Enhancing the Performance of Automated Guided Vehicles Through Reliability, Operation and Maintenance Assessment

by

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Abstract

Automated guided vehicles (AGVs), a type of unmanned moving robots that move along fixed routes or are directed by laser navigation systems, are increasingly used in modern society to improve efficiency and lower the cost of production. A fleet of AGVs operate together to form a fully automatic transport system, which is known as an AGV system. To date, their added value in efficiency improvement and cost reduction has been sufficiently explored via conducting in-depth research on route optimisation, system layout configuration, and traffic control. However, their safe application has not received sufficient attention although the failure of AGVs may significantly impact the operation and efficiency of the entire system. This issue becomes more markable today particularly in the light of the fact that the size of AGV systems is becoming much larger and their operating environment is becoming more complex than ever before. This motivates the research into AGV reliability, availability and maintenance issues in this thesis, which aims to answer the following four fundamental questions: (1) How could AGVs fail? (2) How is the reliability of individual AGVs in the system assessed? (3) How does a failed AGV affect the operation of the other AGVs and the performance of the whole system? (4) How can an optimal maintenance strategy for AGV systems be achieved?

In order to answer these questions, the method for identifying the critical subsystems and actions of AGVs is studied first in this thesis. Then based on the research results, mathematical models are developed in Python to simulate AGV systems and assess their performance in different scenarios. In the research of this thesis, Failure Mode, Effects and Criticality Analysis (FMECA) was adopted first to analyse the failure modes and effects of individual AGV subsystems. The interactions of these subsystems were studied via performing Fault Tree Analysis (FTA). Then, a mathematical model was developed to simulate the operation of a single AGV with the aid of Petri Nets (PNs). Since most existing AGV systems in modern industries and warehouses consist of multiple AGVs that operate synchronously to perform specific tasks, it is necessary to investigate the interactions between different AGVs in the same system. To facilitate the research of multi-AGV systems, the model of a three-AGV system with unidirectional paths was considered. In the model, an advanced concept PN, namely Coloured Petri Net (CPN), was creatively used to describe the movements of the AGVs. Attributing to the application of CPN, not only the movements of the AGVs but also the various operation and maintenance activities of the AGV systems (for example, item delivery, corrective maintenance, periodic maintenance, etc.) can be readily simulated. Such a unique technique provides us with an effective tool to investigate larger-scale AGV systems. To investigate the reliability, efficiency and maintenance of dynamic AGV systems which consist of multiple single-load and multi-load AGVs traveling along different bidirectional routes in different missions, an AGV system consisting of 9 stations was simulated using the CPN methods. Moreover, the automatic recycling of failed AGVs is studied as well in order to further reduce human participation in the operation of AGV systems. Finally, the simulation results were used to optimise the design, operation and maintenance of multi-AGV systems with the consideration of the throughputs and corresponding costs of them.

The research reported in this thesis contributes to the design, reliability, operation, and maintenance of large-scale AGV systems in the modern and rapidly changing world.

Keywords: Automated Guided Vehicles, Petri Nets, Reliability, Maintenance, Coloured Petri Nets, Fault Tree Analysis, Simulation, Optimisation

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Publications

Journal papers

(1) R. Yan, L. M. Jackson, S. J. Dunnett, Automated guided vehicle mission reliability modelling using a combined fault tree and Petri net approach, International Journal of Advanced Manufacturing Technology, 92(5-8): 1825–1837, 2017.

(2) R. Yan, S. J. Dunnett and L. M. Jackson, Novel methodology for optimising the design, operation and maintenance of a multi-AGV system, Reliability Engineering & System Safety, 178: 130-139, 2018.

Conference papers

(1) R. Yan, S. J. Dunnett and L. M. Jackson, Reliability Modelling of Automated Guided Vehicles by the Use of Failure Modes Effects and Criticality Analysis, and Fault Tree Analysis, 5^{th} Student Conference on Operational Research, University of Nottingham, UK, 2016.

(2) R. Yan, S. J. Dunnett and L. M. Jackson, Reliability modelling of automated guided vehicles using Petri nets, 2016 European Safety and Reliability Conference, Glasgow, UK, 2016.

(3) R. Yan, S. J. Dunnett and L. M. Jackson, Optimising the maintenance strategy for a multi-AGV system using genetic algorithms, 2018 European Safety and Reliability Conference, Trondheim, Norway, 2018.

(4) R. Yan, S. J. Dunnett and L. M. Jackson, Maintenance modelling of complex automated guided vehicle systems, The Annual Reliability and Maintainability Symposium, Florida, USA, 2019.

Completed Papers (ready for submission)

(1) R. Yan, L. M. Jackson, S. J. Dunnett, New comparison methodology for the performance evaluation of multi-load and single-load automated guided vehicles.

(2) R. Yan, L. M. Jackson, S. J. Dunnett, A stochastic simulation model for optimising automated guided vehicle systems with reliability considerations.

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Nomenclature

$A_{\mathrm{i,j}}$	Basic failure event A occurred in any phases from i to j
A_{i}	Basic failure event A occurred in phase i
C_A	Capital cost of an AGV per year (£)
C_R	Route cost per year (£)
C_c	Average cost of each AGV corrective maintenance (£)
C_e	Cost of one onsite engineer in a year (£)
C_{ms}	Business costs of a maintenance site per year (£)
C_p	Periodic maintenance cost per AGV (£)
D_i	Detectability of the failure
E	A finite set of transitions
F	Cumulative distribution function
F_i	Failure frequency
G_i	Criticality function
I_C	Fussell-Vesely Importance Measure for Cut Set
I_{CM_i}	Criticality Measure of Importance
L_A	Loading capacity of AGVs
M	Net marking
M_r	The final marking after r transitions
M_0	The initial marking of the net
M_1	The resultant marking
N_A	Number of AGVs
N_{BA}	Number of backup AGVs
N_E	Number of maintenance engineers on site
N_F	Total number of failures occurring in the system per year
N_p	Number of periodic maintenances per year
N_t	Number of tasks completed
OT_i	Total operation time of i
PF_j	System failure in phase j
P_j	Failure probability of phase j
Q_i	Probability of failure up to the end of phase i
Q_{sys}	System unreliability
R_w	Unit route width
S_i	Severity level
T	Operation time (Hours)
T_p	Time interval of periodic maintenance
T_r	Repair time (Hours)
w	Weighting factor

X_{nw}	Number of items delivered without waiting time
X_w	Number of items delivered with waiting time
X_z	Number of items delivered within one zone
f_i	Fitness of i-th individual
$q_{A_{i,j}}$	Probability of failure of basic event A in all phases from i to j
ΔEff	Improvement of system efficiency
η	Operational efficiency
λ	Failure rate (failures / year)

Acronyms

AGV	Automated Guided Vehicle
AHSPN	AGV Health State Petri Net
ASCS	AGV Software Control System
BBN	Bayesian Belief Networks
CMPN	Corrective Maintenance Petri Net
COPN	Component Petri Net
CPN	Coloured Petri Net
CROPN	Coloured Resource-Oriented Petri Net
CS	Cut Set
CV	Computer Vision
DAPN	Conflict Detection and Avoidance Petri Net
DC	Direct-Current Motor Drive Unit
FCFS	First Come First Served
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FTA	Fault Tree Analysis
GA	Genetic Algorithm
GPS	Global Positioning System
HPC	High-Performance Computing
LIDAR	Light Detection and Ranging
LNS	Laser Navigation System
MCS	Minimum Cut Set
MFOP	Maintenance-Free Operational Period
MHIA	Material Handling Industry of America
MPN	Master Petri Net
PaPN	Path Petri Net
PDF	Probability Density Function
PLC	Programmable Logical Controller
PMPN	Periodic Maintenance Petri Net
PN	Petri Net
PPN	Phase Petri Net
RePN	Recycle Petri Net
RFAPN	Recycle of Failed AGV Petri Net
RoPN	Route Petri Net
RTPN	Reroute Petri Net
SPN	Subsystem Petri Net
STO	Shentong

1 Introduction

1.1 Background

The concept of Automated Guided Vehicle (AGV), which runs along a predefined route to perform prescribed tasks without the involvement of an on-board operator, was first introduced in 1955 [1]. Due to the great potential of the AGV in improving the production efficiency & safety and lowering the production costs, since then a variety forms of AGVs have been developed and increasingly used for intelligent transportation and distribution of goods or materials in support of industrial or commercial production lines and distribution applications, such as printing, manufacturing and hospitals. Some of them are shown in Figure 1.1, where the images are copied from [2]. In 2016, the global AGV market size was estimated at USD 1.12 Billion [3] while the total industrial vehicle market was valued at USD 25.66 Billion [4]. There is no doubt that the market share of AGVs will grow enormously in the next few years with the rising demand for automation. This can be easily inferred from the increasing tendency of the number of AGVs being produced globally. In 2015, there are only 14,000 AGVs were produced globally. This figure rises to 37,000 AGVs in 2018. Moreover, such an increasing tendency does not show any sign of declining in the coming years [5]. The growth of e-commerce is one of the major drivers of the growth of the AGV market. At present, Europe is temporarily the world's largest market of AGVs. But it is predicted that the Asia-Pacific region will overtake Europe to lead the AGV market in the near future because some of the world's fastest developing economies, such as China and India, are located in this region [3].

As mentioned earlier, to date there have been a variety of forms of AGVs were developed to meet the needs in different applications. But according to their functions, they can be roughly divided into three categories, i.e. unit load AGVs, towing AGVs, and automated forklift AGVs [2].

(a) Hospitals

(b) Printing

(c) Manufacturing

Figure 1.1 Applications of AGVs [2]

- **Unit load AGVs** can transport goods on forks or decks. They are able to carry a discrete load, such as a large roll of paper, packed materials or an automobile engine as shown in Figure 1.1(a) and 1.1(b). This type of AGVs is ideal for performing repetitive actions.

- **Towing AGVs**, as shown in Figure 1.1(c), have the ability to transfer more loads by towing more than one trailer, each carrying a discrete load. However, towing vehicles involve more human interactions since operators must repeatedly transfer loads or connect trailers to AGVs. Consequently, they are often challenged in terms of efficiency improvement. A well-designed system is required to have maximum productivity with the highest safety and efficiency.

- **Automated forklift AGVs**, see Figure 1.2, have a forklift truck attached so that the AGVs can take loads stored at higher levels with unmanned operation. This reduces the interactions between AGVs and operators and makes automated forklift AGVs be the most popular type of AGVs. Since this type of AGVs has versatile functions, so far, they have been used in a number of different applications, such as trailer loading/unloading, warehousing and so on [6].

Figure 1.2 Forklift AGVs [6]

AGVs can also be customised to meet specific design and operation requirements by taking several features together. In this case, they are known as hybrid AGVs. They can have either fully automatic or manual operation for handling material transport. In addition, they can possess multiple functions, such as towing, lifting, loading and unloading or even automatic Radio-Frequency Identification (RFID) bar code scanning and reading [2]. For example, the company, 'Dematic', the world's largest AGV supplier, developed their own hybrid AGV. Their AGV provides fully automatic laser guidance and manual material handling transport, automatic trailer loading and unloading, automatic battery charging, and other advanced technologies [7]. Therefore, hybrid AGVs are ideal to deal with those more complex tasks. But it is worth noting that the operation of hybrid AGVs always requires a more complex control system that is very difficult to achieve. Hence, the research and development of hybrid AGVs is still ongoing, which is attracting increasing interest today. A fleet of AGVs operates synchronously to form a fully automatic transport system, which is known as an AGV system.

1.2 AGV Specifications

All AGVs have some components and subsystems in common. For example, a motor is required to provide movement; a power source, usually a battery, is required to provide power for the other AGV components; appropriate safety systems are also essential to avoid collisions with people and obstacles. The safety of AGVs is regulated by BS EN 1525:1998 “Safety of industrial trucks. Driverless trucks and their systems” in the UK [8]. The Automated Guided Vehicle System Industry Group of the Material Handling Industry of America (MHIA) released a safety standard for driverless, automatic guided industrial vehicles and automated functions of manned industrial vehicles in 2012 [9]. This standard defines the safety requirements relating to the elements of design, operation, and maintenance of automatic guided industrial vehicles. These standards are being continually updated to accommodate the developments of new technologies on AGVs and AGV systems.

The specifications of the AGVs for the application in different operating environments will be different. For example, the capacity of an AGV should at least 40 tonnes in order to transport containers in a dock. However, only up to 1-tonne capacity is required for the transport of goods in a distribution center. Besides capacity, other specifications including lift height, travel speed, and guidance type should be considered as well. In brief, despite the types of AGVs, they all need to work in an orderly fashion to transport items or materials from one location to another. Therefore, a transportation network connecting all stationary installations must be designed. The AGVs operating in the same network will run on the pre-designed paths and are navigated using different technologies such as guide tape, laser targeting, wired and vision guidance. The design of such transportation networks is known as flowpath design [10, 11].

1.3 Research Motivations

As the number of AGVs in individual AGV systems is increased gradually and the application of AGVs is extended to more areas, their efficiency and operation have naturally become a priority issue to be addressed via identifying new flow-path layouts and developing more advanced traffic management strategies (e.g. vehicle routing) [10]. For this reason, previous research effort in the AGV area was mainly focused on route optimisation and traffic management. For example, Giuseppe established an approach in 2013 to optimise the flow-path such that the average time for carrying out transportation tasks can be minimised and the utilisation degree of AGVs can be maximised at the same time [12]; Wu and Zhou created a simulation model to avoid collisions, deadlock, blocking and minimise the route distance as well with a coloured resource-oriented Petri Net [13]. However, to date, little effort has been made to investigate the safety and reliability issues of the AGV components and subsystems as well as their probability of success in completing prescribed missions. Although Fazlollahtabar created a model recently to maximise the total reliability of the AGVs and minimise the repair cost of AGV systems [14], the AGV was considered as a whole in the model. Consequently, some fundamental questions, such as 'How does AGVs fail?' and 'What is the probability of an AGV developing fault?' have not been answered. To answer these questions, Duran et al. tried to identify the basic failure modes of the light detection and ranging (LIDAR) system and the camera-based computer vision (CV) system on AGVs in 2013 by the approach of Fault Tree Analysis (FTA) and Bayesian Belief Networks (BBN) [15]. In their work, human injury, property damage, and vehicle damage were defined as the top events in the fault tree. However, the failures of many individual AGV components and subsystems are not included in the fault tree developed by them.

A further literature review has shown that, to date, scant attention has been paid to the reliability and availability issues of AGVs. Although these issues have been significantly improved by replacing the manual vehicles with AGVs thereby minimising the possibility of operator error, new potentially serious hazards may be present in the application of AGVs due to software and hardware errors. Moreover, the reliability issues and maintenance strategy could vary for different AGVs and AGV systems due to the difference in AGV specifications. So, it is of great significance to have a full understanding of the effects of the failures of the AGV component, subsystems and working phases on the reliability of AGVs and AGV systems. In most of AGV systems, the failed AGVs have to be towed back by a human operator, so the system cannot be seen as full automation [16]. Moreover, the maintenance and failure management issues of AGV systems were not yet properly studied before due to the limited application of AGVs. However, the use of AGVs has become very popular today and moreover, modern AGV systems are becoming more complex and larger in structure for delivering complicated tasks. The reliability and availability of AGVs is becoming a matter of concern worthy to study. This explains why the reliability and availability issues of modern AGVs are receiving more concerns than ever before.

1.4 Reliability and Maintenance Methods

Since no equipment has an absolute zero failure rate, reliability improvement has arisen as a natural consequence of analysis throughout the history of engineering. As industries realised that the practice of learning by mistakes was not acceptable, after learning the lessons from many accidents, some methods have been developed for identifying and predicting failures and hazards. System reliability analysis, using Failure Mode Effect Analysis (FMEA) and Fault Tree Analysis (FTA) methods, has been developed over the last 50 years. The long-term practice has proved that the FMEA is a powerful tool to systematically analyse engineering systems by identifying potential failure modes and examining the corresponding effects on the system [17]. On the other hand, FTA has been widely adopted in industrial practice to evaluate engineering systems [17]. It is a top-down deductive approach for explaining the occurrence of an undesirable event by considering an array of component failure modes. The combined use of FMEA and FTA not only enables the analysis of the failure modes of all AGV subsystems but also enables the analysis of the chance that whether an AGV mission can be successfully completed. However, both methods show limitations in the analysis of AGV systems. For example, they are only able to analysis a single AGV, however most modern AGV systems contain multiple AGVs [10]. The practice has shown that the failure of an individual AGV in a multi-AGV system will not only lead to the failure of a mission but will also block the path where the other AGVs in the system may need to use to reach their targets. Therefore, in order to further investigate the effect of system layout, number and capacity of AGVs, dispatch rule and route optimisation of AGVs, and maintenance of AGVs on the system performance, a more advanced methodology should be adopted. Petri Net (PN) provides an effective tool to achieve this purpose [18]. It enables not only the analysis of all failure modes of all the subsystems but also an analysis of the mission of AGVs and AGV systems. In addition, the PNs can be easily modified if the mission changed.

With the aid of these methods, the criticality of individual AGV subsystems and components can be assessed and, the reliability and availability of the AGVs can be improved by optimising the design configuration and the maintenance strategy of the AGV system.

1.5 Research Aim and Objectives

To fulfil the need of continual scaling up and modernisation of AGV systems whilst maintaining high reliability and availability levels of them, the aim of the research reported in this thesis is to develop a detailed and systematic approach to evaluate the reliability of AGV systems and also ensure their availability by optimising the corresponding maintenance strategies. Firstly, preliminary research is conducted for identifying the critical risks of key AGV subsystems and the crucial mission phases in the operation of a single-AGV system by using advanced reliability analysis techniques and simulation methods. Then, a basic multi-AGV system consisting of three AGVs and three stations is investigated as an example for developing a scientific methodology for optimising the layout design, operation and maintenance of a multi-AGV system. Following that, a more complex multi-AGV system is studied in order to understand the situation of the AGV systems in real-life applications such as in warehouse environment and flexible manufacturing systems.

