	0	0	0	0	0	830	820	780	745	860	807	0	0	0	0	0	0	0	0	0	0	0	0
800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



B2 Height Test

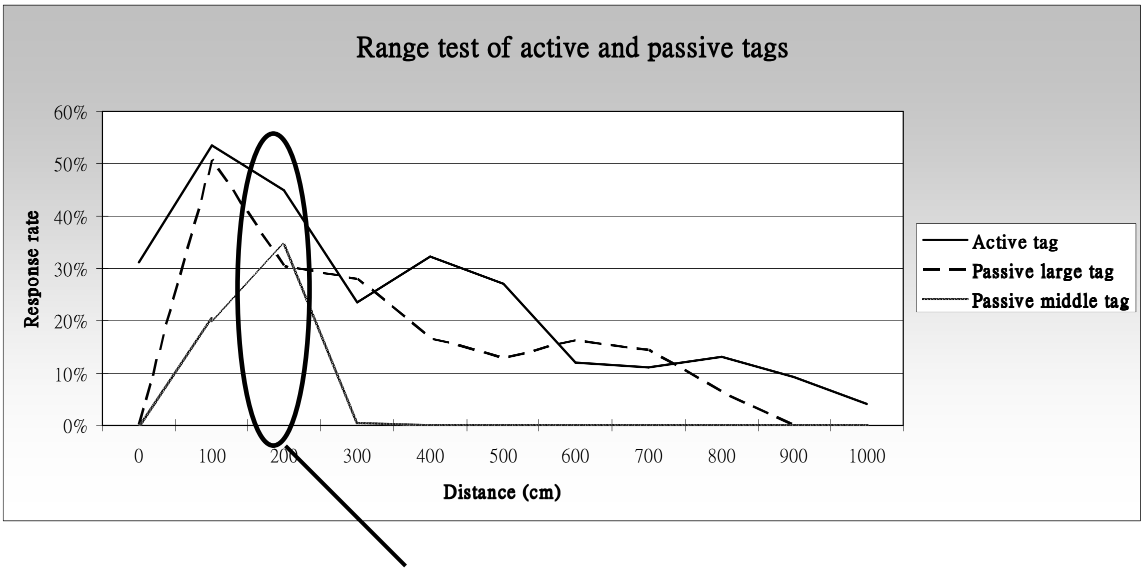
	Total Read in 1 Min (Active)						Total Read in 1 Min (Passive large)						Total Read in 1 Min (Passive middle)						Total Read in 1 Min (Passive small)					
Height (cm)	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
0	2300	2200	1980	2500	2600	2316	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	1950	2300	2000	2450	2650	2270	0	0	0	0	0	0	66	57	70	79	60	66.4	900	890	850	905	880	885
40	1990	2800	2500	2550	2690	2506	0	0	0	0	0	0	73	79	65	90	91	79.6	950	948	880	920	955	930.6
60	2400	2500	2550	2470	2550	2494	0	0	0	0	0	0	516	540	499	526	480	512.2	0	0	0	0	0	0
80	2690	2680	2750	2750	2650	2704	970	976	969	972	960	969.4	996	998	990	998	998	996	0	0	0	0	0	0
100	2900	2800	2500	2400	2300	2580	980	988	982	979	970	979.8	944	950	980	970	972	963.2	0	0	0	0	0	0
120	2200	2400	2200	2600	2300	2340	980	982	985	985	990	984.4	980	984	990	979	982	983	0	0	0	0	0	0
140	2600	2400	2700	2700	2800	2640	977	980	965	962	965	969.8	976	960	965	978	976	971	0	0	0	0	0	0
160	2500	2400	2450	2500	1980	2366	880	860	866	879	882	873.4	920	920	900	905	925	914	0	0	0	0	0	0
180	2550	2650	2500	2450	2000	2430	570	490	565	572	540	547.4	480	520	375	450	490	463	0	0	0	0	0	0



Effective coverage of reader

B3 Range test

	Total Read in 1 Min (Active)					Total Read in 1 Min (Passive large)				Total Read in 1 Min (Passive middle)			Total Read in 1 Min (Passive small)				
Distance at Y/X axis	0	100	200	300	400	0	100	200	300	0	100	200	0	100	200	300	400
0	0	2400	1250	500	<10	0	0	0	0	0	0	0	0	0	0	0	0
100	1900	2000	1800	780	800	850	860	804	0	1000	0	0	0	0	0	0	0
200	2000	480	1330	500	1500	970	545	0	0	978	760	0	0	0	0	0	0
300	1000	270	677	400	550	734	419	262	0	0	27	0	0	0	0	0	0
400	1900	600	450	950	700	700	143	0	0	0	0	0	0	0	0	0	0
500	800	1500	850	280	140	660	0	0	0	0	0	0	0	0	0	0	0
600	550	920	<5	<10	750	830	0	0	0	0	0	0	0	0	0	0	0
700	270	800	400	<10	0	715	0	0	0	0	0	0	0	0	0	0	0
800	700	700	287	0	0	300	0	0	0	0	0	0	0	0	0	0	0
900	380	825	<10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	220	350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