The above research purposes will be reached by successfully achieving the following objectives:

1. Understand the failure modes of key AGV subsystems.
2. Investigate the relationships between AGV subsystem failures and mission failures. Furthermore, use advanced techniques to investigate the reliability of AGVs and identify the critical risks of the AGV subsystems that are very likely to happen and can cause serious consequences. Then based on the research results, further identify the key mission phases in which the AGV is more likely to fail than in other phases of the operation of a single-AGV system.
3. Based on Objective 2, develop the simulation models for multi-AGV systems. Then, use the developed models to assess the performance of the multi-AGV systems and the influence of individual AGVs' reliability on it.
4. Investigate the influence of AGVs' loading capacity on the performance of AGV systems.
5. Optimise the design, operation and maintenance of a multi-AGV system with the consideration of both performance and cost of the system.
6. In-depth research on the adaptability and capability of PN-based simulation technology in dealing with more complex AGV systems.

Through conducting the above research, it is believed that we will have a better understanding of not only the reliability and availability issues of the AGVs and AGV systems but also the appropriate operation and maintenance strategies of them.

1.6 Thesis Outline

The thesis is composed of the following Chapters:

In Chapter 2, a literature review is conducted for understanding the necessary background information, and the research history about AGVs and AGV systems. In order to align the effort of the literature review to the research purpose of this thesis, the research on performance criteria, reliability and maintenance of AGV systems are particularly discussed in detail. Through conducting this literature review, the problem domain and the motivations behind it are well understood.

In Chapter 3, the research methodology adopted in this thesis is proposed and the reasons of choosing different methods are also discussed.

In Chapter 4, the fundamental research is conducted for identifying the critical AGV subsystems and the working phases in the missions of an AGV in a single AGV system by using Failure Mode, Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA). In the meantime, the limitations of FTA in dealing with the issues in complex dynamic systems are discussed. This serves as one of the most important reasons for selecting PN simulation modelling as an alternative tool in further research. The PN simulation results are validated by comparing them with the analytical results obtained from FTA. From the research described in Chapter 4, it is found that PN simulation is more efficient and adaptive than analytical approaches, particularly in dealing with complex dynamic systems.

In Chapter 5, the single AGV system is adapted to a multi-AGV system by extending the PN model to the CPN model, which enables the simulation of the AGVs with different missions. By increasing the number of AGVs from one to three while scaling up the system size at the same time, the research has demonstrated the applicability of CPN models to the simulation of more complex industrial applications.

In Chapter 6, the potential advantages of increasing the loading capacity of an AGV over increasing the number of AGVs are investigated. In addition, several dispatch rules set especially for the multi-load AGVs are simulated and their performances are compared in the same system.

In Chapter 7, multiple multi-load AGVs are simulated in a rigid AGV system layout with 9 stations. The interactions between the vehicles are considered. More realistic factors including rerouting policy of AGVs blocked by failed AGVs and onsite and offsite maintenance are also investigated. Moreover, the AGV systems with and without failure consideration are also developed to highlight the impact of the failure of individual AGVs on the performance of the whole AGV system.

In Chapter 8, a multi-objective optimisation using Genetic Algorithm (GA) is studied to improve the reliability and availability of AGV systems. The impact of AGV system layouts, different maintenance strategies such as periodic and corrective maintenance processes to the system performance is investigated.

In Chapter 9, the capabilities of the original model developed in Chapter 7 is dedicatedly extended to evaluate more complex AGV systems that consider irregular system layout, waiting time, or tandem system layout. In the end, the simulation results of several scenarios are demonstrated and discussed.

In Chapter 10, the thesis is concluded by summarising the research outcomes and key contributions of this thesis to the reliability and AGV field. Following this, further research that needs to be conducted in the future in this area is suggested.

2 Literature Review

2.1 Overview

In the past decades, much effort has been made to improve the design and accelerate the application of AGVs. This chapter encompasses the literature that was reviewed in order to identify the research gaps still existing in this field today and then based on which to define the research methodology that will be taken in this thesis. To date, the research on AGVs and AGV systems has been approached from a variety of aspects, including: flowpath layout, vehicle scheduling, the number of vehicles required, battery management, vehicle routing, and deadlock resolution [10, 11]. In summary, these design parameters can be roughly classified into three decision-making levels, namely strategic, tactical and operational. For example, (1) the flowpath design is a strategic level problem that has significant influence on the performance of AGV systems; (2) the number of vehicles, vehicle scheduling, and battery management belong to a kind of lower tactical level problems that are for further optimising and enhancing the performance of AGV systems based on the given flowpath designs; (3) the vehicle scheduling, vehicle routing and deadlock resolution are regarded as operational level problems, the successful resolution of which is beneficial to improve the efficiency of AGVs via reducing the travel distance and waiting time of AGVs. However, the literature review has shown that, so far, the AGV failures and their impact on the performance of AGV systems have not been sufficiently studied previously. In the scenarios that there are only a few AGVs running in the system, the AGV failures may cause little congestion issue in the AGV system. However, when there are a large number of AGVs are in operation, their failures may cause serious traffic congestion and consequently affect the performance of AGV systems significantly. For this reason, the reliability and maintenance issues of AGVs are critical to the efficient operation of AGV systems. They should be studied particularly in the light of the fact that AGVs are being increasingly used in the various modern industries today. Thereby, one of the major purposes of this thesis is to fill this gap of technology by conducting elaborate research in the relevant field.

In order to further understand the state-of-the-art of AGV technologies, the relevant research about the aforementioned factors and their influences on the operational performance of AGV systems will be briefly reviewed in this chapter. In the remaining part of this chapter, available studies about flowpath layout and traffic management of AGV systems will be reviewed in Section 2.2.1; the studies about the performance criteria of AGV systems, dispatching and scheduling of AGVs, and AGV positioning will be reviewed respectively in Sections 2.2.2, 2.2.3, and 2.2.4; the loading capacity of AGV will be discussed in Section 2.3; the limited available research on battery management, reliability, availability and maintenance strategies of AGVs will be looked into in Sections 2.4 and 2.5, respectively. The identified knowledge gaps in AGV research are listed in Section 2.6. The state-of-the-art of the reliability analysis techniques and optimisation methods is reviewed in Section 2.7. Besides these, different research approaches including analytical, numerical, and experimental simulation methods and the relevant published works will also be mentioned in the literature review. The chapter will be finally concluded in Section 2.8, with the focus of the identified research gaps currently existing in the field of AGVs and AGV applications.

2.2 Design and Operation of AGV Systems

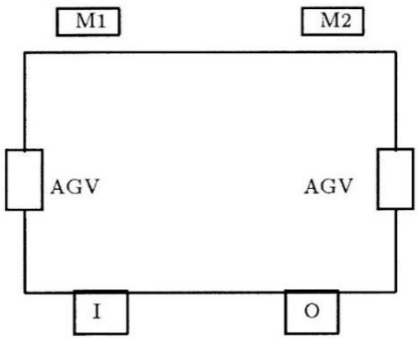
2.2.1 Flowpath Layout

Flowpath layout, also known as guidepath design, is one of the most important and priority issues to be considered in the design of an AGV system [10, 11]. It determines the route that the AGVs will follow during operation, thereby having a significant influence on the cost of material transportation. A flowpath layout defines the connections between stations, machines, target positions and other structures, which are usually assumed to be stationary or fixed and via them, the AGVs can reach desired pick-up and delivery points. However, it is worth noting that there is a difference between ‘flowpath’ and ‘guidepath’, i.e. the moving directions of AGVs on guidepaths are always fixed while their moving directions on flowpaths can be modified as required [19]. A successful flowpath layout design will enable the AGV system to have short AGV traveling distance and high efficiency, thereby saving both time and cost [10].

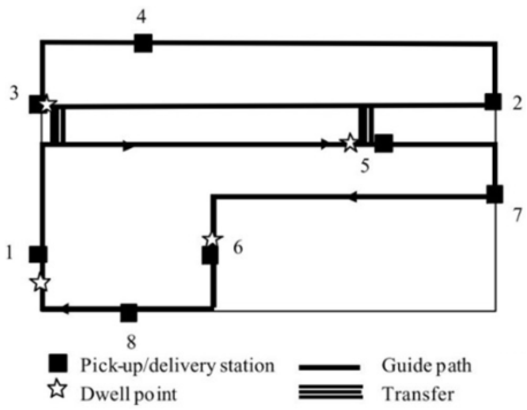
At present, there are three types of flow topologies that are popularly adopted in layout design. They are respectively single loop, tandem configuration, and conventional topology, as shown in Figure 2.1. In each layout design, AGVs can travel along the paths in either one direction (i.e. unidirectional) or in two directions (i.e. bidirectional). Among these designs, single loop is the simplest case, in which the flowpath consists of a single loop only [20]. A typical single loop layout is illustrated in Figure 2.1(a) [21]. Where, an AGV picks up raw material from the input point ‘I’ and carries the material to machine ‘M1’ for accepting processing for the first time. After the material is processed by machine ‘M1’, the AGV will carry the processed material to machine ‘M2’ for further processing. Finally, the AGV will carry the material after further processing to the output point ‘O’ and drop off the material there. After dropping off the material at the output point ‘O’, it is regarded that the AGV has finished the allocated job in the present cycle. Then, it will return to the input point ‘I’ from the output point ‘O’ and start a new cycle of job by repeating the loading and unloading process. In 1992, Tanchoco and Sinriech’s established a method to find the optimal single-loop flowpath design [20]. An integer programming formulation was employed to identify an initial valid loop. Following that, all possible valid single loop guidepaths will be identified by using an enumeration procedure. Finally, the optimal locations of the pick-up/delivery stations along a given loop are obtained by using a mixed integer programming formulation based on a from/to material flow matrix. As opposed to using more complicated guidepaths, the benefit of using a simple flowpath under light and average shop workload is that it can be easily realised with the aid of a simpler controller. However, it was found that the single loop layout is inefficient, and it will require more space and AGVs when the scale of the system and the required workload increase. Moreover, vehicle interference would be an issue when multiple AGVs travel at different speeds in the same single loop. Hence, the following two alternative flow topologies are developed in modern applications.

The tandem guidepath system was first introduced by Bozer and Srinivasan in 1991 [22]. According to [22], the tandem guidepath system usually consists of a few zones, but there is only one AGV operating in every zone. The zones are connected via transfer stations. In this way, the deadlock and conflict problems can be eliminated. Herein, deadlock refers to the situation where a part of the system stalls, i.e. the vehicle is blocked by other AGVs in an unsolvable situation [23]. Conflicts usually arise when several AGVs try to run on the same route or pass the same crossing points. These two factors have a huge impact on AGV speeds, expected travel time, and route planning. The concept of tandem guidepath system was further improved later on. For example, as shown in Figure 2.1 (b) [24], the tandem configuration consists of a few non-overlapping unidirectional loops. One or more AGVs can run in each loop and transfer between adjacent loops can be made through pre-designed transmission points [24]. Apparently, most deadlock and conflict problems can also be avoided in such a design. Farling et al. developed a typical tandem configuration, grouping together several single loops without overlapping [25]. In their work, the impact of different factors, including system size, number of loops in the tandem layout, load/unload time, failure rate of machines in the AGV system, and the tandem AGV systems performance with respect to the mean flowtime of AGVs, were investigated by the approach of simulation written using Arena® a popular simulator. The mean flow time is defined as the average amount of time it takes for jobs to complete their sequence through the system. The simulation results have disclosed that system size, load/unload time, and machine failure rate factors have significant influence on the operation of the AGV system. Moreover, it was found that the impact of the load/unload time on the performance of the systems considered in [25] can be mitigated by adding more loops to the traditional tandem configuration.

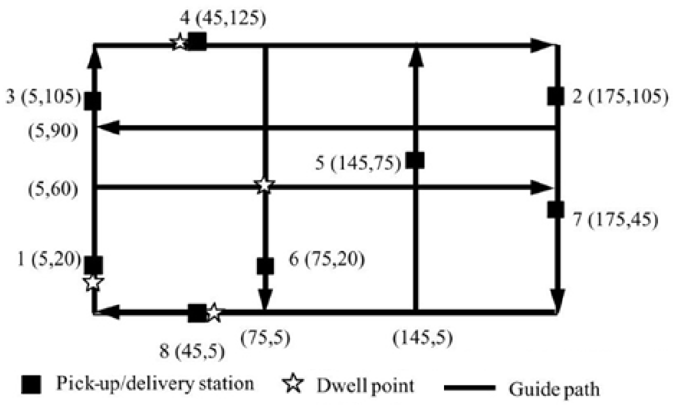
A conventional topology introduces more features, such as crosses and junctions, into the layout, as shown in Figure 2.1 (c) [26]. AGVs in conventional layouts are able to reach any targeted positions usually with more than one different routing options. The conventional flowpath system can be either unidirectional or bidirectional. The system with bidirectional paths is more complex but permits an improvement in efficiency, time and space saving [11]. However, the complexity of AGV systems with bidirectional networks increases enormously. Hence, problems like blocking, conflict, collisions, and deadlocks will arise more frequently in bidirectional applications [27]. The sudden occurrence of these problems may directly lead to the failure of the control system or even lead to physical hazards to the environment and humans. Deadlocks and collisions are usually not considered in the single loop tandem configuration because there is only one AGV operates in the zone.



(a) Single loop



(b) Tandem configuration



(c) Conventional topology

Figure 2.1 Flowpath layouts of AGV systems

More detailed description about the aforementioned flowpath layouts can be found from [21, 24, 26].

In 2007, Wu and Zhou studied the deadlock and blocking issues existing in bidirectional layouts [13]. They tried to construct the shortest route with the aid of coloured resource-oriented Petri Nets (CROPN) by prioritising the deadlock-free conditions. By setting the deadlock-free operation condition initially, the study provided a method to generate the route of AGVs without blocking. However, the model they constructed is a static model, which cannot precisely describe the operation of a real-life AGV system. To overcome this issue, Nishi and Tanaka tried a Petri Net decomposition approach in order to reach the same goal in dynamic environments [28]. The comparison with the results obtained by Wu and Zhou [13] has shown that the performance of the AGV system was indeed improved by optimising the task assignment and routing simultaneously.

The conventional bidirectional flowpath system is not popular in material handling systems because it adds more complexities to the control management problem. In 1992, Bozer and Srinivasan compared the performance of tandem and conventional AGV systems that consisted of 8 AGVs and 20 workstations [26]. It was found that a conventional AGV system performs better if there are only three or four vehicles in operation. However, the route optimisation of the conventional topology was very limited due to the assumption of single-AGV zones at that time. Yu and Egbelu developed a heuristic partitioning algorithm for a tandem AGV system with variable paths rather than loops [29]. A conventional layout was converted into a tandem AGV system layout. Then a comparison between the two layouts was conducted with respect to system performance under the same operating conditions. It was found that the modified tandem layout requires less AGVs to complete the same tasks in most cases. In addition, tandem layout required a shorter AGV usage time to complete the task than the conventional layout did. Also, the control problems related to vehicle routing and deadlock resolution in the tandem layout is relatively simpler due to the absence of traffic congestion and conflict from the tandem layout. On the other hand, as the route optimisation was conducted previously for various purposes (e.g. minimising travel time, travel distance, and optimal number of vehicles required, etc.), it is not easy to carry out the comparison of different topologies [10]. For this reason, there is not an official standard today for specialising the layout design of AGV systems.

2.2.2 Performance Criteria

The performance of AGV systems can be assessed by using a variety of performance criteria, such as total travel distance, queue length, material handling cost and so on [30]. The objective of flowpath design is to achieve the desired values of these performance criteria. In 1987, Gaskins and Tanchoco [31] investigated the unidirectional flowpath layout problem to minimise the travel distance of loaded vehicles. The zero-one integer linear programming method is formulated and presented as a network so that the optimal travel direction can be readily inferred. Zero-one is used to represent the connections or the arcs between the nodes (stations). 'One' means the arc is included in the final flow path design, and 'zero' means the arc is not included. With the aid of this mathematical approach, the optimal paths in the system can be obtained. However, this model could become very complex when it is used for describing practical problems and consequently shows low computational efficiency. Luo and Wu used a mixed integer programming approach to increase productivity by optimising the dispatching rules of AGVs and storage locations, considering the loading and unloading processes simultaneously in an automated container terminal using AGVs [32]. In 2002, Lim et al. used total vehicle travel time, including the loaded and empty vehicle travel times and waiting time caused by congestion or vehicle interferences as the objective function of optimisation [33]. Satisfactory results were obtained in all these previous studies.

However, from the above review it is noticed that the research interest of most of these pioneer works was focused on the optimisation of cost, travel time of the AGVs and their queue length (i.e. the waiting time in queue). However, with the increasing application of AGVs, it is recognised that more factors should be considered for achieving an optimal solution for the design, operation and maintenance of an AGV system. For example, the travel distance of empty AGVs was overlooked in the existing literature. However, the ignorance of empty AGV flow can lead to an overestimation of the system dynamic efficiency because AGVs are usually asked to use the shortest route to reach a target station rather than to deliver tasks available at the closest target. Therefore, Johnson focused his study on empty vehicle traffic [34] and found that ignoring empty vehicles could lead to an underestimation of the number of vehicles and their working time required by the tasks. Hence, Kaspi considered both empty and loaded vehicles in 2002 for optimising the direction of unidirectional routes [35]. Their research results have shown that the optimal flow of empty AGVs can be determined while the reachability between stations in the system can be also ensured at the same time.

2.2.3 AGV Scheduling and Dispatching

The AGV scheduling systems are responsible for deciding when, where and how AGVs should operate. They can be approximately divided into two categories, i.e. offline scheduling and online scheduling. If all tasks are fixed or known in advance, offline scheduling can be adopted. In this case, all actions of AGVs in the system are predefined so that the system can run smoothly. However, any small change in a task or the occurrence of a failure in the system can make the system difficult to run [11]. As the most operational environments of AGVs are stochastic, dynamic online scheduling is more favoured. In 1992, Sabuncuoglu and Hommertzheim proposed an online dispatching algorithm that considered multiple decision criteria such as criticality of workstations, availability of workstations, and the distance between AGVs and workstations [36]. The algorithm uses the information of system load and the status of jobs that are classified in hierarchical levels. The advantage of the algorithm was demonstrated by comparing it with other traditional dispatching rules in terms of the mean flow time and mean tardiness (i.e. the job handling time after its due time). The comparison results disclosed that the online dispatching algorithm improved the system performance significantly under high utilization rates or load levels. In 2012, Udhayakumar and Kumanan developed different priority dispatching rules to minimise the time required for all operations that should be completed in the production schedule [37]. The priority dispatching rules that they developed included the greatest total work, selection of the job that has the smallest remaining processing time, selection of the job that has the longest remaining processing time and so on. In their research, two optimisation methods, namely Ant colony optimisation and Particle swarm optimisation algorithm, were employed to minimise the travel distance and the number of backtracking movements so that the scheduling problem could be solved efficiently.

2.2.4 Vehicle Positioning

The optimisation of the positioning strategy of idle vehicles is beneficial to reduce the travel time of an empty vehicle from its current parked position to the next pickup station. It is also helpful to distribute resources of idle vehicles evenly over the entire network. In [38], heuristic algorithms were employed to determine the home location of every vehicle in an AGV system. In the research, different models that considered single/multiple vehicle systems and unidirectional/bi-directional flows were developed for reducing the response time of loaded and empty vehicles. Good results were achieved, but the limitation is that the static positioning strategy was adopted in that research and consequently, all optimised positions are assumed to be fixed. In order to overcome this issue, a dynamic positioning strategy for a multi-vehicle system was developed by Kim in 2001 [39]. In the dynamic positioning strategy, the AGV will be assigned a new parking position as soon as it becomes idle every time. This policy is equally applicable to all AGVs operating in the system. In [39], the numerical algorithms for the static and dynamic positioning strategies dedicated to a bidirectional loop flowpath were developed for minimising the mean response time of the vehicles. It was proved that the dynamic positioning strategy is indeed helpful to reduce the response time of AGVs [40]. In 2014, two zero-one programming models were further proposed for dealing with the vehicle positioning problems in a multi-cell AGV system [41]. In the first model, multiple machines or manufacturing resources were allocated in each cell, and the uncertain parameters in the AGV positioning problem, such as transport costs, maximum total cost, travel time, were modelled mathematically. In the second model, the space limitation and vehicle availability issues were further considered so as the model can better describe the issues that may encounter in the actual design and operation of a multi-cell AGV system.

2.3 Loading Capacity of AGV

Since the unit price of AGV is always expensive (varying from \$10000 to \$130000 depending on the types of AGVs [42]), it is essential to optimise the number of AGVs early at the design stage of an AGV system. An insufficient number of AGVs means that the AGV system may not be able to complete all planned tasks in due time, while the overestimation of the number of AGVs will make the AGV system inefficient not only in finance but also in operation. This is because the chance of deadlocks and conflicts will increase when there are more AGVs operating in one system. Consequently, the operational efficiency of the AGV system will be reduced inevitably. Also, it is well known that different types of AGVs are designed dedicatedly to different applications. For these reasons, there are many factors that must be considered when determining the vehicles for a specific application. These factors may include the number of AGVs, capacity of AGVs, speed of AGVs, numbers and locations of pick-up and delivery points, etc. Among these factors, the capacity of AGVs is definitely one of the most important factors that should be considered in the design of an AGV system.

To date, single-load AGVs, also known as unit-load AGVs, are considered in most AGV-related studies. Herein, ‘unit-load’ refers to that a number of goods are packed together and transported as a single object. Therefore, the size of unit-load will have a significant influence on the performance of the AGV system and should be determined in advance. In other words, if the unit-load size of an AGV is increased, then both the transportation costs and the required number of AGVs in the system can be reduced. Although it was suggested in [43] that machine utilisation, flow time, and work in process in AGV systems can be improved by reducing the unit-load size because the parts that belong to the same job can be processed simultaneously at different stations, this however could lead to the increased demand of transportation.

Nowadays, the methods for determining the optimal number of single-load AGVs have been well established. This aspect of research can be traced back early to Müller's work reported in [1], in which the first approach to roughly calculating the number of single-load AGVs required in a system was developed through investigating the total working time and the frequency of transportation. The achievement of that work established a solid foundation for further research on the optimisation of the number of AGVs. However, the estimation results of the vehicles' total work or travel time are dependent on the randomness of the system (e.g. number of congestions). Moreover, some key factors that may significantly influence the performance of AGV systems, such as the speed and loading status of AGVs, were not considered in the pioneering research done by Müller in [1]. Since then, much effort has been made in order to optimise the number of AGVs by various approaches. For example, three more factors that may affect the required number of vehicles, i.e. guidepath layout, locations of workstations, and vehicle dispatching strategies, were considered by Egbelu in 1987 [44]; a branch and bound approach to minimise the number of AGVs required to meet a prescribed productivity was developed by Proth and Sauer in 1997 [45], and so on. However, the scenarios and influence conditions that were considered in these studies were still limited. They have not considered the influences of the layout of the AGV system, the routing of AGVs, and the interference between AGVs. Therefore, a new model for a task assignment based on shortest-job-first and meta-heuristic Tabu Search was developed by Vivaldini in 2016 in [46] to optimise the number of vehicles with the consideration of the routing problem at the same time. In that study, the orders of the tasks are pre-planned by assuming that the tasks have been defined in advance. This assumption is reasonable for the application of AGVs in warehouse environment, where the transportation data (e.g. applications, delay of a given load, and relocate activities) are usually known in advance.

In order to further improve the efficiency of AGVs, a new concept AGV, known as a multi-load AGV, was developed for carrying more than one load/item [47]. As opposed to the single-load AGVs, the multi-load AGV is able to pick up multiple items at each station and is also able to pick up items from multiple stations. It is expected that the application of multi-load AGVs has potential to replace the application of multiple single-load AGVs in the same system, so that the issues related to cost, total travel distance, deadlock, collision and conflict can be readily addressed [47]. In order to validate the effectiveness of multi-load vehicles, the control strategy for a single multi-load AGV in a single-loop flowpath was studied by Liu and Hung [48]. From this study, it was found that different control strategies, task-determination rules and delivery-dispatching rules had a big impact on the performance of the AGV systems. The advantages of multi-load AGVs are further demonstrated by comparing them with single-load AGVs. For example, a two-load AGV system was simulated and then compared with single-load AGV systems by Ozden in 1988 [47]. A similar comparison of single-load and multi-load AGVs was also conducted by Grunow in 2004 [49]. But in comparison of Ozden's work in 1988 [47], the advantages of multi-load AGV systems over single-load AGV systems were better demonstrated in Grunow's work in 2004 [49], because the latter considered the comparison of the AGV systems that respectively consist of multiple two-load AGVs and multiple single-load AGVs, the operation of which are potentially more influenced by dispatching rules and system layouts in complex application environment.

It is worth noting that the scheduling and dispatching rules for multi-load AGVs are more complex than those for single-load AGVs. Up to date, the research on the interaction between multiple multi-load vehicles and the development of efficient scheduling and dispatching algorithms are still insufficient, although they have gained attention. For example, an improved combinatorial auction methodology for a dynamic assignment of transportation of multi-load AGVs was proposed by Fauadi et al. [50]. In their work, different performance measures, including system throughput, fully loaded travel, and average waiting time, were considered. Moreover, two case studies were given. One was for the scenario considering two three-load AGVs and another was for the scenario considering four two-load AGVs. However, due to the number of AGVs considered in this study is small, the impact of deadlock and conflict was not significant in the two case studies given in the research.

2.4 Battery Management

At present, the majority of modern AGVs are powered by batteries. Therefore, the management of battery usage is crucial to guarantee the safe operation and efficiency of AGVs. In order to demonstrate the influences of different battery usage schemes on throughput, system congestion and cost, a simulation model was developed by McHaney in [51]. It was found that more AGVs will be required after considering the time taken for recharging and replacing the batteries, although the influence of battery replacement can be ignored if it is done during the period of natural breaks. In order to mitigate the influence caused by battery recharging, a control strategy was developed by Ebben in 2001 in [52], which managed AGVs by setting battery recharging to be one of the constraints. In that research, the scenarios that considered different types of batteries and a various number of battery swaps in the system were investigated, and the corresponding number of charging stations as well as the resultant system performance and cost were evaluated. It was found that the required number of AGVs increases due to battery swap. Recently, an innovative AGV wireless battery recharging method was proposed by Zhang in 2014 in [53]. If it can be used in future practice, this new technology will eliminate the current concerns about AGV batteries, including battery swap, number of battery stations, etc. However, how AGV battery fails and the potential influence of battery failures on the throughput and cost of AGV systems are still unclear till today.

2.5 Safety and Reliability of AGVs

For a system that has only a few AGVs, the failure of the AGVs will not cause significant traffic congestion. Moreover, the faulty AGVs can be quickly replaced by backup ones (if available). Hence, the operation of such a small-scale AGV application system can be easily managed [10]. However, the application of AGVs is booming today. Large-scale AGV application systems are being increasingly used in a variety of fields [10]. For example, there are more than 130 AGVs have been used to transfer load units in Yangshan automatic harbour [54]. For such a large-scale AGV application system, any AGV failure in the system can lead to traffic chaos due to all AGVs operated on a congested, limited number of travel routes. Therefore, the safe and reliable operation of AGVs is crucial to assure the efficiency and productivity of such kinds of AGV systems. This accounts for the increasing interest in investigating the safety, reliability, and failure management issues of AGVs and AGV systems. In recent years, the effort for improving the safety and reliability of AGV systems has been made by various approaches. For example, the safety requirements and safety functions for a decentralised controlled AGV system, namely KARIS, was proposed by Trenkle and Seibold [55]. In KARIS, each AGV is assumed to perform path planning and motion execution tasks autonomously [56]. In the research, three major hazards, i.e. collision with a person, tilting over and KARIS failing, were identified. The influences of AGV speed, braking distance and detection area, as well as the mean time to dangerous failure, were analysed. In order to prevent these kinds of hazards, some suggestions, such as determining the optimal braking distance, using the sensors provided by different manufacturers, using approved components and so on, have been given. A method dedicated to the failure control management for underground transportation system, a special case study of AGVs, was developed by Ebben in 2001 [52]. In the research, a few failure scenarios, e.g. AGV failure, equipment failure, system recovery, and repair, were considered. It was suggested by Ebben that once an AGV fails, the recovery vehicle will be used to tow the failed AGV to the service station for repair. In [52], it was further studied how the location and time of the AGV failure affect the performance and throughput of the AGV system during the specified period. Finally, the simulation results suggested that the application of standby AGVs can help to maintain the ideal performance of the AGV system. In 2014, a bi-objective stochastic program was developed by Tavana and Fazlollahtabar for optimising the performance of an automated manufacturing system with the aid of time and cost measures [57]. In that work, perceptron neural networks were adopted in order to convert the bi-objective optimisation problem into a single optimisation problem by defining a suitable weight between the time and cost objectives. It is worth noting that in this research, the reliability of the manufacturing system was considered as a cost function for meeting the need of the steadiness and stability of the system, which is important to ensure the top-level performance and consistency of the system as the influence of AGV failures on the system performance cannot be neglected. However, despite these efforts the reliability of AGVs and the root causes of their failures have not been fully understood.

The availability of a system refers to the probability that the system is operational during a given time period [17]. It is an important criterion for assessing the performance of an AGV system, and therefore should be guaranteed by conducting appropriate maintenance, either major or minor. In the current practice of AGV applications, preventive and corrective maintenance are two popular maintenance strategies being adopted. The former is conducted periodically despite the actual health condition of the AGVs, while the latter is conducted only when an AGV fails. As observed from other industries, the advantages and constraints of these two maintenance strategies [58, 59] should also be observed when they are applied to AGV systems. Consequently, the application of different maintenance strategies will definitely have different influences on the availability of AGV systems, as mentioned in [60] and [61]. However, such an issue has not been fully studied today because most of the AGV maintenance services are provided by AGV manufacturers or suppliers. Most of these AGV manufacturers and suppliers have 24/7 global help desk to receive any AGV failure and maintenance enquires. In addition, they also provide different maintenance services to their clients. For example, AEROCOM UK provides preventative, fault protective maintenance, and have reactive maintenance team available at any time [62]. The company Thansbotics, suggests different preventive maintenances with different inspection intervals to their customers to prevent costly, unplanned downtime of production lines [63]. However, the study on the optimal maintenance strategy is still of great significance to reduce the maintenance cost. In addition, from the point of view of the cost-effective operation of AGV systems, the impact of the downtime caused by AGV failures and AGV maintenance on the operation and performance of AGV system is also an important topic worthy to study.

2.6 Knowledge Gap in AGV Research

From the above literature review, it can be said that a lot of valuable research has been conducted before to improve the design and operation of AGVs and AGV systems. These key areas alongside those uncovered research areas are identified as:

1. There is limited research investigating the bidirectional flowpath system although it has been shown to have a positive effect on improving the performance of AGV systems;
2. Failure mode analysis of AGVs and their key components have rarely been studied systematically;
3. Optimal number of AGVs required in an AGV system is still under research;
4. More potential advantages of multi-load AGVs and the optimal design of multi-load AGV system have not been studied sufficiently;
5. The control and management of AGV systems are identified as one of the most important problems that need to be solved urgently as the application of AGVs is growing enormously;
6. Reliability and remaining life prediction of AGVs have rarely been studied before. The critical components, subsystems and working phases of the AGVs should be identified;

7. The optimal maintenance strategy of the AGV system, for maximising the availability of AGVs and minimising their influence on the efficiency and performance of AGV systems, has never been studied. This is partially because most of the available research on AGVs is focused on improving the efficiency and reducing the operational cost of small-scale AGV systems;
8. The impact of AGV battery failure on the performance of AGV systems has not been considered before.

2.7 State-of-the-Art of Reliability Analysis and Optimisation Techniques

To understand the state-of-the-art of the reliability analysis techniques and facilitate the assessment and optimisation of the design, operation and maintenance of AGV systems, the relevant terminologies and existing reliability analysis and optimisation methods are reviewed in this section.

2.7.1 Reliability Assessment

Reliability engineering, a sub-discipline of systems engineering, aims to minimise the likelihood of the occurrence of accidents and maintain the performance or required functions of a system with the aid of a variety of theoretical and practical tools. Several reliability engineering terminologies that are important to the research of this thesis are briefly explained in the following.

Reliability, *R(t)*, is defined as the probability that a component or a system performs as specified without interruption or failure for a specified period. U*nreliability*, *F(t)*, is defined as the probability that a system has failed once or more times in the interval [0, *t*], given that it was working at $t = 0$. It can be calculated by

$$F(t) = 1 - R(t) \tag{2.1}$$

A*vailability*, *A(t)*, is defined as the probability that a component or a system is operating at time t, given that it was operating at time 0. *Unavailability*, *Q(t)*, is defined as the fraction of total time that a system has not operated correctly and is unable to perform its task. The relationship between the two functions is

$$Q(t) = 1 - A(t) \tag{2.2}$$

2.7.2 Maintenance Strategy

Maintenance strategy, which aims to find the trade-off between system output quantity and quality and system risk or/and availability, is an important but complex problem [64]. Different maintenance strategies are usually adopted based on many variables, such as the practical applications, budgets, available maintenance resources and so on. Currently, there are three maintenance strategies, namely corrective maintenance, preventive maintenance, and predictive maintenance, are being popularly used in the practice of engineering. They are respectively described below.

Corrective maintenance, also known as run-to-failure or reactive maintenance, takes action to fix the fault only after breakdown happens. Since it saves the time and cost of regular inspection, it is only applicable to the equipment that is not essential for the operations and is low in cost. But as the system suddenly fails without notice, unplanned maintenance may involve more unexpected overhead costs including more loss of production and higher costs for repairing the faults. Usually, those faults causing sudden breakdown of the system can be detected and fixed early if performing regular inspection of the system [65].

Preventive maintenance, also known as periodic or routine maintenance, is regularly performed in order to keep the system up and running. It is usually scheduled either based on time or the amount of work that has been completed. Preventive maintenance is performed when the system is still able to complete the specified task. Comparing with corrective maintenance, preventive maintenance is planned in advance, which can help to find those minor errors and incipient faults in the system and avoid more loss of production and higher repair costs. However, nothing wrong may be detected during preventive maintenance, thereby causing loss of production due to the unnecessary break. Herein, it is worth noting that sometimes a system (e.g. redundant/safety system) may fail but is not noticed by the operator. This type of failures is very dangerous and called unrevealed failure. By contrast, those failures that can be immediately noticed and readily detected are called revealed failures.

Predictive maintenance, also called condition-based maintenance, is conducted based on the actual health condition of the system. It has potential to help the operator to avoid the loss of production due to unnecessary break. However, the successful application of such a maintenance strategy relies on reliable condition monitoring data collected by a sensor or a sensor array, accurate signal processing techniques, and correct condition monitoring and fault diagnosis methods. The condition monitoring system may give false alarms sometimes once an error occurs in the operation of either one of these procedures. False alarm can lead to unnecessary break as well. In addition, the condition monitoring systems need extra capital investment, and the interpretation of condition monitoring data requires complex knowledge and expertise.

Since different maintenance strategies have shown different pros and cons, they are often used in combination in the engineering practice to achieve an optimal solution to the specific system.

2.7.3 Failure Modes Effects and Criticality Analysis

Failure Modes and Effects Analysis (FMEA) is a well-known technique that has been popularly used for dealing with the safety and reliability issues in complex systems, such as identifying the potential effects that may arise from malfunctions of military, aeronautics and aerospace systems [17]. It is a structured, qualitative analysis for evaluating the severity of potential failure modes in a system. This method is usually applied to identify those components, subsystems, or items that are prone to develop a fault and then reduce the effects of particular failure modes. Therefore, it can help to identify the weakness in system design and the important components or subsystems which could fail during operation in a system. Moreover, FMEA can be also used to identify potential failure modes of a system, their root causes, effects, and secondary effects on both the functions of local components and the performance of the whole system. At present, there have been a few published standards for guiding the implementation of FMEA, such as MIL-STD-1629A and SAE J1739 [66, 67]. In addition, some companies have also developed their own FMEA implementation procedures to meet the specific production requirements such as cranes, electric motors, aerospace seating and so on [68]. In engineering practice, the FMEA is often implemented at the early stage of system development. This is because it can help to improve the reliability and availability of the systems by early eliminating the defects, weakness or other negative factors identified by the FMEA at the design stage of the systems.

Currently, there are two basic FMEA implementation methods, known as functional and hardware FMEAs. The functional FMEA decomposes the system into sub-systems or components depending on the availability of system information and the objectives of the analysis. The FMEA is implemented by using this method until a satisfactory design is achieved and the hardware to perform desired functions is identified. As opposed to functional FMEA, the hardware FMEA considers each component independently and establishes their likely effects on the operation and performance of the systems. An example of a typical FMEA worksheet is given in Table 2.1 [17]. Each column will be filled out with the relevant information of the components or subsystems, based on which the potential failure modes can be readily identified. The physical means of the columns in the table are explained below:

- Identification - usually contains the list of component names.
- Function – short description of the functions of the corresponding components.
- Failure Mode – all possible failure modes that can lead to the failure of the

components should be included.