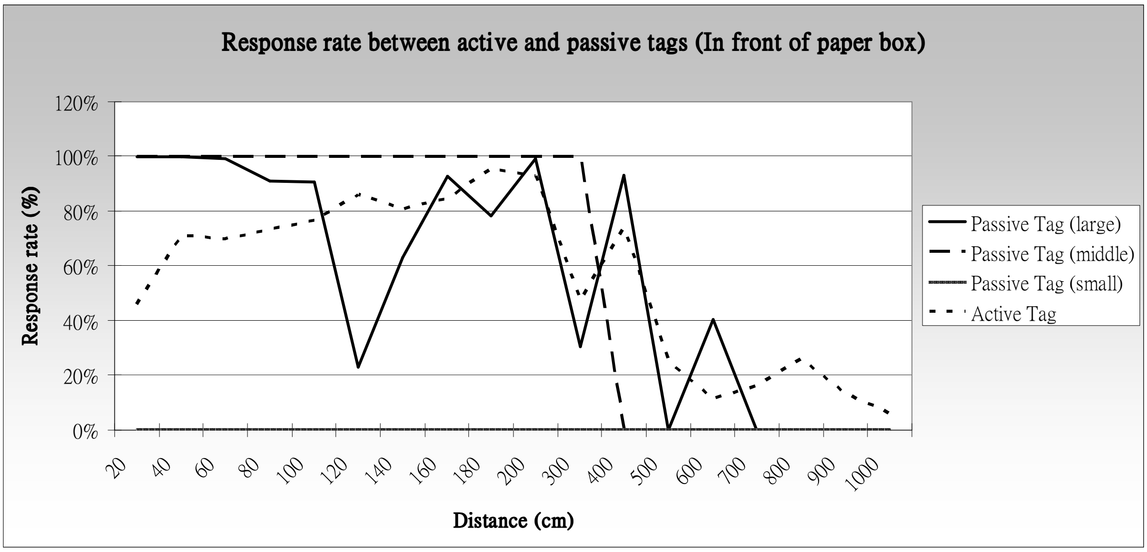


Effective coverage of reader

B4 Material test

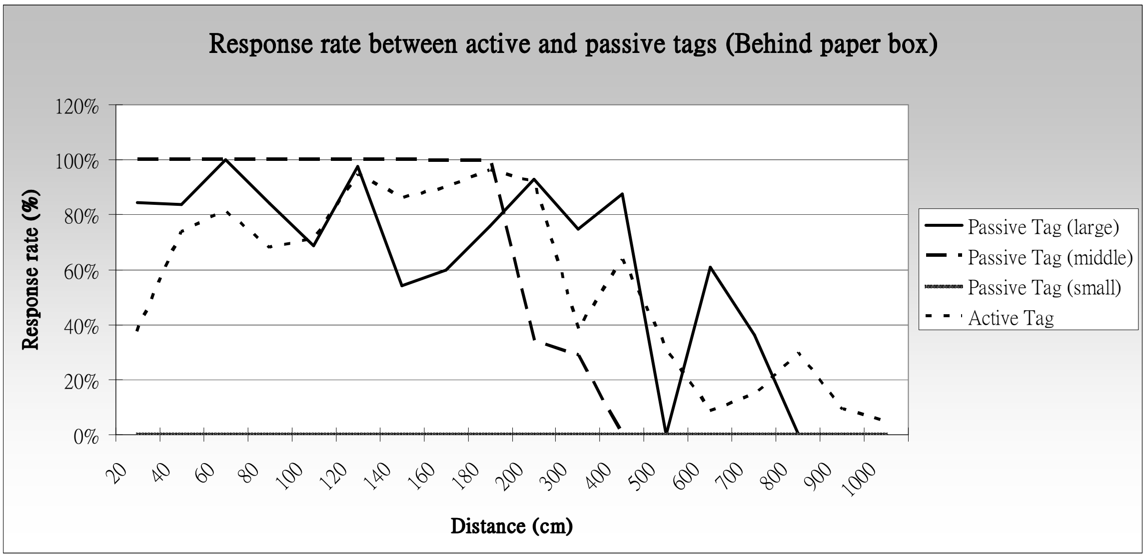
B4.1 In front of the SKU

	Total Read in 1 Min (Active)						Total Read in 1 Min (Passive large)						Total Read in 1 Min (Passive middle)						Total Read in 1 Min (Passive small)					
Distance (cm)	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
20	1100	1100	1500	1400	1100	1240	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
40	2000	2100	1900	2100	1500	1920	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
60	1900	1900	1700	2100	1800	1880	998	992	994	987	985	991.2	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
80	2000	2000	2000	2100	1800	1980	928	967	819	933	903	910	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
100	1900	2100	2100	2300	1900	2060	932	900	898	894	914	907.6	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
120	2500	2400	2100	2200	2400	2320	480	239	211	84	142	231.2	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
140	2200	2200	2000	2100	2400	2180	635	570	580	687	677	629.8	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
160	2200	2100	2500	2400	2200	2280	952	938	911	925	916	928.4	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
180	2400	2500	2800	2800	2400	2580	804	825	789	724	771	782.6	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
200	2500	2400	2500	2400	2700	2500	998	996	970	996	995	991	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
300	1100	1100	1200	1800	1200	1280	306	295	307	312	297	303.4	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
400	1800	1800	2000	2200	2200	2000	951	920	947	907	938	932.6	0	0	0	0	0	0	0	0	0	0	0	0
500	850	750	420	900	480	680	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
600	200	260	230	300	550	308	417	407	355	420	414	402.6	0	0	0	0	0	0	0	0	0	0	0	0
700	380	500	450	450	370	430	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
800	750	680	600	800	700	706	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
900	350	380	480	280	270	352	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	155	110	150	200	180	159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