- Failure effect – both the local effect and system effect should be considered. The local effect is the localised effect of the failure mode which could be output/input relationships or potential secondary failures. The system effect is the global potential consequence to the whole system due to the corresponding failure mode.
- Other columns such as 'Failure detection method' and 'Remarks' can be added to the worksheet to meet different requirements of specific studies.

Table 2.1 Example of FMEA worksheet

Identification	Function	Failure Mode	Failure Effect		Failure detection method	Compensating Provisions	Remarks
			Local Effect	System Effect			
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

The conventional FMEA covers the comprehensive analysis of components/subsystems, failure modes, and local and global failure effects. As an extension of the FMEA, the failure modes can be further ranked according to their probabilities of occurrence and the severity levels judged based on the available data. This enhanced FMEA is the so-called Failure Modes Effects and Criticality Analysis (FMECA). Herein, 'criticality' is a terminology used to reflect the combined impact of a feature metric on the safety and reliability of the system being inspected. The criticality assessment can be conducted by either deriving a risk priority number (RPN_i) or calculating a criticality number [69]. In the FMECA, the criticality ranking is based on the categorised severity of the failure mode effect, and the occurrence probability of the failure of that severity level.

The RPN_i was designed for ranking the failure modes of the item according to their failure rates, detectability, and severity of their failure effect. The RPN_i for the failure mode i is the product of those three factors denoted in Equation (2.3). In principle, the larger the value of RPN_i, the more critical (or important) the corresponding failure mode of the AGV component will tend to be.

$$RPN_i = S_i \times F_i \times D_i \qquad (i = 1,2,\cdots,N) \tag{2.3}$$

where N refers to the total number of failure modes of the AGV components being considered; S_i, F_i and D_i are the severity level, frequency, and detectability of the failure of the i-th failure mode, respectively.

To the best of the author's knowledge, the FMEA has not been used to analyse AGVs in previous literature. This motivates the author to conduct a detailed FMEA of a typical laser navigated single-load AGV, which paves the way to the further reliability analysis of the AGVs and AGV systems in this thesis. In the research, the criticality of each failure mode of the AGV is inferred by combining its severity, detectability, and occurrence frequency. However, the FMEA has also shown some disadvantages [70]. For example, it is not able to evaluate the dependency and relationship between components or subsystems in systems. Moreover, the FMEA uses some empirical knowledge in the assessment, which may leads to unreliable assessment result sometimes.

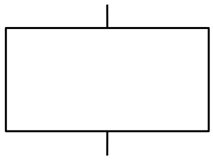
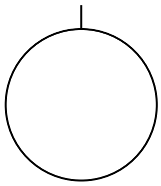
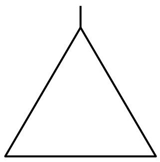
2.7.4 Fault Tree Analysis

Through inspecting the logic between the undesired events that could happen in a system or a mission, Fault Tree Analysis (FTA) allows to trace back the root cause of a system or mission failure by using a systematic top-down approach. Moreover, the probability or frequency of a system or mission failure can be calculated via Boolean algebra. The FTA provides a straightforward and intuitive presentation of the logic between undesired events and is therefore regarded as an effective, systematic, accurate and predictive method for dealing with the safety and reliability problems in complex systems, such as the safety issues in a nuclear power plant [71]. A more detailed description of the FTA can be found in [17].

In order to construct a fault tree, the undesired outcome, also known as the 'Top Event', should be defined first. Then, the Fault Tree (FT) will be developed based on the various causes of the 'Top Event'. Following this logic, the tree is continually redefined through a series of intermediate events until component failure events, known as basic events, are obtained. Here, the intermediate event denotes an event that can be described as a combination of other events or basic events through logic gates. Once the failure probabilities of basic events are available, the quantitative analysis of the FT can be conducted to calculate the system failure parameters and event importance measures. In terms of structure, a fault tree is composed of a variety of events and gates. The 'Top Event' and intermediate events are indicated by rectangular boxes. The corresponding information about the events is given in the boxes. In the FT, circles are used to represent basic events, labelled with abbreviations or codes standing for failure modes. They cannot be broken down further unless additional information is provided. The relationship between the events is indicated by gates. The gates with different functions are donated using different symbols. Some events and basic gates that are often used in FTA are listed in Table 2.2 and Table 2.3 [17], respectively, to facilitate understanding.

Once the construction of the fault tree is completed, logical analysis can be conducted. In this process, the cut sets (CSs) will be found. A CS is a list of failure events that will lead to the occurrence of the top event once all these failure events occur simultaneously. In addition, as there are always many CSs in industrial engineering systems, the CSs should be simplified by eliminating those redundant terms. In order to find the minimal, necessary and sufficient conditions for the occurrence of the top event, the concept of minimum cut sets (MCSs) is introduced. This is known as the qualitative FT analysis. These MCSs are the smallest combination of those basic events that can cause the undesired top event. The FT model is a qualitative model because what it shows are the logical relations between the events. But it can be evaluated quantitatively as well based on the failure possibilities in a system.

Table 2.2 Event symbols

Event Symbol	**Event Name**	**Meaning of symbol**
	Top event or intermediate event	System or component event description.
	Basic event	The lowest level fault that cannot be further broken down. It usually represents a component failure mode.
	Transfer symbol	It indicates that this part of the fault tree is developed elsewhere on the fault tree.

Once the MCSs are identified, quantification of the FT can be conducted using Boolean logic. Selected basic mathematical laws of Boolean algebra are given here as examples. The symbols "." and "+" are used to represent the logical AND and OR operators respectively [72].

1. Commutative Law:

$$A.B = B.A \tag{2.4}$$

$$A + B = B + A \tag{2.5}$$

2. Associative Law:

$$A.(B.C) = (A.B).C \tag{2.6}$$

$$A + (B + C) = (A + B) + C \tag{2.7}$$

3. Distributive Law:

$$(A + B).(C + D) = A.C + A.D + B.C + B.D \tag{2.8}$$

4. Idempotent Law:

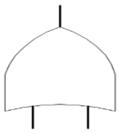
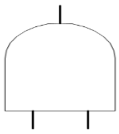
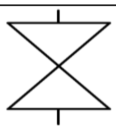
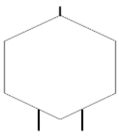
$$A + A = A \tag{2.9}$$

$$A.A = A \tag{2.10}$$

5. Absorption Law:

$$A + A.B = A \tag{2.11}$$

Table 2.3 Gate symbols

Gate Symbol	**Gate Name**	**Causal Relation**	**Valid Number of Inputs**
	OR	Output event occurs if at least one of the input events occur.	≥ 2
	AND	Output event occurs if all input events occur simultaneously.	≥ 2
	NOT	Output event occurs if the input event does not occur.	1
	INHIBIT	Output event only occurs if input event occurs and the condition event exists.	2

It is worth noting that the 'NOT' gate in the FT is generally not encouraged as it will make the FT non-coherent. Once 'NOT' gates are present in a fault tree, they will imply that both the failure of components and working states can lead to system failure [73]. Traditionally, this is regarded as a poor system design, where both components and working states can cause the failure of the system. In addition, 'NOT' logic can also increase the complexity of both qualitative and quantitative analyses because it results in a non-coherent fault tree structure [74]. For non-coherent fault trees, each possible cause of system failure is called a prime implicant set, which is a combination of component failure states and component working states. They both are necessary and sufficient to cause the top event failure.

In the process of the FTA, a criterion, namely importance measures, is used to rank components, basic events, or cut sets based on their contribution to the occurrence of a system failure [75, 76, 77, 78]. According to the calculation results of this criterion, the top contributors to system unreliability can be readily identified so as to improve system reliability more effectively. Nowadays, a few different component importance measures have been defined based on the different interpretations of the concept component importance. They are briefly described below.

Birnbaum's Measure of Importance, also known as the criticality function, defines the probability that the system is in a critical state for a particular component. It means that if the component fails, the system will breakdown. The criticality function (G_i) for a component *i* at time *t* can be expressed as:

$$G_i\big(q(t)\big) = \frac{\partial Q_{sys}(t)}{\partial q_i(t)} \tag{2.12}$$

It is the partial derivative of the system unreliability ($Q_{sys}(t)$) with respect to failure probability of component *i* ($q_i(t)$).

Criticality Measure of Importance, (I_{CM_i}), takes into account the failure probabi1ity of component *i* itself on the base of Birnbaum's Measure of Importance. It calculates the probability that the system is in a critical state for component *i* and that has failed, which can be obtained by

$$I_{CM_i} = \frac{G_i\big(q(t)\big)q_i(t)}{Q_{sys}(t)} \tag{2.13}$$

Fussell-Vesely Importance Measure for Cut Set, (I_C), ranks the minimal cut sets based on their contribution to the occurrence of top event. It calculates the probability of occurrence of the minimal cut set *i* ($P(C_i)$) given that the system has failed, i.e.

$$I_{C_i} = \frac{P(C_i)}{Q_{sys}\big(q(t)\big)} \tag{2.14}$$

The application of the FTA has been extended to the analysis of phased missions, which are made up of consecutive time intervals, phases, with distinct and differing objectives. Accordingly, different phased missions will have different failure logic models. The failure of a mission is expressed as the loss of the function of the system during at least one of the phases. It was studied firstly by Esary and Ziehms in 1975 [79]. In that study, a mission was seen as being successfully completed only after all phases are completed successfully. In [80], a method for computing the probability of system failure in each phase was developed by La Band and Andrews by using non-coherent fault trees with NOT gates. This was achieved by combining the causes of system failure by the end of phase p with the causes of system success from the start of the mission to the end of phase $p-1$. The analytical method for obtaining the unreliability of each phase was presented. The mission unreliability can be obtained by calculating the sum of the phase unreliability. Figure 2.2 shows a system that works successfully from the beginning of the mission to the end of the phase $p-1$ but fails during phase p. The fault tree of each phase is manifested by the logic of relevant basic failure events, which could have occurred in the phase. Assuming the components are unrepairable, then if a component is found failed in a phase, it could have failed in any of the phases before the end of the current phase. This can be expressed using Equation (2.15):

$$A_{i,j} = A_{\mathrm{i}} + A_{\mathrm{i+1}} + \cdots + A_j \tag{2.15}$$

where A_{i} represents the basic failure event A occurring in phase i and $A_{\mathrm{i,j}}$ represents that event A occurs in any phases from i to j.

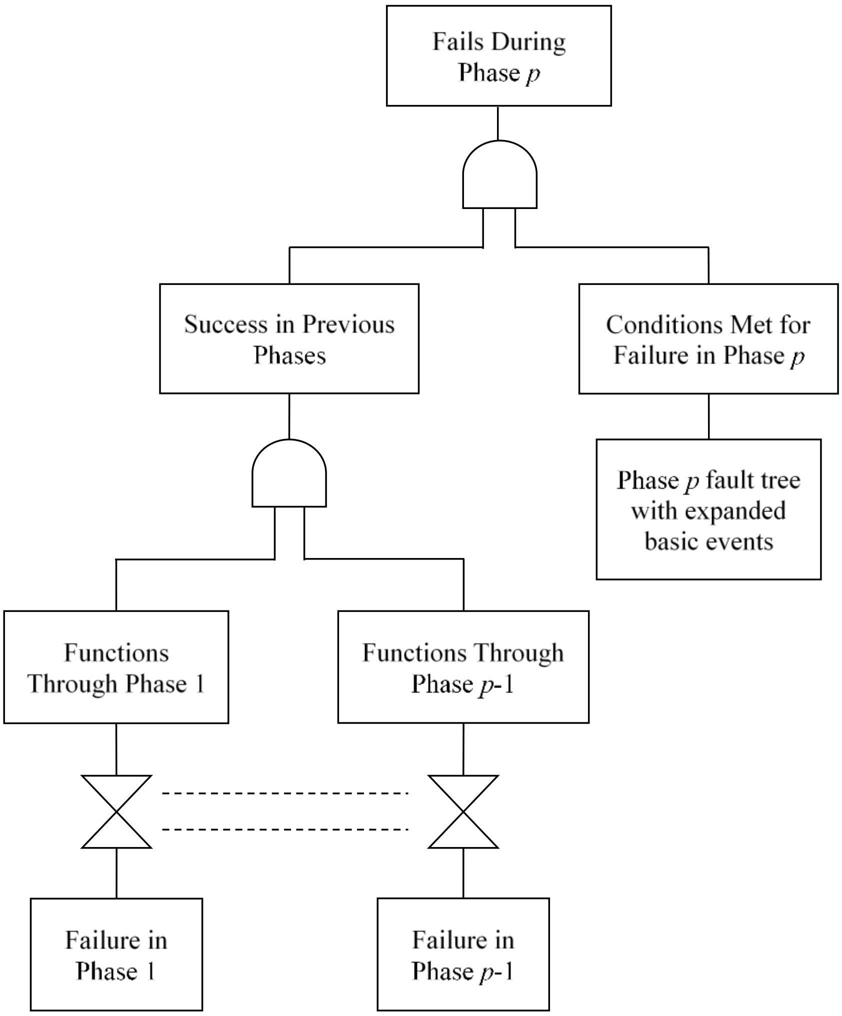


Figure 2.2 General phase p failure fault tree

The application of the FTA to study the AGV related problems is still few today except that the basic failure modes of the light detection and ranging (LIDAR) system and the camera-based computer vision (CV) system of AGVs were identified by Duran et al. by using the FTA in 2013 [15]. In their study, human injury, property damage and vehicle damage were defined as the three top events in the fault trees. The contributions of the LIDAR and CV failures to these top events are illustrated in Figure 2.3 [15]. By further applying the probabilistic analysis using Bayesian Belief Network, they confirmed that the reliability and availability of the AGV LIDAR and CV subsystems are important to the system safety. However, their research did not cover all components and subassemblies in the AGVs.

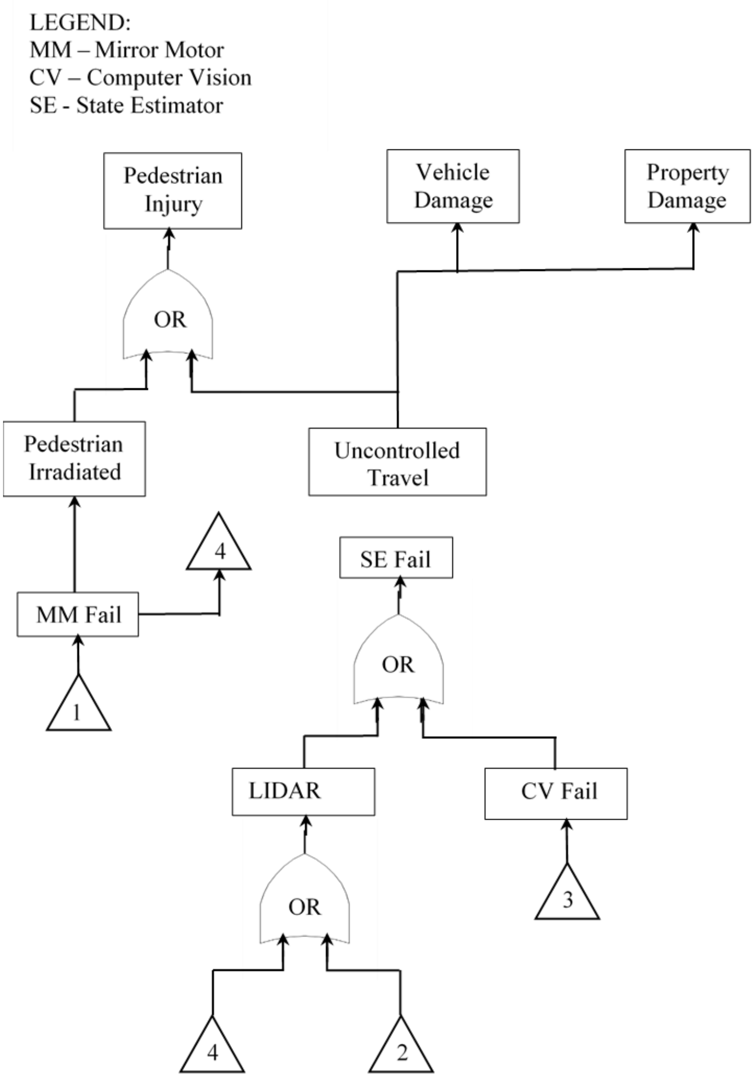


Figure 2.3 Top-level FTA for AGV

However, both the FTA and FMECA show limitations in practical application. For example, although the top down analysis of the FTA discloses the causes of failures occurring in a system, the detectability of the ‘failure causes’ are not taken into account in the process of the FTA. In addition, the FTA is not good at identifying all possible basic failure events and the local effects due to the failure since it is a deductive top-down method. By contrast, the FMECA considers the criticality and detectability of ‘failure causes’, however it only gears towards analysing the failure modes of individual component, while fails to analyse the reliability of the whole system like the FTA does. This is why the FTA and FMECA are used in combination in the research of this thesis.

2.7.5 Simulation Modelling - Petri Net

With the aid of FTA, the reliability of the system of interest can be obtained analytically. However, when the system is large and complex, or the mission to be performed is made up of many phases, FTA would become inaccurate and computationally expensive. To overcome this issue, some alternative reliability evaluation methods are developed by the approach of simulation modelling, one of which is Petri Net (PN) developed by Petri [18]. Simulation modelling is a computer-based method, which uses mathematical algorithms and equations to solve real-life problems efficiently and cost-effectively. In comparison of analytical analysis, simulation modelling method allows us to deal with more complex issues and moreover is easier to be verified and understood.

Similar to the FTA, PNs provide an intuitive graphical representation of the reliability problem of interest. But by contrast, the PN method is more suited to dealing with the reliability issues in complex systems that involve more components, functions, and more complex system configurations than in a simple system. PNs have shown many advantages in performing system simulation and modelling [81]. For example, it removes redundant information in the model of the system so that the problem can be simplified. Also, the PN model can be easily adapted to modelling different problems by simply modifying the network settings.

The PN method is, in essence, a direct bipartite graph. As shown in Figure 2.4, it basically consists of the following four types of symbols:

- Circles – represent the places, which are conditions or states such as mission failure, phase failure, or component failure depending on the issue being considered.
- Rectangles – represent the transitions, more abstractly actions or events. It is worthy to note that in the case of timed transitions, a solid rectangular bar can be used when the time spent for completing the transition is zero. Otherwise, the rectangular bar is hollow.
- Arcs – represent connections between places and transitions. It should be noted that arcs with a slash on and a number, *n*, next to the slash represent a combination of *n* single arcs and each arc has a weight *n*. The weight will be 1 when there is no slash.
- Small marks – represent tokens that carry the information in the PN.

To ease understanding, an example of the movement of tokens through a net is illustrated in Figure 2.4.

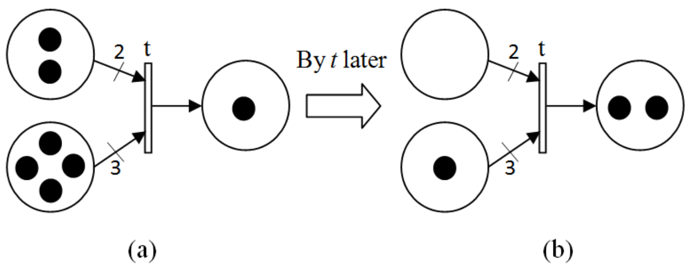


Figure 2.4 Enabling and switching of transition, (a) before enabling transition, (b) after enabling transition

From Figure 2.4(a), it is seen that there are two inputs and one output place connected to a timed transition with a time delay *t*. The input places have arcs with weights 2 and 3, respectively. The transition is enabled when the number of tokens contained in every input place is not less than the corresponding arc weights. Once the transition is enabled, the number of tokens corresponding to the arc weight will be taken out from the corresponding input place to fulfil the transition after the time delay t associated with the transition. If the transition time t is greater than zero, the PN is known as a timed Petri Net. For example, as shown in Figure 2.4, two and three tokens are respectively taken out of the upper and lower input places, and one more token will be present in the output place. But it is necessary to note that after completing the transition, the number of tokens that are increased in the output place is also dependent on the corresponding arc weight. For example, if the arc weight connected to the output place is 'n', then n more tokens will appear in the output place after enabling the transition. After the transition, there will be zero, one, and two tokens in the corresponding places, as shown in Figure 2.4(b). This forms a new distribution of tokens in the places of the PN. This is called marking, which represents a PN configuration with the distribution of tokens in the places.

The movement of tokens through a PN can be transformed into matrix form as shown in Equation (2.16).

$$M_r = M_0 + B^T E \tag{2.16}$$

where M_r is the final marking after r transitions. E represents a finite set of transitions, which forms a column matrix, $(m, 1)$. Here, m indicates the number of transitions in the net, representing how many times each transition has fired after r transitions. M_0 refers to the initial marking of the net. It is a $n \times 1$ column matrix, where n is the number of places. B is known as the incidence matrix, which is a $m \times n$ matrix. Each element in matrix B, b_{ij}, corresponds to the effect that the transition i has on the place j. It should be noted that B^T is the transpose of matrix B. In order to explain this method more clearly, the matrix expression for the example shown in Figure 2.4 is presented. Since there are three places in total and there are 2, 4 and 1 tokens respectively in them, the initial marking of the net is expressed as:

$$M_0 = \begin{bmatrix} 2 \\ 4 \\ 1 \end{bmatrix} \tag{2.17}$$

According to the numbers of the places and the transitions, as well as the connections and the weight of each arc in the figure, the matrix, B, is denoted as:

$$B = [-2 \quad -3 \quad 1] \tag{2.18}$$

In matrix *B*, the values -2 and -3 represent the input places respectively lose two and three tokens after the transition according to the weights of the arcs connecting to them. The value 1 means the output place will obtain one more token after the transition.

Since there is only one transition only firing once, then has

$$E = [1] \tag{2.19}$$

After the associated time delay *t*, the resultant marking, M_1, can be calculated by using Equation (2.20), i.e.

$$M_1 = M_0 + B^T E = M_r = \begin{bmatrix} 2 \\ 4 \\ 1 \end{bmatrix} + \begin{bmatrix} -2 \\ -3 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 2 \end{bmatrix} \tag{2.20}$$

where, M_1 is the matrix expression of the resultant PN after the transition in Figure 2.4(b).

Despite the outstanding merit of flexibility, it is found that conventional PN has difficulty in describing complex systems or a system that is designed to carry out complex tasks and missions [82]. To further improve the ability and capability of PN, many extension forms of PN have been developed. For example, as shown in Figure 2.5, a type of arc that is terminated with a circle was developed, which is called inhibit arc. This kind of arc prevents the firing of transitions when the input place is marked, thereby enhancing the decision power of PN. From Figure 2.5, it is noticed that the top input place is connected with the transition by an inhibitor arc. Since there is a token in the place, this transition cannot fire.

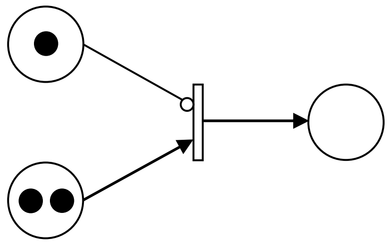
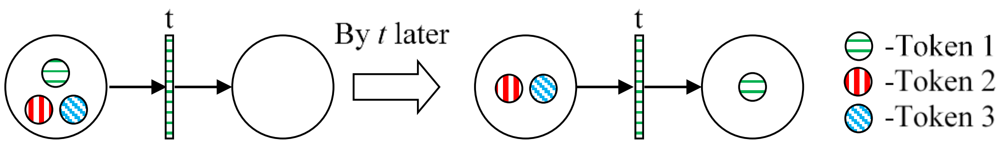
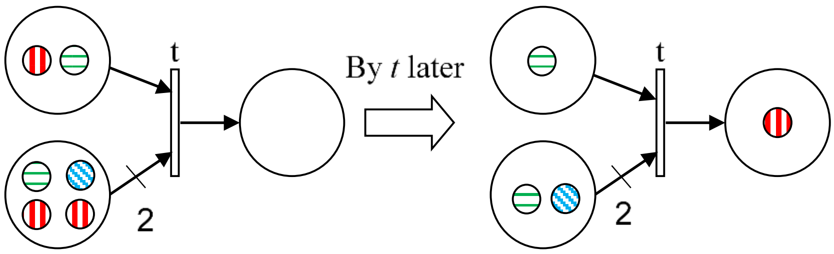


Figure 2.5 PN with an inhibitor arc

Apart from the modifications of arcs, an enhanced PN, namely Coloured Petri Net (CPN), was introduced in [83]. Different from the conventional PN, the individual tokens in the CPN model are characterised by different colours, which represent different identities or different information. For example, these coloured tokens could represent components with different functions or workers undertaking different jobs. Therefore, the CPN is also known as a high-level PNs which is more informative than the conventional PNs. In addition, the colours of the tokens in the CPN model are also associated with transitions, so that the transitions can be activated if and only if the tokens with the same colour enable the transition. To facilitate understanding, two CPN transition examples are illustrated in Figure 2.6. In order to ensure that black and white figures can also clearly express the information, different filling patterns are also adopted to characterise the tokens that are characterised using different colours. Moreover, a key has been included in the figure, where token 1 represents green, token 2 red and token 3 blue. As the transition in Figure 2.6(a) is green, only the green token (token 1) can enable the transition. It should be noted that the coloured tokens can also activate non-coloured transitions and the tokens in the output places will still carry the colour information, as shown in Figure 2.6(b). However, as observed, only tokens with the same colour are able to enable the transition. No further firing of the transition will occur in Figure 2.6(b) as there are not enough tokens of the same colour to activate the transition.



(a) CPN with a coloured transition



(b) CPN with a normal transition

Figure 2.6 Diagrams of the CPN

To date, the PN has become a popular tool used for evaluating the reliability of a system or a mission. For example, an extended object-oriented PN model was proposed by Wu in 2015 to analyse the reliability of a phased mission with common cause failures [84]. Considering industrial applications, a PN-based wind turbine asset model was developed by Le and Andrews to study the degradation, maintenance and inspection processes of different wind turbine components [85]. In the area of AGVs and AGV systems, many PN-based models have been developed for eliminating deadlock in the AGV systems through performing system design and analysis. For example, a coloured resource-oriented Petri Net (CROPN) method was developed by Wu and Zhou by addressing the resources in automated manufacturing systems, and then the CROPN was used to find the shortest routes for the AGVs while avoiding both deadlock and blocking in the AGV systems [13]. One of the CROPNs developed by them is shown in Figure 2.7.

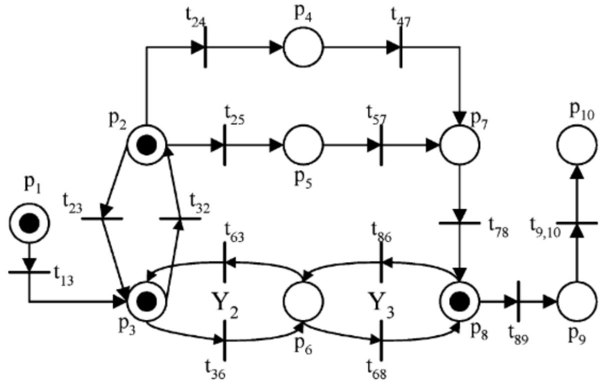


Figure 2.7 An example of the CROPN in [13]

In the figure above, the places represent the resource zones, target destinations, or joint junctions in the AGV system. The arcs represent the guidepath connecting the zones. In addition, the tokens represent the four AGVs in places P1, P2, P3, and P8, respectively. Also, the PNs were used by Luo et al. to design a programmable logical controller (PLC) for preventing the collisions of vehicles in an AGV system [86]. In their study, two different ordinary PNs, namely a control-hardware PN and a closed-loop PN, were constructed. The former was used to model the control elements including sensors, up-down counters, coils, and wiring loops. The latter, designed based on the former, was used to describe the control specification of collision-prevention in an AGV system. In addition, the PN based method was developed by Nishi and Maeno to optimise the routing planning for the AGVs in semiconductor fabrication bays [87]. Despite so many applications, so far, all existing PN based models were developed mainly for investigating route planning and control strategies of the AGV systems. Its application in studying the reliability of AGVs and AGV systems has not been reported in open literature.

2.7.6 Optimisation Method - Genetic Algorithm

Optimisation algorithms are executed iteratively to find optimal or satisfactory solutions [88]. They can be classified into two categories, i.e. deterministic algorithms and stochastic algorithms. Deterministic algorithms follow a rigorous procedure or specific rules so that the solution can gradually approach to a better solution. But despite the optimisation process, the same output will be produced for a particular input. By contrast, stochastic algorithms always involve some degree of randomness so that its optimisation paths and values are not exactly repeatable.

Nowadays, two kinds of stochastic algorithms are popularly used in the practice of optimisation. They are heuristic and metaheuristic algorithms. Heuristics are a kind of greedy problem-dependent techniques. They can be adapted to different problems. It can help to find a reasonably good solution, but it is possible to be trapped in local optimums. As opposed to heuristics, metaheuristics are a sort of problem-independent techniques. Therefore, they can work like a black box. Since they allow to explore more in space, they can usually perform better in achieving the purpose of optimisation.

In this thesis, optimisation is conducted to find the optimal layouts, configurations, and maintenance strategies for the AGV systems. The purpose is to minimise the cost of production while maximising the production in a given time duration simultaneously. The obtained optimal solution will enable the AGV system to achieve the best performance in multiple aspects. Since deterministic algorithms are not good at dealing with discontinuity problems [88], it is not suitable to undertake the optimisation of the problems that involve many discrete variables, like the problems considered in this thesis. For this reason, only metaheuristic algorithms were considered when selecting an appropriate optimisation tool in this thesis.

So far, Genetic Algorithm (GA) has been widely regarded as a most mature metaheuristics for dealing with multi-objective optimisation problems attributed to its powerful capability of achieving universal optimisation regardless of initial conditions [89, 90]. Inspired by the biological evolution of living species, the GA was proposed first by John Holland in 1970s [91]. It has several outstanding advantages over other metaheuristics. For example, as compared to the simulated annealing algorithm that uses only one point moving in a search space to find better solution [92], the GA uses a population to explore the whole search space. Therefore, it is less likely to fall in local optimums. Also, the GA is particularly good at dealing with discrete problems while other metaheuristics like particle swarm optimisation were designed mainly for solving continuity problems [88, 93]. In the area of AGVs, the GA has now been applied to solving various problems in AGV systems, such as the scheduling and dispatching problems considered in [94, 95, 96, 97].

To implement the GA, an initial population of individuals (also known as chromosomes consisting of genes) will be generated first, and the fitness of every chromosome in the population will be evaluated by using the predefined fitness functions, which is constructed based on the optimisation objectives. Then, any two individuals in the population will be randomly selected as parents for carrying out evolution by the approach of either crossover or mutation mechanism. The offspring chromosomes will be judged again by calculating their fitness values, and then based on which to select a new generation of parents for carrying out evolution again. The same evolution process will be iterated until the predefined number of iterations is reached or a satisfactory population is obtained, depending on the termination condition set in the GA algorithm. Herein, it is worth noting that at every time of evolution, the chromosomes with higher fitness values will always have more chance to be selected as parents so that their genes will have higher probability to be passed on. The crossover of the parents' genes is conducted based on the principle of randomness. In the process, the mutation of an individual's genes may happen also randomly, which will be beneficial to prevent early or premature convergence of the solution. The premature convergence of the solution may not only slow the iterations to reach a globally optimal solution, but could also lead to a local optimum [98]. Through repeating the evolution, the average fitness of the individuals in the population will be increased gradually and a saturated value will be finally obtained when the GA calculation is normally terminated. Then, the individual that has the largest fitness value will represent the optimal solution of the problem of interest.

As mentioned above, the crossover operation is applied to two parent chromosomes, which are randomly selected based on a predefined crossover rate. The genes from two 'parent' individuals are combined by using crossover mechanism to generate the genes of a new offspring. Today, a few notable crossover methods have been developed, such as single-point, multi-point, and uniform crossovers [99]. In a single-point crossover operation, a random crossover point can be selected at any point within the genes of the chromosomes. By combing two sets of genes from both parent chromosomes, an offspring chromosome can be produced. An example of the process of single-point crossover is illustrated in Figure 2.8.

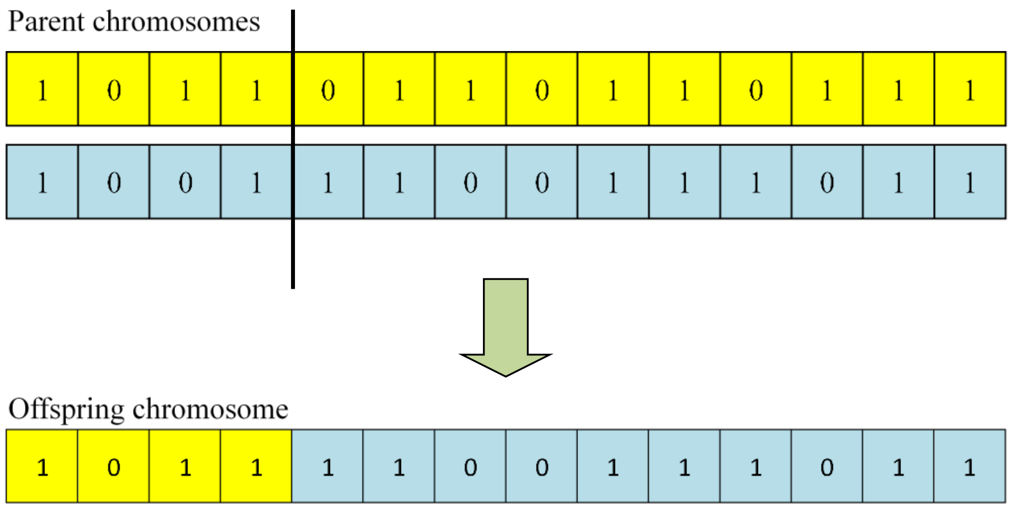


Figure 2.8 One-point crossover operator

In the figure, assume the randomly selected crossover point is after the 4th number. Then the new offspring chromosome is produced by combining the first four numbers in the genes of the top parent chromosome and the bottom parent chromosome's genes starting from the 5th number.

Multi-point crossover is a generalisation of the single-point crossover, wherein alternating segments are swapped between multiple crossover points to get new offspring chromosomes. In a uniform crossover, the parent chromosomes are independent with each other. Each number or bit of the offspring chromosome is chosen from the two parents according to a distribution. These crossover operators are generic and their efficiency and effectiveness could vary for different problems.

An example of the operation of mutation is illustrated in Figure 2.9. As mentioned earlier, mutation is helpful to maintain the genetic diversity of the population and prevents the solutions trapping to the local best by restoring the lost genes during the evolution and finding more unexplored information beyond the given population. During a mutation operation, the value of each gene of a chromosome could be modified based on a given probability. It is worth noting that both the values of the crossover and mutation rates are usually found by experimental approaches.

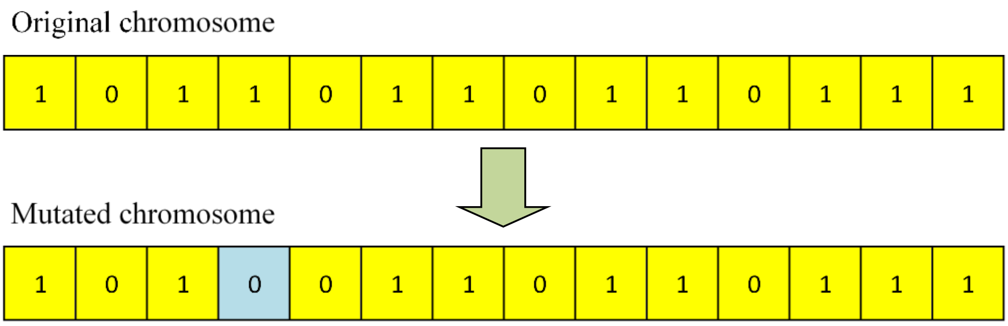


Figure 2.9 Mutation operator

2.8 Conclusion

Based on the literature review conducted above and the knowledge gaps identified in the field of AGVs, this thesis uses appropriate methods to develop a detailed and systematic approach to evaluate the reliability of AGVs and AGV systems and find optimal solution for achieving the best performance of the AGV systems, which provides an effective tool for filling the knowledge gaps 1-7 identified in Section 2.6. If necessary, the identified knowledge gap 8 can be also filled by using a similar approach in the future. In contrast to the available literature, this thesis is identified by a number of new contributions, such as all AGV systems being investigated in the thesis have bidirectional paths; advanced reliability analysis techniques and simulation methods are developed to perform a comprehensive risk assessment of key AGV subsystems and identify the crucial mission phases in the operation of a single-AGV system; the performance of multi-load AGV systems is investigated systematically and compared with single-load AGV systems; the AGV systems are optimised so as the optimal number of AGVs, the optimal capacity of AGVs, and the best maintenance strategy of the AGV systems can be achieved.