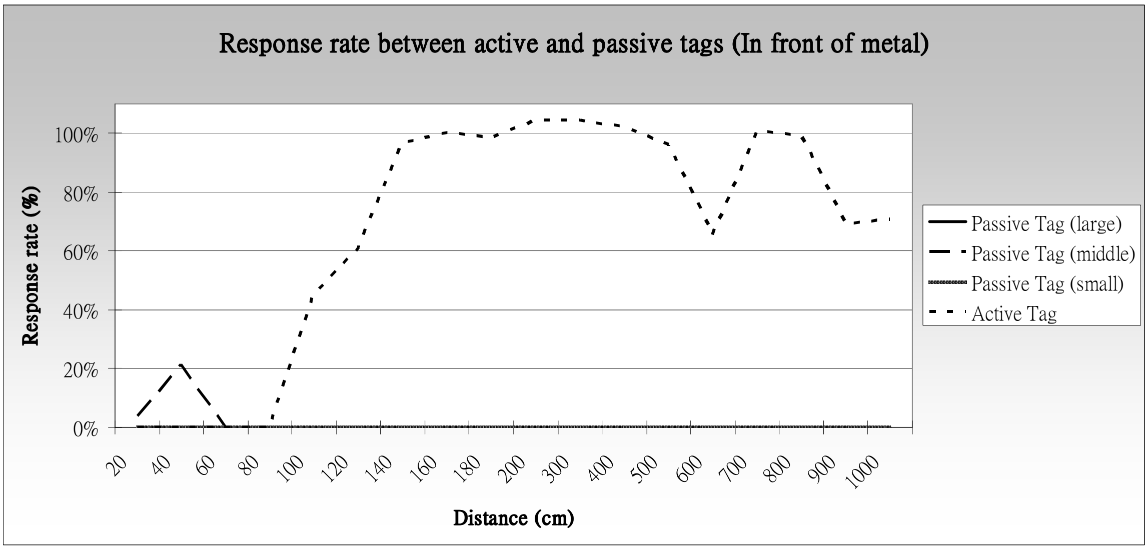
B4.2 Behind the SKU

	Total Read in 1 Min (Active)						Total Read in 1 Min (Passive large)						Total Read in 1 Min (Passive middle)						Total Read in 1 Min (Passive small)					
Distance (cm)	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
20	1100	1000	900	950	1100	1010	834	847	855	846	844	845.2	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
40	2000	1900	1950	2100	2000	1990	811	816	845	872	846	838	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
60	2100	2200	2200	2400	2100	2200	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
80	1700	2000	1900	1900	1700	1840	847	827	836	853	846	841.8	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
100	1900	2000	2000	1900	1800	1920	875	844	583	527	599	685.6	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
120	2500	2580	2600	2520	2600	2560	992	984	930	989	988	976.6	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
140	2200	2400	2300	2350	2360	2322	540	539	544	538	553	542.8	1000	1000	1000	1000	1000	1000	0	0	0	0	0	0
160	2400	2380	2500	2400	2420	2420	633	568	661	577	549	597.6	994	998	1000	995	998	997	0	0	0	0	0	0
180	2500	2580	2650	2650	2600	2596	779	727	796	710	778	758	997	998	996	1000	996	997.4	0	0	0	0	0	0
200	2466	2500	2550	2400	2500	2483.2	907	958	928	930	925	929.6	334	356	366	338	318	342.4	0	0	0	0	0	0
300	1100	980	1000	1020	1050	1030	771	745	740	724	767	749.4	470	139	249	280	300	287.6	0	0	0	0	0	0
400	1800	1750	1650	1600	1800	1720	980	890	875	880	756	876.2	0	0	0	0	0	0	0	0	0	0	0	0
500	800	900	780	900	850	846	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
600	200	250	247	250	200	229.4	608	598	620	644	580	610	0	0	0	0	0	0	0	0	0	0	0	0
700	380	385	390	420	380	391	415	377	420	350	246	361.6	0	0	0	0	0	0	0	0	0	0	0	0
800	780	800	850	850	750	806	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
900	200	250	377	240	200	253.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	130	87	125	150	120	122.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



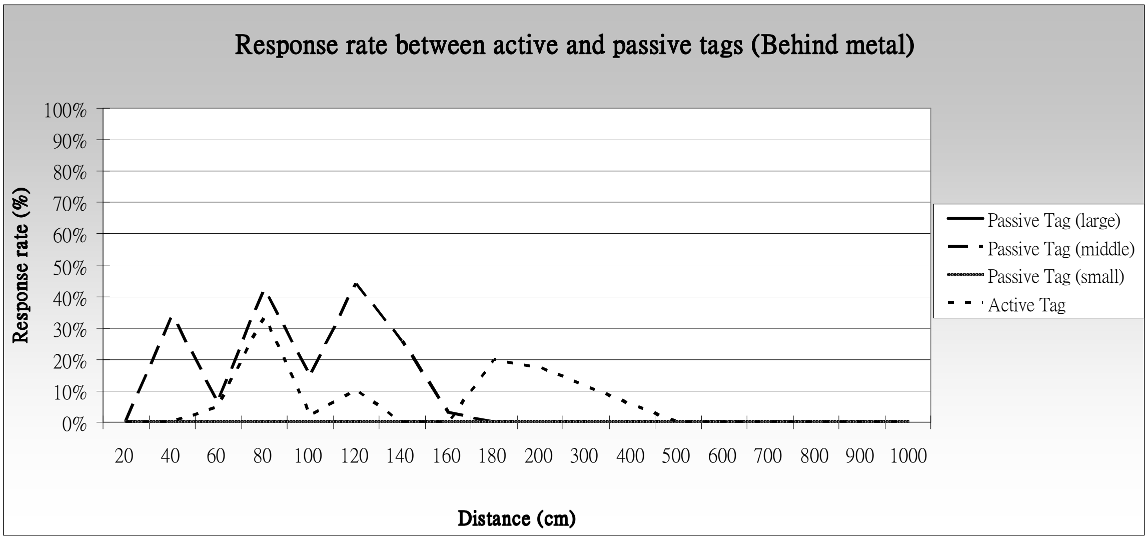
B4.3 In front the metal

	Total Read in 1 Min (Active)						Total Read in 1 Min (Passive large)						Total Read in 1 Min (Passive middle)						Total Read in 1 Min (Passive small)					
Distance (cm)	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
20	0	0	0	0	0	0	0	0	0	0	0	0	25	26	24	28	89	38.4	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	214	187	226	229	214	214	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	1400	1100	1150	1200	1300	1230	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	1700	1750	1600	1650	1600	1660	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
140	2500	2700	2650	2660	2550	2612	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	2700	2716	2700	2680	2700	2699.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	2600	2650	2680	2658	2700	2657.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
200	2800	2900	2850	2900	2950	2880	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	2800	2800	2900	2880	2800	2836	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
400	2800	2750	2700	2800	2750	2760	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
500	2600	2550	2650	2600	2580	2596	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
600	1700	1800	1750	1770	1800	1764	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
700	2700	2700	2760	2750	2700	2722	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
800	2600	2650	2700	2750	2700	2680	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
900	1800	1900	1850	1900	1850	1860	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	1900	1850	2000	1900	1880	1906	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



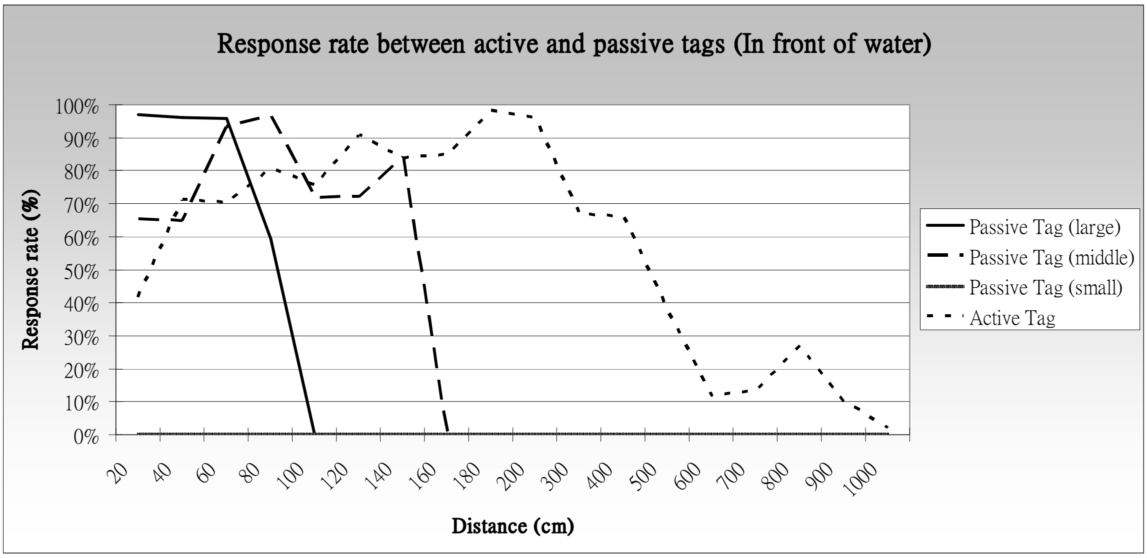
B4.4 Behind the metal

	Total Read in 1 Min (Active)						Total Read in 1 Min (Passive large)						Total Read in 1 Min (Passive middle)						Total Read in 1 Min (Passive small)					
Distance (cm)	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
20	0	0	0	0	0	0	970	974	985	974	956	971.8	641	666	639	653	662	652.2	0	0	0	0	0	0
40	0	0	0	0	0	0	960	964	962	959	963	961.6	645	651	644	653	643	647.2	0	0	0	0	0	0
60	150	120	80	140	150	128	964	952	956	958	961	958.2	929	918	938	927	946	931.6	0	0	0	0	0	0
80	780	900	980	950	920	906	603	586	589	598	597	594.6	967	974	968	964	966	967.8	0	0	0	0	0	0
100	70	40	55	57	73	59	0	0	0	0	0	0	717	726	729	710	706	717.6	0	0	0	0	0	0
120	280	278	300	250	260	273.6	0	0	0	0	0	0	709	725	727	724	726	722.2	0	0	0	0	0	0
140	0	0	0	0	0	0	0	0	0	0	0	0	845	837	848	848	842	844	0	0	0	0	0	0
160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	620	580	480	500	520	540	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
200	480	450	480	500	420	466	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	300	290	320	320	318	309.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
400	140	150	147	140	139	143.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



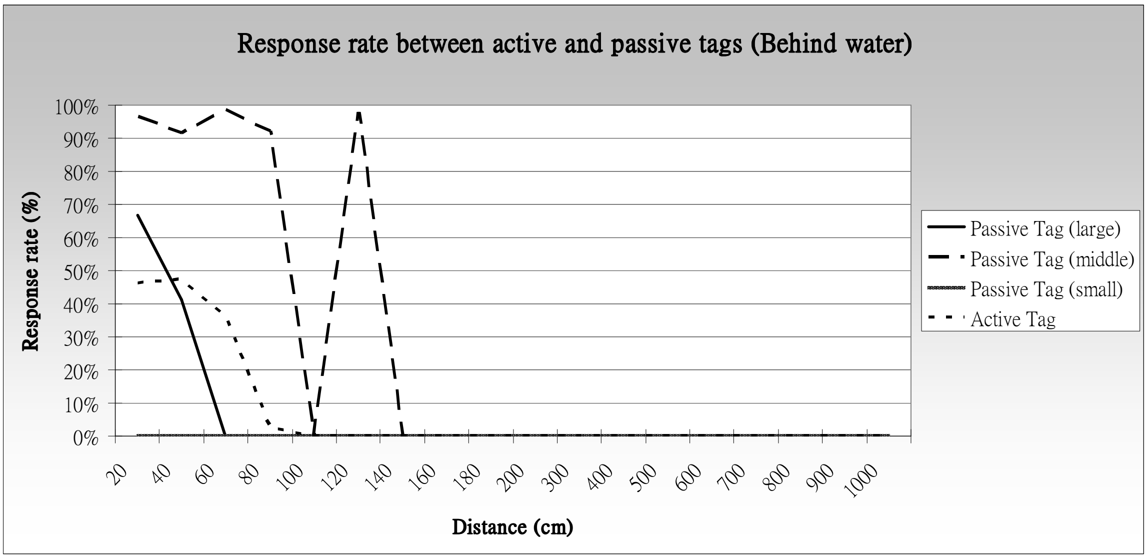
B4.5 In front of the water bottle

	Total Read in 1 Min (Active)						Total Read in 1 Min (Passive large)						Total Read in 1 Min (Passive middle)						Total Read in 1 Min (Passive small)					
Distance (cm)	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
20	1200	900	1100	1300	1100	1120	970	974	985	974	956	971.8	641	666	639	653	662	652.2	0	0	0	0	0	0
40	1900	2000	1950	1850	1900	1920	960	964	962	959	963	961.6	645	651	644	653	643	647.2	0	0	0	0	0	0
60	1950	1850	1700	2000	2000	1900	964	952	956	958	961	958.2	929	918	938	927	946	931.6	0	0	0	0	0	0
80	2100	2300	2200	2200	2100	2180	603	586	589	598	597	594.6	967	974	968	964	966	967.8	0	0	0	0	0	0
100	2000	1900	2100	2300	1900	2040	0	0	0	0	0	0	717	726	729	710	706	717.6	0	0	0	0	0	0
120	2400	2550	2500	2400	2400	2450	0	0	0	0	0	0	709	725	727	724	726	722.2	0	0	0	0	0	0
140	2100	2150	2200	2350	2500	2260	0	0	0	0	0	0	845	837	848	848	842	844	0	0	0	0	0	0
160	2250	2200	2300	2300	2400	2290	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	2650	2550	2750	2700	2600	2650	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
200	2650	2500	2600	2700	2500	2590	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	1800	1700	1900	1850	1750	1800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
400	1700	1800	1700	1850	1900	1790	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
500	1100	950	1100	950	980	1016	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
600	350	257	280	300	370	311.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
700	370	300	450	400	300	364	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
800	800	780	700	700	650	726	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
900	200	275	280	290	300	269	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	57	87	54	20	54	54.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



B4.6 Behind the water bottle

	Total Read in 1 Min (Active)						Total Read in 1 Min (Passive large)						Total Read in 1 Min (Passive middle)						Total Read in 1 Min (Passive small)					
Distance (cm)	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
20	1200	1300	1200	1250	1300	1250	639	683	684	671	660	667.4	971	963	960	964	962	964	0	0	0	0	0	0
40	1300	1300	1250	1200	1350	1280	402	409	428	415	403	411.4	920	914	919	905	915	914.6	0	0	0	0	0	0
60	1100	950	1000	900	950	980	0	0	0	0	0	0	982	986	988	986	985	985.4	0	0	0	0	0	0
80	80	100	70	38	40	65.6	0	0	0	0	0	0	912	918	926	935	916	921.4	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0	979	980	979	980	980	979.6	0	0	0	0	0	0
140	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



Appendix C - Results from the GA experiments

Table C.1 – Performances at p_{cross} = 0.8 and 0.9, p_{mut} = 0.0015 and 0.03, population size = 100 and generation = 500

GA parameters				Average	Standard Deviation	Best Result
Probability of Crossover	Probability of Mutation	Population size	Generations			
0.8	0.0015	100	500	85.07	35.34	49.23
0.8	0.03	100	500	83.63	36.12	46.01
0.9	0.0015	100	500	84.98	36.34	44.67
0.9	0.03	100	500	85.09	35.76	48.33

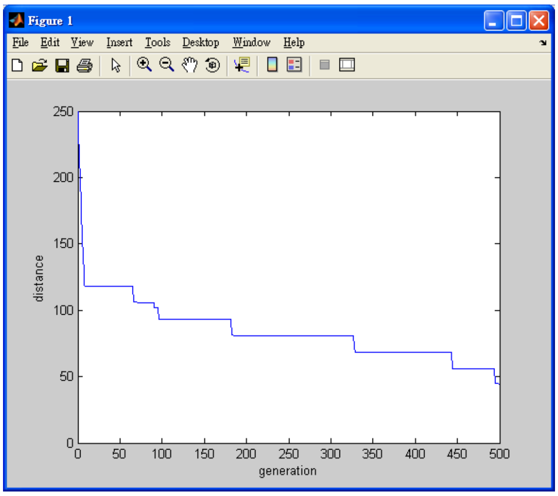


Figure C.1 – Fitness value at p_{cross} = 0.8, p_{mut} = 0.0015, and generation = 500