3 Methodology

3.1 Overview

In order to reach the research objectives defined in Chapter 1 and fill up the research gaps identified in Chapter 2, a research methodology is proposed in this Chapter. In the context, the research methods for reliability analysis, the methods for AGV system modelling, and the methodology for optimising AGV systems are outlined first in this Chapter, and the reasons for using these methods are explained based on the discussion of their advantages and disadvantages. Then, the potentials of these methods in achieving the aims and objectives defined in Chapter 1 are discussed. Finally, the Chapter is completed with a brief discussion of the merits of the proposed methodology in dealing with the issues in the design of AGV systems.

3.2 Research Methods

In the research roadmap of this thesis, the study will start with the understanding of a fundamental question, i.e. how does an AGV fail? To answer this question, the key subsystems in a typical AGV are identified first by performing the Failure Mode, Effects and Criticality Analysis (FMECA) of the whole AGV unit. Then, the impact of the failures of these subsystems on successfully completing the missions of the AGV is studied by the approach of the Fault Tree Analysis (FTA) and the Petri Net (PN) modelling. Next, the research is further extended to investigate the interaction between the AGVs in multi single-load AGV systems and the influences of the reliability of individual AGVs on the overall performance of the AGV systems by the approach of the CPN. Subsequently, the similar problems in multi-load AGV systems are also investigated using the CPN following the research on the influence of the load-carrying capacity of individual multi-load AGVs on the efficiency and performance of the entire multi-load AGV systems. Furthermore, the AGV systems are optimised by the approach of the Genetic Algorithm (GA) with the consideration of a number of variables, such as the number of AGVs, the load-carrying capacity of individual AGVs, the maintenance strategy of the AGV systems, etc. Finally, the adaptability of the developed CPN model for dealing with various real-life AGV problems is tested to demonstrate the potentially extensive application of the proposed technique in the future design, operation and maintenance of AGV systems.

To carry out the roadmap described above, a detailed research methodology is developed and detailed as follows.

3.2.1 Failure of AGV Subsystems

In order to understand the root causes of the failure of an AGV, the structure and the subsystems of a typical AGV are defined first. Then, considering the FMECA is an ideal method for qualitatively assessing the failure modes of subsystems and ranking their criticality, it is applied in this thesis to analysing the failure modes of each subsystem in the AGV and their consequent effects. Then, based on the analysis results, a FMECA table for the AGV subsystems is constructed for facilitating further research using the RPN. In the table, detailed information about failure modes, local and system effects, the severity of consequence, the detectability and frequency of failures are listed. Then, the RPN of each failure mode can be readily calculated based on the severity, detectability, and failure frequency information listed in the table. Finally, the criticality of each failure mode of the subsystems can be ranked based on the calculation results of the RPN.

However, the FMECA is found neither able to describe the relationship between different AGV subsystems nor able to describe the relationship between the different phases of the mission of the AGV [17]. Moreover, the FMECA may lead to subjective conclusions sometimes due to the implementation of the FMECA partially relies on the empirical knowledge of experts. This is why the FTA of the AGV system is further conducted.

3.2.2 Impact of AGV Subsystem Failure on AGV Missions

Beside an AGV is composed of several subsystems, the mission of a typical AGV in a material distribution warehouse is implemented also by a few phases. The failure of one or more subsystems may lead to the failure of a phase, which will directly result in the failure of the whole mission. The FTA is employed in this thesis to describe such logic in the operation of a single-AGV system. The taxonomy of the fault tree for the mission of the AGV usually consists of three levels. They are mission level, phase level, and subsystem level, respectively. Herein, 'mission failure' is defined as the top event of the fault tree and the failures of mission phases are defined as intermediate events. Since the failure of any phase can lead to the failure of the whole mission of the AGV, the phase failure events are connected together via an 'OR' gate in the fault tree. Then, the phase level of the fault tree is constructed by defining the failure of each phase as the top event and the failures of AGV subsystems, which are required to perform their functions during each phase, are defined as the lower-level events. Finally, at the subsystem level of the fault tree, the failure of each AGV subsystem is defined as the top event and the corresponding failure modes of each AGV subsystem are defined as the basic events.

Using the interrelationship between the different events at different fault tree levels, the failure probabilities of the AGV subsystems, phases, and overall mission are calculated. Then, based on the calculation results the crucial mission phases at which the AGV is more likely fail in the operation can be readily identified.

However, due to the potential of the FTA quantification process becomes restricted as the size and complexity of the AGV system increase and the difficulty of using the FTA to investigate the deadlock and conflict issues existing in AGV systems [17, 80], PN modelling is adopted as well in the thesis for achieving the same goals as the FTA and providing a more powerful tool for assessing more complex AGV systems. Based on the same logic developed in the FTA, the PN model is constructed to describe the failure of the subsystems (i.e. subsystem PNs), the failure of the phases (i.e. phase PNs), and the operation of the AGV in the mission (i.e. master PNs), respectively. The information of the subsystem failure from the subsystem PNs will be fed to the phase PNs. Then, the information of the phase failure from the phase PNs will be fed to the master PNs, which govern the change of the phases and determine the success of the mission in the end. Once the PN model is developed, the reliability of the AGV for successfully completing a certain number of missions can be calculated via performing simulations. It should be noted that a converged value can be finally achieved by iterating the simulations. Then, the simulation results obtained from the PN model and the analytical results derived from the FTA are compared to ensure the correctness of the assessment.

3.2.3 Investigate the Variables Affecting AGV Systems Performance

After the PN model is successfully developed, the influences of a number of variables that may affect the efficiency and performance of AGV systems are investigated. The variables to be investigated include the failure of individual AGVs, the number and the load-carrying capacity of the AGVs, maintenance strategy, the path width, and the number of backup AGVs used in the system. In the thesis, considering the difficulty of conventional PN models in simulating multi-AGV systems, it is used only for simulating a single-AGV system [84, 100, 101]. The simulation of multi-AGV systems is achieved by using a more advanced PN modelling technique, namely Coloured Petri Nets (CPN). The developed CPN model is not only able to simulate the missions of the AGVs but also able to simulate the movement of AGVs in the system, for example, the failed AGVs will be automatically towed to the maintenance site by a recycling AGV.

In the research, the layout of a simple multi-AGV system is defined first to investigate the impact of the failure of individual AGVs on system performance, which is indicated by the number of missions that are successfully completed in a given time period. Then, with the aid of the developed CPN models, the influences of different maintenance strategies (e.g. corrective and preventive maintenance strategies) and the location of the maintenance site on the performance of the system are investigated.

Furthermore, the layout of a larger multi-AGV system is defined to investigate the impact the number and load-carrying capacity of AGVs on system performance. Through the study, two potential approaches (i.e. increase either the number or the load-carrying capacity of the AGVs) to improving the performance of AGV systems are discussed in order to seek an effective way to design larger multi-AGV systems.

Finally, the performance of multi-load AGV systems is further studied using the developed CPN models with the consideration of the influences of the reliability and availability of individual multi-load AGVs. In addition, the deadlock and conflict issues caused by failed AGVs, the application of backup AGVs, and the influence of onsite and offsite maintenance methods are also dealt with using the developed CPN models.

3.2.4 Optimisation of AGV Systems

In order to achieve a cost-effective design and the best operation and maintenance strategy of multi-AGV systems, the aforementioned variables that may affect the efficiency and performance of the AGV systems as well as the associated cost are optimised by developing a GA, which has been widely regarded as a mature technology for optimising the kind of multi-objective problems. In the study, a fitness function that takes into account both the performance and the cost of the AGV system is designed first. Then, the simulation results from the CPN models are used as the inputs of the GA for performing the optimisation calculation. Finally, the variables that are used to encode the best chromosome in the GA population will be regarded as the optimal design of the AGV system.

3.2.5 Adaptability and Capability of the Developed CPN Models

Finally, the adaptability and capability of the developed CPN models in dealing with more complex AGV systems are investigated. Firstly, the waiting time of the AGVs due to the limiting resources and space of AGV systems is modelled. Then, the regular system layouts respectively with conventional and tandem configurations are modelled by updating the developed CPN models. Furthermore, a system with an irregular layout is modelled and its performance with different numbers of AGVs is evaluated. Finally, a case study that is based on a real-life AGV application in a distribution warehouse is modelled for testing the adaptability and capability of the developed CPN models in potential applications.

3.3 Summary

Nowadays, the study of the reliability, operation and maintenance of AGVs and AGV systems are still insufficient. Therefore, a more detailed research in the relevant aspects is essential for achieving a cost-effective design and optimal operation and maintenance strategy of larger AGV systems. In the research roadmap defined in this Chapter, a FMECA table of a typical AGV will be the starting point to study the failure of key AGV subsystems qualitatively as discussed in Chapter 4. Based on the FMECA, a detailed FTA will be conducted to investigate the relation between the failure modes to the missions of AGVs in the same chapter. The PN modelling and extended CPN modelling will be adopted to simulate the operation, failure, and layout of AGV systems from the end of Chapter 4 to Chapter 7. Using the simulation results, GA optimisation will be employed to optimise both the performance and cost of the AGV systems in Chapter 8. In Chapter 9, the CPN models are further developed to simulate more complex AGV systems and moreover, the adaptability and capability of the developed CPN models in simulating real-life AGV systems are investigated via conducting a case study.

4 Reliability Modelling of a Single-AGV System

4.1 Overview

The reliability of AGVs have received little attention [10]. To further assure the added value of the AGVs, their reliability issues are investigated based on an example of typical single-AGV transport systems. A typical AGV usually runs without the involvement of an onboard operator or driver by following the markers or wires on the paths or by following the guidance by a Laser Navigation System (LNS). In the research, the AGV being investigated refers to those working in distribution centres and warehouses. They are requested to move materials or items in a prescribed area. In terms of the mission of a typical AGV, the AGV should travel to a target location and pick up the material as requested, then travel to another target location and unload the material. Following a Failure Mode Effects and Criticality Analysis (FMECA), the reliability of the AGV system is analysed by performing Fault Tree Analysis (FTA), and the reliability of vehicle missions is evaluated by using the Petri Net (PN) method. By performing the analysis, the failure of the AGV mission can be analysed, and hence the service capability and potential profit of the AGV system can be reviewed.

4.2 Structure of a Typical AGV

With the increasing application of AGV systems, their scales increase gradually to meet the requirements by the increased throughput and productivity. Consequently, more and more AGVs are included in individual AGV systems, the failure of any AGV would cause traffic chaos of the system. Therefore, the reliability issues of these AGVs and their components and subassemblies are receiving more attention today than ever before. The full investigation of the reliability issues of AGVs is not only important to ensure their high reliability and availability and their success of delivering prescribed tasks, but is also essential for optimising their maintenance strategies and minimise traffic chaos of the whole AGV system.

To facilitate the reliability assessment of AGVs, a typical AGV system with a single AGV used in a warehouse for material distribution is chosen for analysis. A typical battery-electric powered AGV is usually composed of a LNS, safety system (SS), manual button, batteries, AGV software control system (ASCS), direct-current motor drive unit (DC), brake system, steering system, and attachments. This kind of AGV is becoming more popular than diesel-electric powered AGVs due to lower overall cost and it is more environmentally friendly. In spite of the power supply method being adopted, an AGV is self-navigated and designed to travels along the flowpaths defined in the system-control software. Herein, it is necessary to note that the flowpaths are virtual. They are not physical flowpaths that are labelled by either fixed magnetic tape or paint laid along the aisles. The movement of the AGV relies on the laser navigation system, which is, in essence, a position measurement system to locate the AGV [102]. It comprises a rotating laser installed on the top of the AGV and beacons mounted along the border of the area to be covered. Rays of laser are sent back and forth between the AGV and these beacon reflectors in the facility so that the AGV can maintain the correct speed and positioning. The ASCS is responsible for processing and interpreting the information received from both the laser navigation system and safety system, and issuing either motion or operation orders. There are a number of inputs and outputs linked to the ASCS. With the aid of a laser detection system installed on the AGV, the safety system is designed to avoid obstacles that may appear on the pathway. These, together with the manual button, are integrated into the control system. The manual button on one side of the AGV is the main switch for emergency stop. The ASCS will then use the gathered information (e.g. current position, obstacles detected, forthcoming danger, and target items or materials) to send commands to the drive unit, brake system, steering system, and attachments. Here, the drive unit, usually a brushless DC electric motor, will provide the power for motion and operation. Attachments refer to those additional components that are used to assist movement and operation. The batteries are also part of attachments. Usually, common lead–acid batteries are used to supply power to the battery-electric powered AGVs, see Figure 4.1.

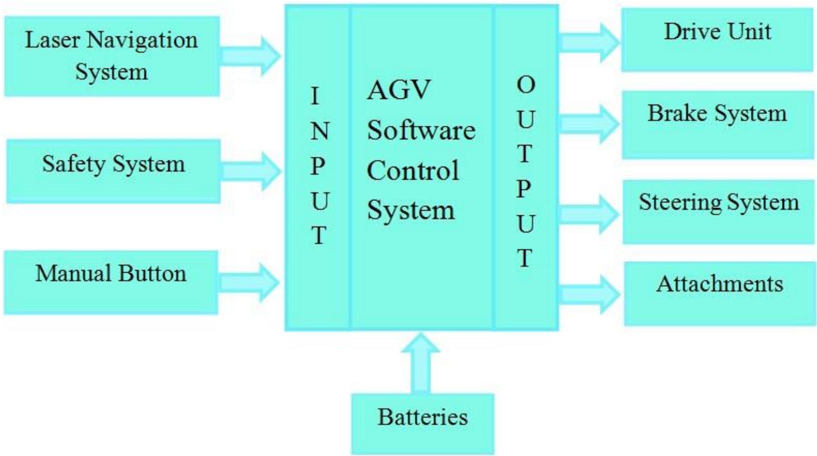


Figure 4.1 AGV structure schematic

4.3 Mission of the AGV

The AGV that is studied here is designed to distribute materials to multiple places in a warehouse. The requirements in the port are described as jobs. Each job is characterised by the pickup (source) station, the unload (target) station, and the time for picking up or dropping off items. At every time when the AGV is allocated to a job, the route for completing the whole mission will be optimised first to find the shortest route from the current position of the AGV to the pickup station and then from the pickup station to drop off station. Then, the AGV will travel to material collection port along the optimised route to pick up materials. After the AGV is loaded, it will travel to storage station and unload the materials. After successfully distributing the materials, the AGV will travel back to its original parking position.

The whole mission can be divided into 6 phases, namely (1) mission allocation and route optimisation, (2) dispatch to station, (3) loading of item, (4) travelling to storage, (5) unloading, and (6) travelling back to base. The phase ‘travelling back to base’ is not necessary in most AGV systems, but it is present here because the base is assumed to be located in the centre of the AGV system. Hence, the optimised route always starts from the base, which can significantly reduce the complexity of route optimisation and is therefore used as a benchmark for the design of more complex AGV systems. The mission can be regarded as successful only when the AGV is able to operate successfully throughout all these 6 phases without any stoppage's due to component and/or subsystem failures or maintenance. Also, the AGVs are usually required to complete a number of missions continuously during a certain period. Such a period is called Maintenance-Free Operational Period (MFOP) [103]. To implement the FMECA, FTA and PN simulation, the length (i.e. time duration) of each phase identified is assigned a value as shown in Table 4.1. The total time that will be spent to complete the whole mission is 0.51 hours (i.e. 30.6 minutes). Here, it is worth noting that the data listed in Table 4.1 are empirical data obtained based on the enquiry and consultation with AGV operators. They are presented only for demonstration purposes, not for reflecting the actual operation of the AGV. They will be different when considering different types of AGVs, lengths of paths, and speeds of AGVs in real-life applications.

Table 4.1 Assumed phase lengths

Phase	**Phase Length** (hour)
1	0.02
2	0.2
3	0.02
4	0.15
5	0.02
6	0.10

4.4 Single AGV Risk and Reliability Analysis Procedures

Three different methods, i.e. the FMECA, FTA and PN simulation, are adopted in this Section to perform the reliability analysis and risk assessment of the single AGV system by using the following steps:

1. Critical AGV subsystems analysis via the FMECA.

2. System level analysis via the FTA.
3. Mission failure analysis via the FTA.
4. Simulation via the PN.
5. Evaluation and Analysis.

The FMECA is used to study the failure of AGV subsystems in detail. Based on the FMECA results, those subsystems that are critical to the reliability of the AGV can be readily identified. To further investigate the relationship between the subsystem failures and mission failures, the FTA is employed as an analytical method for achieving this objective based on the information obtained from the FMECA. Finally, a more flexible simulation method, namely the PN, is further employed to investigate the reliability of the mission, and the investigation results are validated by the analytical results obtained from the FTA.

Applying the FMECA process requires the identification of the failure modes of all components in the AGV system, assessment of their local and system effects, evaluation of the severities of their consequences, and assessing their likelihood by carrying out analysis of their failure data. The outcome of the FMECA will be a number of critical components in the AGV system that are identified based on their risk priority numbers (RPN_i) described in Section 2.7.3. The evaluation of the severity, failure frequency and detectability of AGV failures are performed based on [17] and modified for the research of the AGV system which allows the approach to map the data ranges applicable in the domain. The severity classification used in the research is based on the possible damage level and hazards caused by AGV failure. In addition, the different failure frequency levels are modified uniquely for the AGV subsystems considered.

In the calculation, severity level S_i is assessed using the method depicted in Table 4.2. The failure frequency F_i is assessed based on the ranges listed in Table 4.3. Detectability D_i is assessed based on the information described in Table 4.4. Any of these three parameters can be categorised into 5 levels based on their severity of the consequence or effect of the failure modes. A more detailed severity classification can be done, but may become arbitrary and lead to biased data analytics. The classification of failure frequency levels is conducted by mapping the actual failure frequency of AGV components and subsystems to different ranges. The detectability is the estimate of the probability that a failure mode can be detected, so that the effect of failure can be prevented. Again, to avoid the bias of data analytics, a sliding scale of 1 to 5 is defined as well.