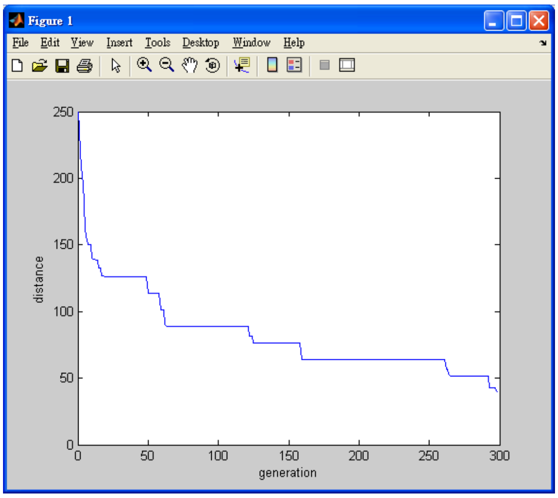


Figure C.2 – Fitness value at p_{cross} = 0.8, p_{mut} = 0.03, and generation = 500

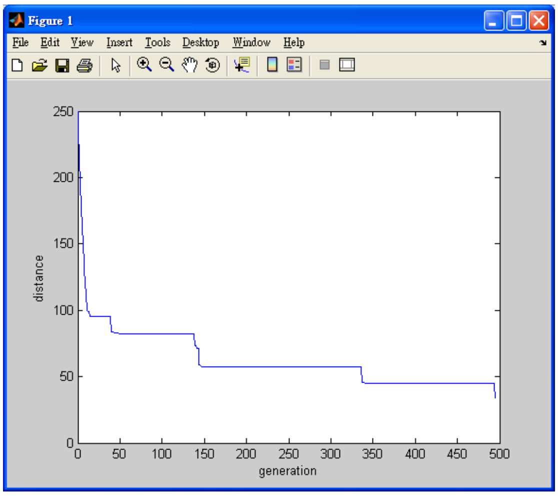


Figure C.3 – Fitness value at p_{cross} = 0.9, p_{mut} = 0.0015, and generation = 500

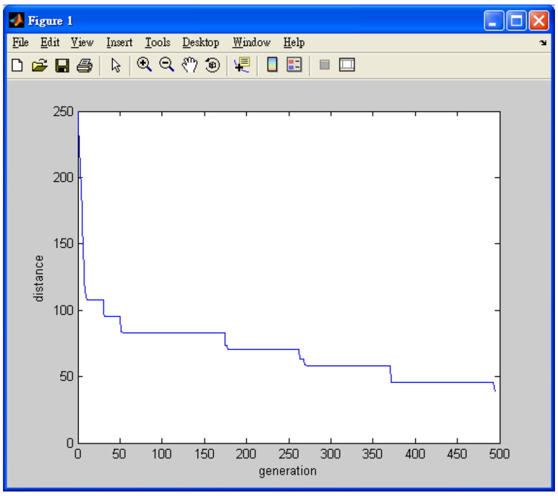


Figure C.4 – Fitness value at p_{cross} = 0.9, p_{mut} = 0.03, and generation = 500

Table C.2 – Performances at p_{cross} = 0.8 and 0.9, p_{mut} = 0.0015 and 0.03, population size = 100 and generation = 1000

GA parameters				Average	Standard Deviation	Best Result
Probability of Crossover	Probability of Mutation	Population size	Generations			
0.8	0.0015	100	1000	66.71	28.21	38.99
0.8	0.03	100	1000	64.54	29.03	36.15
0.9	0.0015	100	1000	66.35	27.89	36.33
0.9	0.03	100	1000	65.52	28.52	37.02

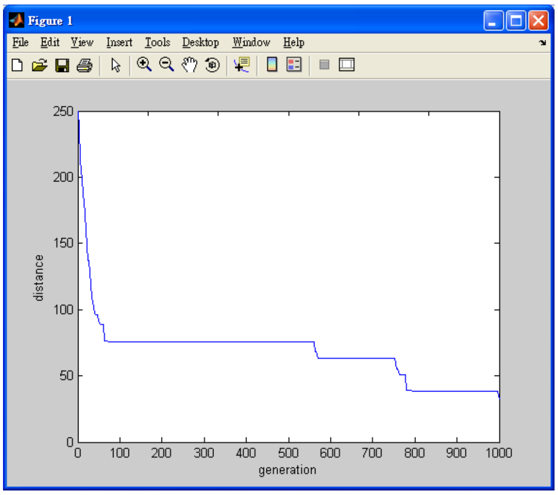


Figure C.5 – Fitness value at p_{cross} = 0.8, p_{mut} = 0.0015, and generation = 1000

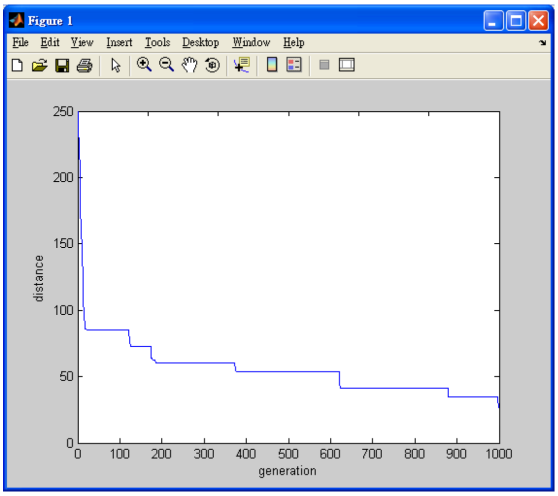


Figure C.6 – Fitness value at p_{cross} = 0.8, p_{mut} = 0.03, and generation = 1000

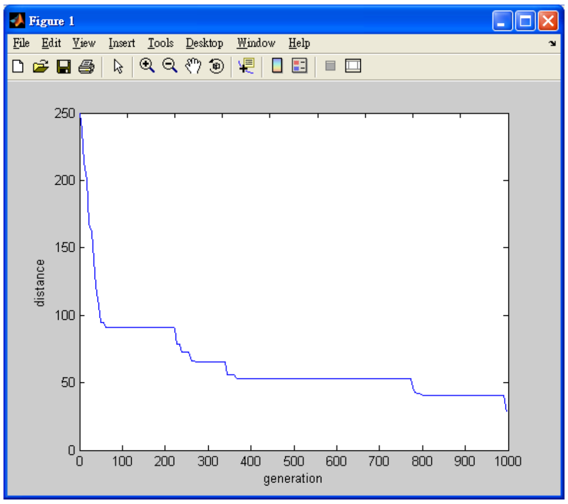


Figure C.7 – Fitness value at p_{cross} = 0.9, p_{mut} = 0.0015, and generation = 1000