Table 4.2 Severity assessment

Severity Level S_i	**Description**
1	No loss of any kind
2	Minor hardware damage, no effect on performance
3	Major property loss, degradation of item functional output such as brake fade.
4	Loss of critical hardware including all input subsystems and brake system of AGVs, human injuries, severe reduction of functional performance
5	Catastrophic loss of life, loss of the entire AGV system, serious damage to ambient environment

Table 4.3 Failure frequency assessment

Failure frequency F_i	**Discipline (where λ is failure rate)**
1	$\lambda \leq 0.01$ failures/ year
2	$0.01 < \lambda \leq 0.1$ failures/year
3	$0.1 < \lambda \leq 0.5$ failures/year
4	$0.5 < \lambda \leq 1$ failures/year
5	$1 < \lambda$ failures/year

Table 4.4 Detectability assessment

Detectability D_i	**Description**
1	Almost certain to detect
2	Good chance of detecting
3	May not detect
4	Unlikely to detect
5	Very unlikely to detect

Once the critical components in the AGV system and their failure modes are identified by using the FMECA method, the logical relations between the AGV mission failure, the failure events of the identified critical AGV subsystems, and their failure modes will be investigated by the approach of FTA. The resultant fault tree can be constructed by using the following method:

1. Three basic logical gates, i.e. AND, OR and NOT, are used to depict the logical relations between the failure events that result in the occurrence of a higher-level event;
2. AGV mission failure is set as the top event in the fault tree;
3. The phase failures and the effects caused by the failures are used as the intermediate events;
4. The various failure modes that lead to intermediate events are defined as the basic events in the fault tree.

Once the fault tree is obtained, the phase unreliability, the failure probability of each AGV subsystem during the period of completing a prescribed mission, and the probability that the AGV is able to complete the whole mission, can be calculated through performing the FTA. Hence, the reliability of the AGV system can be readily obtained. It is worth noting that the FTA is an ideal tool for performing the reliability analysis of an AGV system when it is relatively simple with no dependencies and the mission that it is asked to complete does not involve multiple tasks. However, when any complexities are involved or maintenance needs to be considered, FTA will not be applicable as all basic events considered in the FTA are assumed to be nonrepairable.

In respect to mission simulation, Mura & Bondavalli [104] proposed to use two distinct PNs, i.e. a system net and a phase net, to model phased missions. Such an idea was later on further extended by Chew et al. [101] to simulate more complex systems by using three distinct PNs, i.e. phase PN (PPN), subsystem PN (SPN) and master PN (MPN). These three kinds of PNs are linked together and interact with each other. Such an extended approach is adopted in this research.

4.5 The FMECA of AGV System

The full FMECA analysis of the AGV is performed in order to obtain a detailed understanding of the subsystem failures of the vehicle. To ease the understanding of the FMECA, as an exemplar, the FMECA of the LNS is shown in Table 4.5 the FMECA of all AGV subsystems is given in Table 4.6. As listed in Table 4.6, eight subsystems were identified for analysis. In the table, the subsystems and their functions, sub-items (if relevant), their failure modes generated for the local and system effects, severity ranking, frequency ranking, detectability ranking and risk priority number (RPN_i), are listed. The data for yielding the assessment ratings (1-5) in the table is based on [105] and the knowledge of experts from Automated Materials Handling Systems Association [106]. However, it should be noted that some data is still missed from the table, such as the sub-items of some subsystems, due to the shortage of reliable information. They can be supplemented in the future, and then the criticality will be re-evaluated once they are obtained. The failure frequencies are given in terms of number of failures per year. The resultant RPN can be determined from Equation (2.3) and then based on which the criticality of each event failure mode can be ranked.

The failure or malfunction of this subsystem is assumed to be 100% loss of its functions including failure to detect reflector marks within its working environment, failure to measure the distance with high precision, and failure to provide precise information about the AGV's absolute position. It can be broken down into four basic events, i.e. laser emitter failure, laser sensor failure, GPS failure, and signal transmitter failure. Their major failure modes are identified and their resultant failure effects are analysed. When a failure happens, the AGV will have to stop so that the allocated mission cannot be completed successfully. Besides failures, the path condition can impact the operation of AGV system as well. Although blocked path is unlikely to appear in this single-AGV system, it will bring a significant impact on the operation of a multi-AGV system, which will be discussed in later Chapters.

Table 4.5 The FMECA of the LNS

Identity	**Function**	**Sub-item**	**Failure Mode**	**Failure Effect**		S_i	**Failure rate λ (f/year)**	F_i	D_i	RPN_i
				Local Effect	**System Effect**					
LNS	Locate correct position. Send and receive the information of location coordinates	GPS	Fail to locate AGV	Halt Motion for safety	Routing and dispatching inhibited	3	0.25	3	4	36
		Signal transmitter	Unable to send information of location to the Central system	Halt Motion for safety	Routing and dispatching inhibited	3	0.25	3	4	36
		Laser emitter	Unit fails	Halt Motion for safety	Route block; AGV confliction	3	0.25	3	4	36
		Laser sensor	Unit fails	Halt Motion for safety	Route block; AGV confliction	3	0.125	3	4	36

In the RPN calculation, the failure frequency F_i of each failure mode is derived first based on the failure rate listed in Table 4.5 and the ranges given in Table 4.3. Once the RPNs of all considered failure modes are obtained, their criticalities can be ranked. In Table 4.5 the RPN values of all LNS failure modes are the same. This is because although the failure rate of the laser sensor is relatively lower than the failure rates of others, they are in the same failure frequency range, so they have the same level of effect on the AGV system and missions.

From the FMECA results in Table 4.6, it is seen that 18 failure modes are identified and among which, the drive unit is the most critical subsystem in the AGV due to its largest RPN value and the manual button has the lowest rank of criticality due to its smallest RPN value. Although the FMECA can help to identify the critical components/subsystems, it has several shortcomings when conducting the RPN calculations and the interpretations of the results. Firstly, the quantitative RPN assessment relies on subjective qualitative assessments such as the predicted severity and detectability. Also, the failure rate data is lost as they are transferred to the failure frequency range. Moreover, the relation between different failure components cannot be analysed. In order to overcome these issues, the FTA is adopted for further analysis.

In summary, the research described above has conducted a comprehensive risk assessment of AGVs at vehicle level to date. The assessment results can help the end-users of AGVs to understand how the AGV failed.

Table 4.6 The FMECA of the AGV

Identity/ Sub-system	Function	Sub-item	Failure Mode	Failure Effect		Severity S_i	Failure Rate λ (f/year)	Failure Freq. F_i	Detect-ability D_i	RPN_i	Crit. Rank
				Local Effect	System Effect						
(1) Drive Unit	Perform movement at different speeds and turn		Unit fails	Fail to move at different speeds and turn	Route blocked and AGV conflict	3	1	4	1	12	10
			Circuit Connection Fails	Fail to move at different speeds and turn	Route blocked and AGV conflict;	3	0.5	3	3	27	7
(2) AGV Software Control System	Connected with central system, control the AGV routing, loading and unloading		Control system fails	Unable to move	Task fails;	3	2	5	4	60	2
			Control System malfunction	Unable to move, turn, load and unload	Collision; Task fails;	4	4	5	5	100	1
(3) Laser Navigation System	Locate correct position. Send and	Global Positioning System (GPS)	Fail to locate AGV	Halt Motion for safety	Routing and dispatching inhibited	3	0.25	3	4	36	4

	receive the information of location coordinates	Signal transmitter	Unable to send information of location to the Central system	Halt Motion for safety	Routing and dispatching inhibited	3	0.25	3	4	36	4
		Laser emitter	Unit fails	Halt Motion for safety	Route block; AGV confliction	3	0.25	3	4	36	4
		Laser sensor	Unit fails	Halt Motion for safety	Route block; AGV confliction	3	0.125	3	4	36	4
(4) Safety Systems	Detect other AGVs and any obstacles	Laser emitter	Unit fails	Halt Motion for safety	Route block; AGV conflict	3	0.25	3	4	36	4
		Laser sensor	Unit fails	Unable to commit detection	Collision; Task fails;	4	0.125	3	4	48	3
(5) Attachment	Load and unload items	Transfer part	Worn, fatigue, Looseness	Loss of transport	Drop items; Human injury	4	1	4	2	32	5
		Holding part	Worn, fatigue, Looseness	Loss of pick-up function	Drop items; Human injury	4	1	4	2	32	5

(6) Batteries (lead Acid)	Provide energy for movement, item transfer, navigation system and others		Performance degeneration	Less navigation time	Unpredictable stop	2	1	4	3	24	8
			Leakage	Damage of other devices or even cause fire	Fire; Toxic chemicals to environment	5	0.125	3	2	30	6
			Overheat	Damage of other devices or even cause fire	fire	5	0.125	3	1	15	9
(7) Brake System	Slow down on time and emergency stop	Brake shoe	Worn out; looseness	Longer brake distance	Human injury; Collision	4	0.2	3	2	24	8
(8) Steering System	Change direction		Unit Fails	Unable to turn	Task fails	3	0.25	3	4	36	4
(9) Manual button	Power cut		Button is stuck	Unable to stop manually	Fail in manual control	2	0.05	2	2	8	11

4.6 Fault Tree Analysis of AGV Mission

FTA provides a tool for working directly with the failure rate data. This method allows a system failure to be expressed in terms of the failure of its components and subsystems. Moreover, with the aid of FTA, the probability of system or mission failure can be computed via Boolean logic calculations. Different from the FMECA table format, FTA provides a graph aided method for system analysis and management.

Given the AGV undertakes a mission that comprises a sequential series of objectives of varying time durations, the AGV mission may be regarded as a phased mission, of which the phases are individual objectives or time periods in the mission. In each phase, the relation between the relevant subsystems needs to be understood. The failure models of these phases within the mission have been developed and analysed using the FTA. The construction of the fault trees for phased missions is started by identifying the logic of different phases and their effects on the success of mission. Therefore, 'mission failure' is chosen as the top event, and the 6 phases defined in Section 4.3 are used as intermediate events. The logic between the top event and these branch events is shown in Figure 4.2. It shows that all 'failure in phase' events are joined under an 'OR' gate, so that the mission will fail once the AGV fails during any of these phases as the mission of the AGV has been modelled as a MFOP.

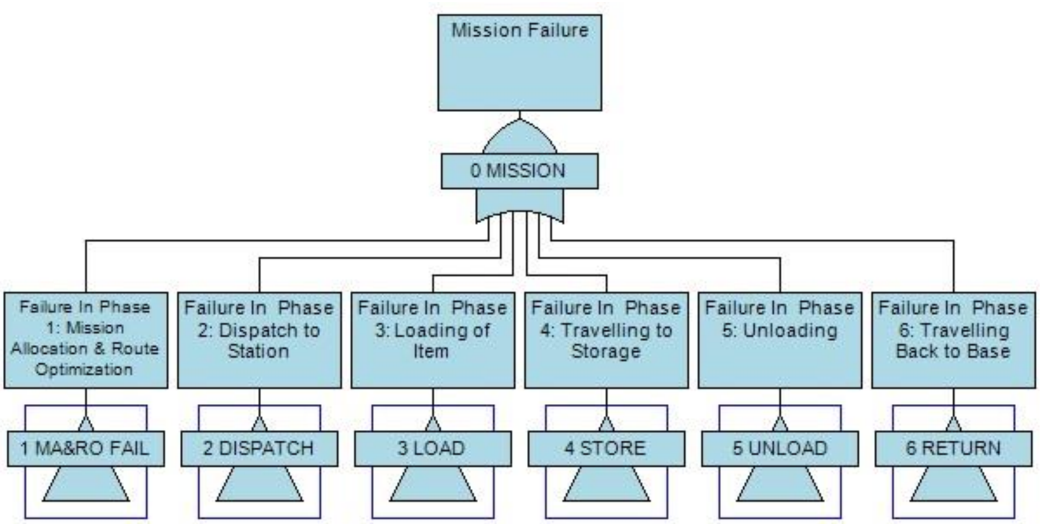


Figure 4.2 Logic between the top mishap and branch events

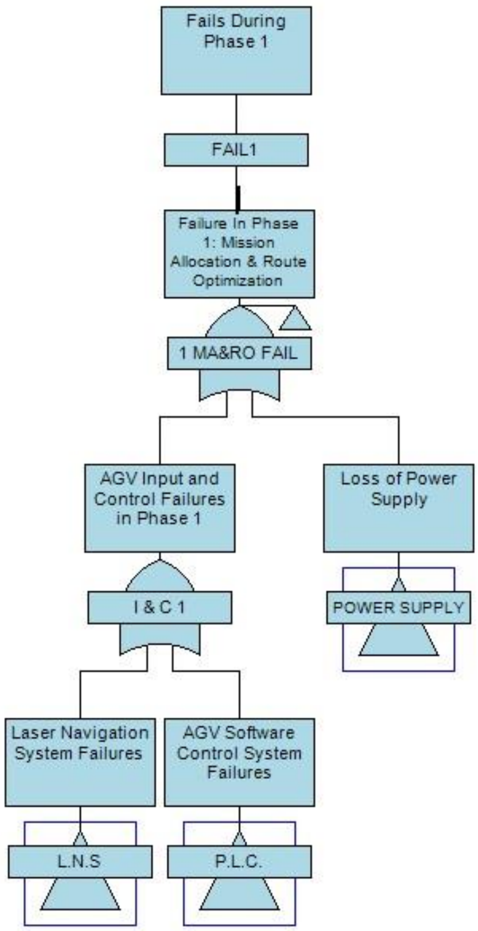
The fault tree is further developed in order to investigate the logic between every phase and the failure modes of the related AGV subsystems. The subsystem failures that can lead to different phase failures are listed in Table 4.7. It is worth noting that the manual button listed in the FMECA table is not involved in the FTA since it is not involved in any normal working phases of the AGV and it will be used only when the AGV is no longer able to complete its mission.

Table 4.7 Subsystems failures causing system failure at each phase

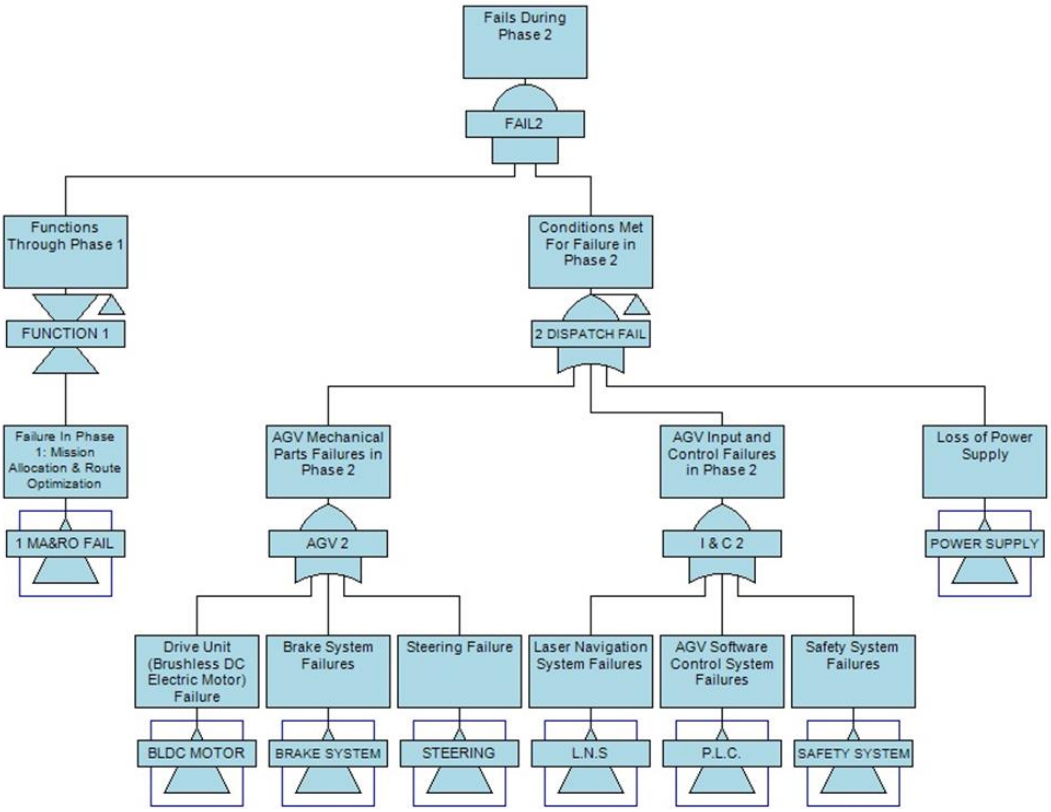
Phase	Component failures causing system failure at each phase
1	ASCS; LNS; Batteries
2	Drive unit; Brake system; Steering system; ASCS; LNS; Safety system; batteries
3	Attachments; Brake system; ASCS; Safety system; Batteries
4	Drive unit; ASCS; LNS; Safety system; Attachments; Batteries; Brake system; Steering system
5	Attachments; Brake system; ASCS; Safety system; Batteries
6	Drive unit; ASCS; LNS; Safety system; Batteries; Brake system; Steering system

The resultant fault trees for all phases are shown in Figure 4.3. Where, the failure during the phase is used as the top event, the failures of those AGV subsystems that are involved in the phase are intermediate events. To illustrate the phase relationships, phase 1 and phase 6 are discussed in detail. Phase 1, shown in Figure 4.3(a), is for 'mission allocation and route optimisation', where firstly the AGV's position needs to be located by the LNS. Then, all routes for completing the phase mission need to be optimised via the ASCS. The phase cannot be completed once either the LNS or ASCS fails to work properly.