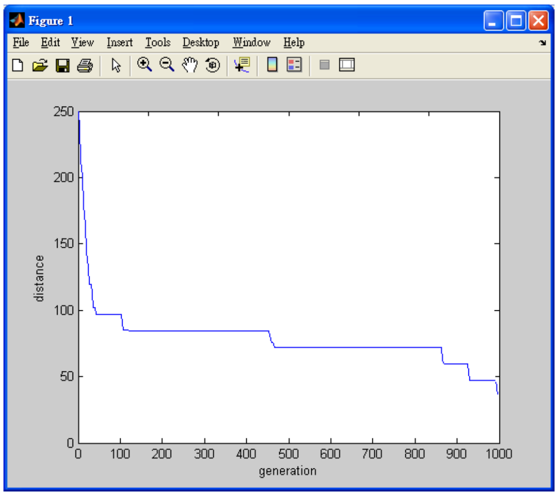


Figure C.8 – Fitness value at p_{cross} = 0.9, p_{mut} = 0.03, and generation = 1000

Table C.3 – Performances at p_{cross} = 0.8 and 0.9, p_{mut} = 0.0015 and 0.03, population size = 100 and generation = 1500

GA parameters				Average	Standard Deviation	Best Result
Probability of Crossover	Probability of Mutation	Population size	Generations			
0.8	0.0015	100	1500	42.54	14.77	26.68
0.8	0.03	100	1500	41.99	15.03	27.95
0.9	0.0015	100	1500	42.89	13.46	26.41
0.9	0.03	100	1500	43.17	14.58	27.19

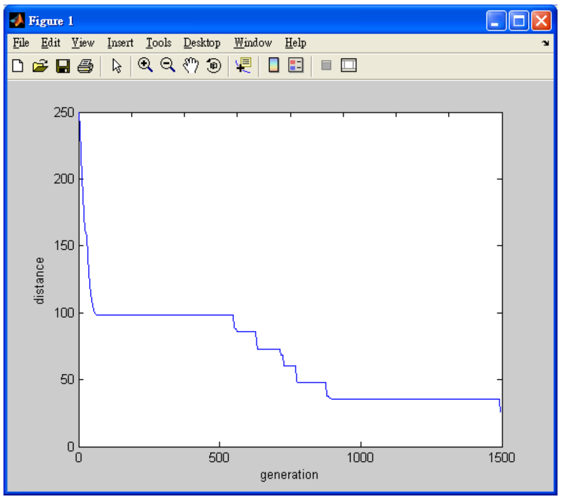


Figure C.9 – Fitness value at p_{cross} = 0.8, p_{mut} = 0.0015, and generation = 1500

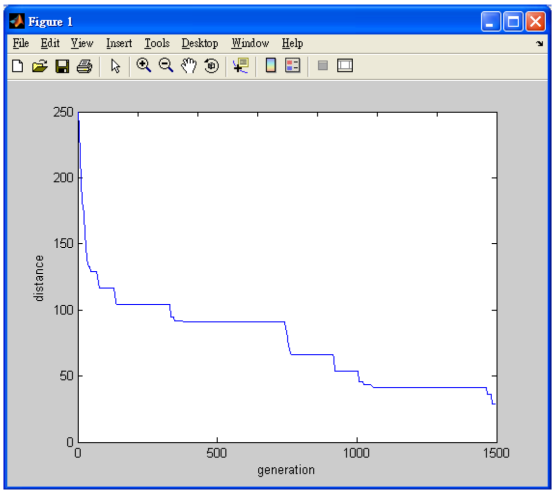


Figure C.10 – Fitness value at p_{cross} = 0.8, p_{mut} = 0.03, and generation = 1500

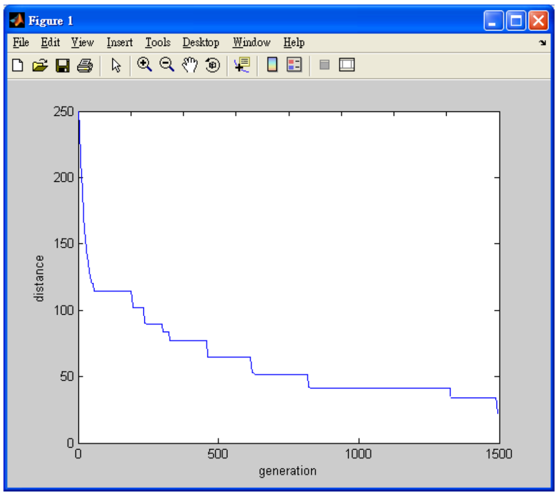


Figure C.11 – Fitness value at p_{cross} = 0.9, p_{mut} = 0.0015, and generation = 1500

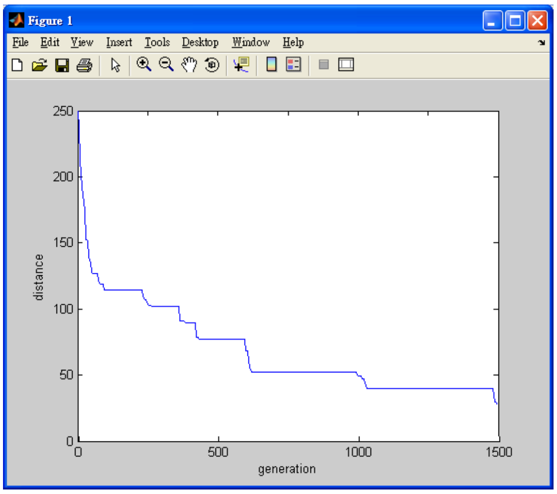


Figure C.12 – Fitness value at p_{cross} = 0.9, p_{mut} = 0.03, and generation = 1500

Table C.4 – Performances at p_{cross} = 0.8 and 0.9, p_{mut} = 0.0015 and 0.03, population size = 100 and generation = 2000

GA parameters				Average	Standard Deviation	Best Result
Probability of Crossover	Probability of Mutation	Population size	Generations			
0.8	0.0015	100	2000	30.08	9.43	19.23
0.8	0.03	100	2000	31.11	7.62	18.05
0.9	0.0015	100	2000	25.62	8.57	14.84
0.9	0.03	100	2000	24.99	7.99	17.45

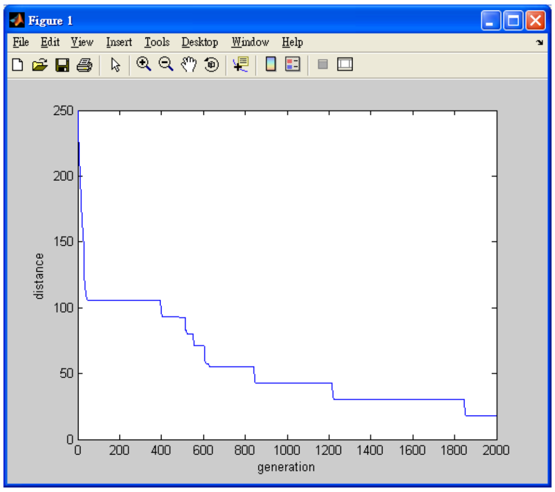


Figure C.13 – Fitness value at p_{cross} = 0.8, p_{mut} = 0.0015, and generation = 2000

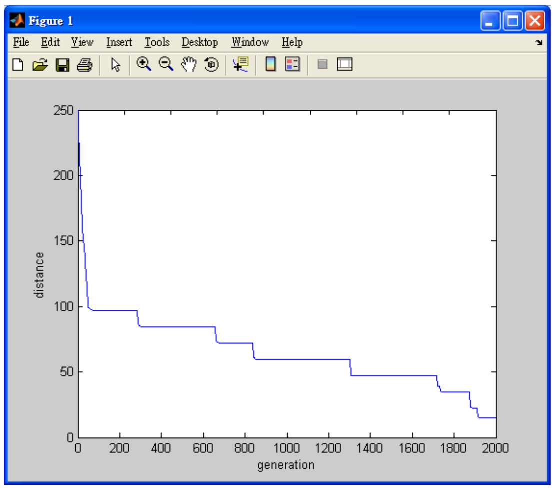


Figure C.14 – Fitness value at p_{cross} = 0.8, p_{mut} = 0.03, and generation = 2000

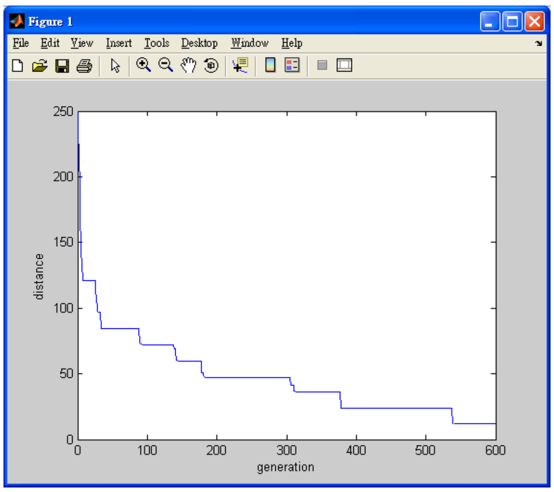


Figure C.15 – Fitness value at p_{cross} = 0.9, p_{mut} = 0.0015, and generation = 2000

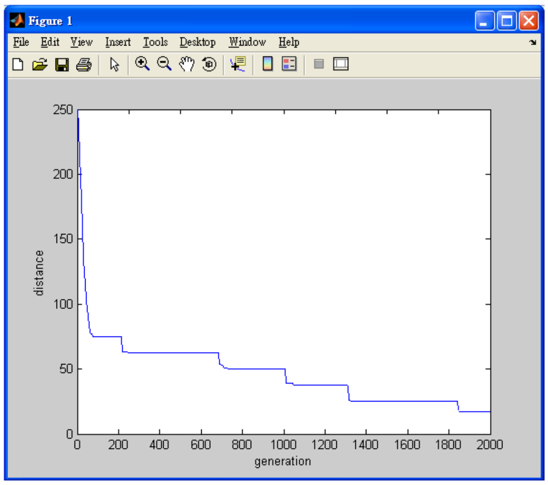


Figure C.16 – Fitness value at p_{cross} = 0.9, p_{mut} = 0.03, and generation = 2000

Appendix D – Scripts for two-layered algorithm

Script for Layer 1

```
function [STR_GA1_sol_pop, STR_GA1_sol_phi, min_GA1_phi, generation_phi,
termin_count, computational_time, FCFS_phi, Forkop ,Prepop] =
STR_GA1_main(num_pops, max_GA1_iters, conver_GA1_rate, STR_GA1_pop,
num_poarea, num_out, num_in, num_outorders)
prob_cross = 0.7;

%      generation_phi[][1] // column vector
terminated = 0;
count_iter = 0;
delta_iter = 30;
generation_phi = zeros(max_GA1_iters+1, 1);
variance_phi = zeros(max_GA1_iters+1,1);
pop_index = [1:1:num_pops];

fprintf('Start Initialization\n');
%fprintf('The population size of STR-GA1 is %3d\n',num_pops);
[sol_phi, operationtime] = initial_GA1_phi(num_pops, STR_GA1_pop, num_poarea,
num_out, num_in, num_outorders);
generation_phi(1,1) = min(sol_phi(:,1));
variance_phi(1,1) = var(sol_phi(:,1));
FCFS_phi = sol_phi(1,1);
fprintf('End of Initialization\n');
chi = 0.7*log(2);
tic;
while (~terminated)
        count_iter = count_iter + 1;
        [pop_normalfitness] = normalize_GA1_fitness(sol_phi,num_pops);    % column
vector
        %pop_normalfitness
        [sorted_popindex] = sort_increasing( pop_index, pop_normalfitness); % row
vector
        %transition_matrices = zeros(floor(prob_cross*num_pops), num_poarea,
num_outorders);
        %transition_matrices = zeros(1, num_poarea, num_outorders);
```

```
%transition_phi = zeros(floor(prob_cross*num_pops), 1);
%transition_phi = 0.;
%num_accepted = 0;
%      generate transtion stage
%for (count1 = 1: (prob_cross*num_pops) )
crossover = 0;
%mutation_sites
if (rand2() > prob_cross)
        mutation_sites = STR_GA1_prob_mutation(variance_phi, sol_phi,
num_poarea, num_out + num_in, count_iter);
        if (mutation_sites > 0)
                %mutation_sites
                %fprintf('mutation!!!\n');
                selected_pop_index=ceil(num_pops*rand2());
                transition_matrix =
STR_GA1_mutation(STR_GA1_pop(selected_pop_index, :,:), mutation_sites,
num_poarea, num_out+num_in);
        else
                crossover = 1;
        end;
else
        crossover = 1;
end;
if (crossover)
        %fprintf('corssover!!!\n');
        %      zero type => randomly select; otherwise, select due to fitness
        [selected_pop_index] = STR_GA1_select_popindex(sorted_popindex,
pop_normalfitness, num_pops, 1);
        transition_matrix =
STR_GA1_crossover(STR_GA1_pop(selected_pop_index, :,:), num_poarea,
num_out + num_in);
end;
sum_abc = 0;
for (count_abc = 1: num_poarea)
        for (count_abc2 = 1: (num_out + num_in))
                sum_abc = sum_abc + abs(STR_GA1_pop(selected_pop_index,
count_abc,count_abc2) - transition_matrix(1,count_abc,count_abc2) );
        end;
```

```
        end;
        %sum_abc
        %if (sum_abc == 0)
        %       fprintf('failed in crossover and mutation!!!\n');
        %end;

        [phi, temp_operationtime] = STR_TA_main(transition_matrix, num_poarea,
num_out, num_in, num_outorders+num_in, num_outorders);
        % phi
        %generation_phi(count_iter, 1)
        if (phi < generation_phi(count_iter, 1) )
                %num_accepted = num_accepted + 1;
                STR_GA1_pop(sorted_popindex(1, 1), :, :) = transition_matrix(1, :, :);
                sol_phi(sorted_popindex(1, 1),:) = phi;
                operationtime(sorted_popindex(1,1),:,:) = temp_operationtime(:,:);      %
check the operation time
                %transition_matrices(num_accepted, :, :) = transition_matrix(1,:,:);
                %transition_phi(num_accepted,1) = phi
                %fprintf('Improved at iteration %3d!!!\n', count_iter);
        else
                if (phi >= generation_phi(count_iter, 1) )

                        limit_accept = exp( - (phi - generation_phi(count_iter, 1)) /
(chi*generation_phi(count_iter, 1)) );
                        if (rand2()<= limit_accept)
                                STR_GA1_pop(sorted_popindex(1, 1), :, :) =
transition_matrix(1, :, :);
                                sol_phi(sorted_popindex(1, 1),:) = phi;
                                operationtime(sorted_popindex(1,1),:,:) =
temp_operationtime(:,:);      % check the operation time
                                %fprintf('accepted the tolerance at iteration %3d!!!\n',
count_iter);
                                %fprintf('The deviation ratio = %12.6f\n',
(phi/generation_phi(count_iter, 1))-1.0);
                        %else
                                %fprintf('failed in acceptance\n');
                                %fprintf('The deviation ratio = %12.6f\n',
(phi/generation_phi(count_iter, 1))-1.0);
```

```
            end;
        end;
    end;
%end;

%      upadate the population
%for (count1 = 1 : num_accepted)
    %STR_GA1_pop(sorted_popindex(1, count1), :, :) =
transition_matrices(count1, :, :);
    %sol_phi(sorted_popindex(1, count1),:) = transition_phi(count1, 1);
%end;

%      check the termination condition
    generation_phi(count_iter+1,1) = min(sol_phi(:,1));
    variance_phi(count_iter+1,1) = var(sol_phi(:,1));
    fprintf('number of iterations %3d            Phi = %12.6f\n', count_iter,
generation_phi(count_iter+1,1) );
    if ( count_iter == max_GA1_iters)
        terminated = 1;
        termin_count = count_iter;
    else
        if( count_iter > delta_iter)
            slope =    ( generation_phi(count_iter - delta_iter+1,1) -
generation_phi(count_iter+1, 1) ) / ( generation_phi(count_iter+1,1) );
            %fprintf('The convergence slope = %12.6f\n',slope);
            if (slope <= conver_GA1_rate)
                terminated = 1;
                termin_count = count_iter;
            end;
        end;
    end;
end;
computational_time = toc;
%computational_time = -1;
%fprintf('The consumed time for smulation is %12.f\n',count_time);
%[pop_normalfitness] = normalize_GA1_fitness(sol_phi,num_pops);    % column
vector
%pop_normalfitness
```

```
[sorted_popindex] = sort_increasing( pop_index, sol_phi); % row vector
result_operationtime = operationtime(sorted_popindex(1,1),:,:);
[Forkop ,Prepop] = Evaulation_operationtime(result_operationtime);
min_GA1_phi = generation_phi(termin_count,1);
STR_GA1_sol_pop = STR_GA1_pop;
STR_GA1_sol_phi = sol_phi;
end
```

Script for Layer 2

```
function [completion_time2, timenodes, operationtime] =
STR_GA2_main(orders_chain, num_orders, num_outorders, updated_timenodes)
global num_forklifts;
global num_channels;
global order_numrws;
global order2fork_convertor;
global arrivaltime;
global rwtype_reg;
global order_rwtype;
operationtime = zeros(num_forklifts + num_channels, num_orders);
size_orders_chain = size(orders_chain,2);
completion_time2=ones(num_orders,1);
completion_time2=completion_time2.*Inf;
%potential = zeros(num_forklifts, 1);
potential = 0;
%normalfitness = zeros(num_forklifts,1);
timenodes = zeros(num_forklifts + num_channels, size_orders_chain);
%differences = zeros((num_forklifts + num_channels), size_orders_chain);

%      end of the initialization
origin_timenodes = updated_timenodes;
%origin_timenodes
%orders_chain

for (count1 = 1: size_orders_chain)
        orderID = orders_chain(1, count1);
        if (orderID <= num_outorders)
                %orderID
                %num_outorders
```

```
        %fprintf('active in STR-GA2\n');
        %tic
        max_iter = min ( (num_forklifts *    order_numrws(orderID,1) ) *
log(num_forklifts), 10);
        %     create the initial population of STR-GA2 for that orders
        [STR_GA2_pop] = initial_STR_GA2_pop2(num_forklifts, orderID);

        [potential(1, 1), timenodes(:, count1)] =
Evaluate_completion_time(STR_GA2_pop(1, :), orderID, num_outorders,
origin_timenodes);

        for (count_iter = 1: max_iter)
            [offspring] = STR_GA2_mutation2(orderID, num_outorders,
STR_GA2_pop, num_forklifts);
            [temp_phi, nodes, temp_op] = Evaluate_completion_time(offspring,
orderID, num_outorders, origin_timenodes);

            if (temp_phi<potential(1,1))
                potential(1,1) = temp_phi;
                STR_GA2_pop(1,:) = offspring(1,:);
                operationtime(:,orderID) = temp_op(:,1);       % count_operation
time
                timenodes(:, count1) = nodes(:,1);
                %fprintf('accepted mutation\n');
            end;
        end;

        completion_time2(orderID,1) = potential(1,1);
        origin_timenodes(:,1) = timenodes(:,count1);
        %toc
        %origin_timenodes
    else
        %origin_timenodes(:,1)
        %tic
        index = [1:1:num_forklifts];
        forkID = order2fork_convertor(orderID);
        rwtype=order_rwtype(orderID,1);
        % inbound order
```

```
        timenodes(:,count1) = origin_timenodes(:,1);
        completion_time = 0.;
        for (count_rw = 1 : order_numrws(orderID,1))
            vector = zeros(num_forklifts,1);
            for (countfork = 1: num_forklifts)
                vector(countfork, 1) = timenodes(countfork,1);
            end;
            [sort_index] = sort_increasing(index, vector);
            forkID = sort_index(1,1);
            pickup_time = max(timenodes(forkID, count1),
arrivaltime(forkID,1));
            completion_time = max(completion_time, pickup_time);
            timenodes(forkID, count1) = pickup_time + rwtype_reg(rwtype, 4);
            operationtime(forkID,orderID) = timenodes(forkID, count1) -
pickup_time;
        end;
        %for (count_abc = 1: num_forklifts)
        %       differences(count_abc,count1) = timenodes(count_abc,count1) -
origin_timenodes(count_abc,1);
        %end;
        %differences(:,count1)
        %operation = max(differences(:,count1))
        completion_time2(orderID,1) = completion_time;
        origin_timenodes(:,1) = timenodes(:,count1);

        %toc
    end;
    %fprintf('after count %3d th orders chain\n',count1);
    %origin_timenodes
end;
%fprintf('finished an order\n');
end
```