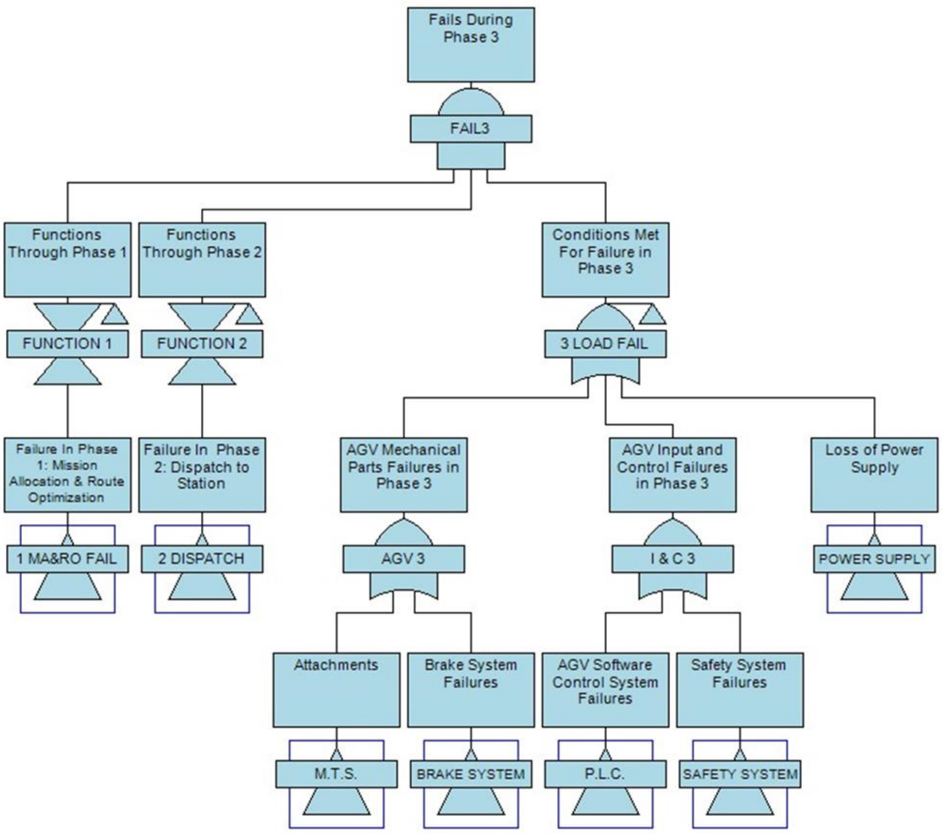
The fault tree developed for Phase 6 is shown in Figure 4.3(f). In this phase, the AGV will travel from the storage back to the base. During this period, the ASCS will control the AGV to travel along the optimised route, the LNS will locate the AGV as it moves, the motor will drive the vehicle, the steering system will enable vehicle turning, the safety system will perform an obstacle scan, and the brake system will slow down the vehicle when turning and stop the vehicle to avoid collisions if necessary. Obviously, the success of phase 6 of the mission relies on the synchronous cooperation of all these subsystems. The failure of either of them can lead to the failure of the AGV during phase 6. In addition, phase 6 can be started only after all of the previous phases 1-5 have been completed successfully. This is shown in Figure 4.3(f) with the events from 'Functions Through Phase 1' to 'Functions Through Phase 5' and 'Conditions Met For Failure in Phase 6' joined under an 'AND' gate. The event 'Functions in phase 1' is the event 'Failure in Phase 1' under a 'NOT' gate, likewise for phase 2 to phase 5. In general, the mission failure in phase j+1 is the combined result of successful phases 1 to j and the system failure occurring in phase j+1 via an 'AND' gate and the 'NOT' gate is used to represent system success during phases 1 to j. In these models, all of the corresponding subsystems in each phase are required to work properly and synchronously as well and all previous phases must have been completed successfully.



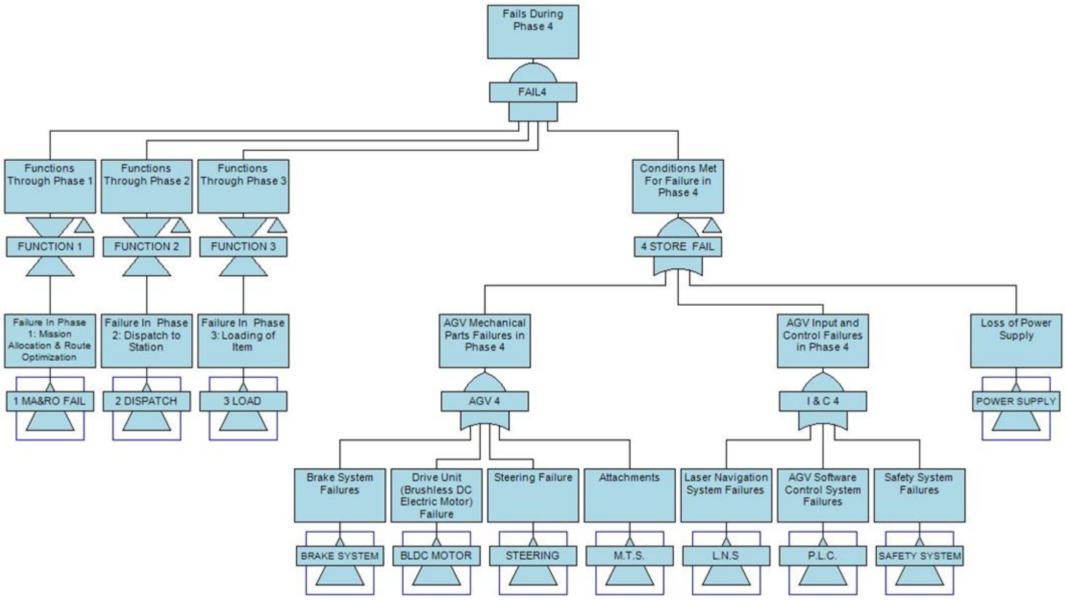
(a) Phase 1



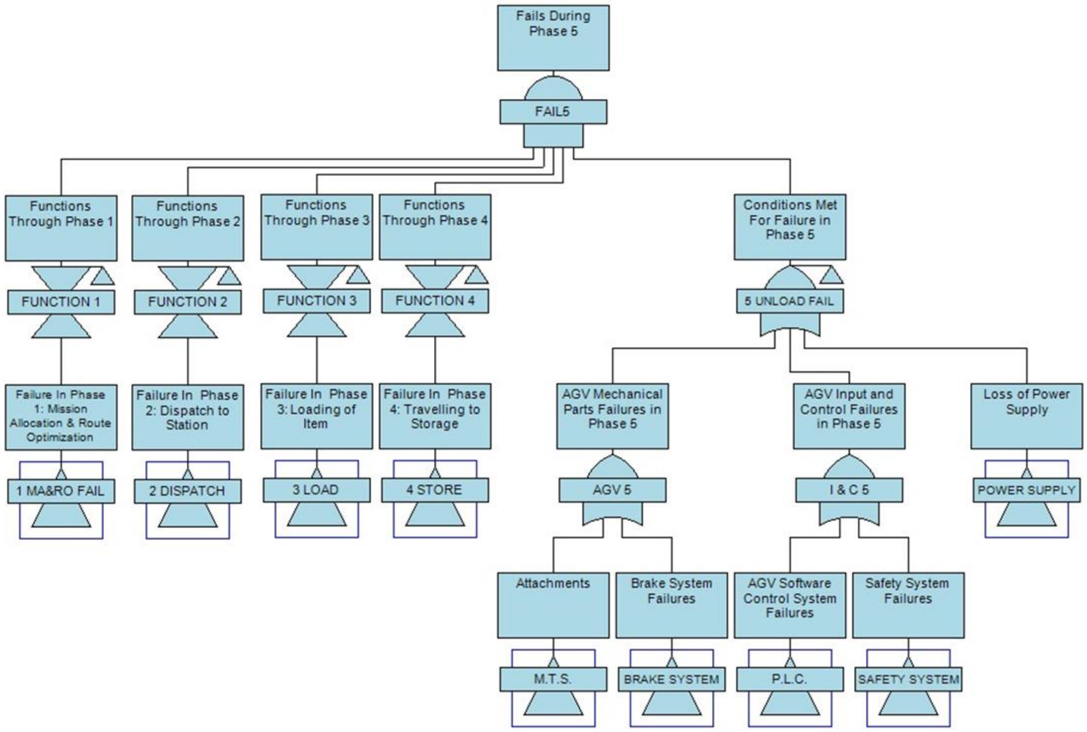
(b) Phase 2



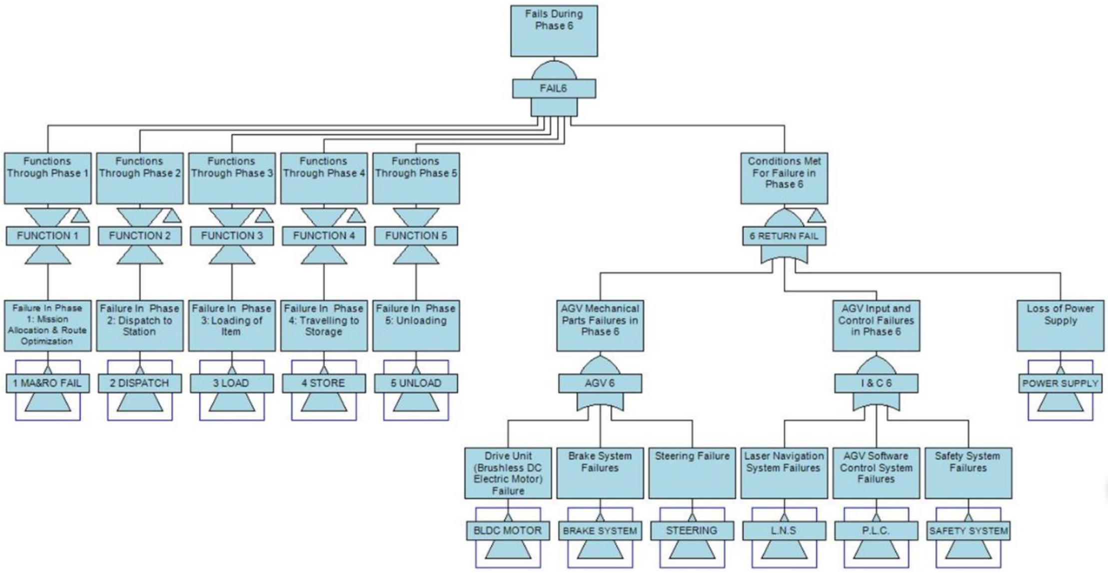
(c) Phase 3



(d) Phase 4



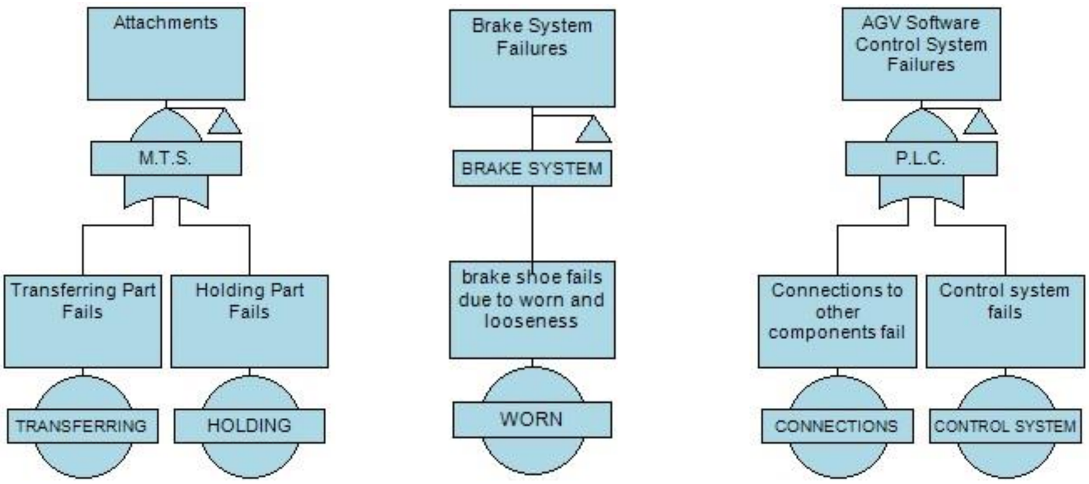
(e) Phase 5



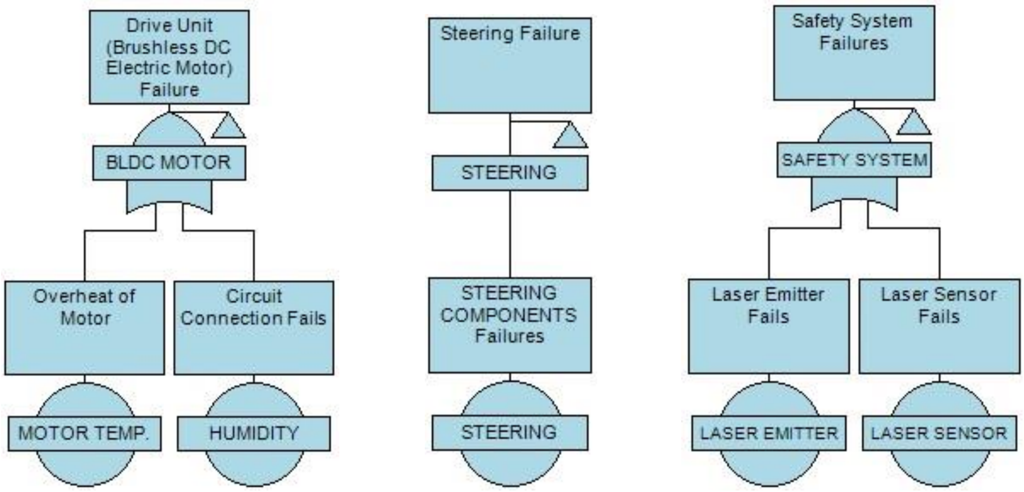
(f) Phase 6

Figure 4.3 Fault trees for six phases

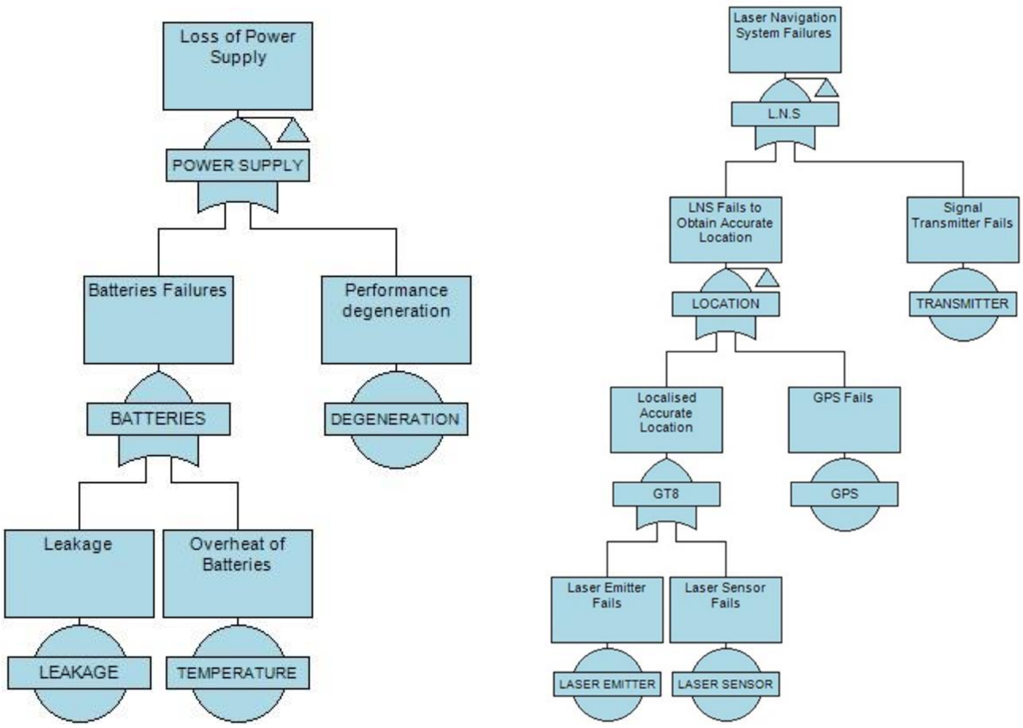
Furthermore, in order to complete the FTA, the fault trees for all the identified critical AGV subsystems are further constructed (namely the triangular events surrounded with a blue rectangular in each diagram of Figure 4.3). The corresponding fault trees for all subsystems are shown in Figure 4.4. As an example, the failure of the laser navigation system (LNS) is shown in Figure 4.4(h). This subsystem failure can be broken down into four basic events, i.e. laser emitter failure, laser sensor failure, GPS failure, and signal transmitter failure. In total, eight subsystem level fault trees have been constructed, varying in size from just 1 gate and 5 events to 3 gates and 11 events.



(a) Attachments (b) Brake system (c) AGV Software control system



(d) Drive unit (e) Steering system (f) Safety System



(g) Power supply (h) Laser navigation system

Figure 4.4 Subsystem level of fault trees

The later the phase in the mission, the larger its fault tree is, as the number of phases that must have been completed successfully increases. For example, the fault tree of phase 6 requires the successful completion of all the previous five phases, this results in the tree containing 73 individual events and 44 gates.

Following this understanding of the interrelations between the failures of the AGV system, this information can be used to establish the failure probability of the AGV subsystems and phases. As a systemic FTA method has been developed in [101] dedicated to modelling phased mission with MFOP, it is used in this research to calculate the mission reliability and phased unreliability of the AGV within MFOP based on the phase lengths assumed in Table 4.1 and the FMECA information obtained in Table 4.6. The details of the calculation method are given below.

Firstly, the system failure in phase j, i.e. T_j, is calculated by using the following equation:

$$T_j = (\text{Phase } 1 \text{ to } j-1 \text{ Success}).(\text{Phase } j \text{ Failure}) \tag{4.1}$$

As an example of how these results were obtained, consider phases 1 and 2. Due to the existence of 'NOT' gates in the phase fault trees for failure during any phase after the first one, the fault trees are non-coherent discussed in Section 2.7.4. In this case, the occurrence of the system failure in the phase can be expressed using the prime implicants. This is referred to as qualitative fault tree analysis. For example, the prime implicants for failures within phase 1 and phase 2, respectively represented by T_1 and T_2, can be computed using the following expressions:

$$\begin{aligned} T_1 &= Failure\ in\ P1 \\ &= ASCS_1 + LNS_1 + Battery_1 \end{aligned} \tag{4.2}$$

$$\begin{aligned} T_2 &= (Failure\ in\ P2).(Success\ up\ to\ P2) \\ &= \big(DC_{1,2} + Brake_{1,2} + steering_{1,2} \\ &\quad + ASCS_{1,2} + LNS_{1,2} + SS_{1,2}\big).\overline{(ASCS_1 + LNS_1 + Battery_1)} \end{aligned} \tag{4.3}$$

where subscript '1' denotes failure in phase 1 and subscript '1,2' denotes failure in any phase from 1 to 2. Expressions T_1 and T_2 are obtained from the fault trees for phases 1 and 2, respectively. "+" and "." represent the 'OR' and 'AND' gates in the fault tree, respectively. The 'NOT' gates are mathematically expressed by a bar above the terms. In addition, different from ".", symbol "·" represents dot product as shown in Equation (4.4). It is worth noting that as the number of components and phases increases, the derivation of prime implicants will become more complex. Once the prime implicants are known, the calculation of unreliability in phase 1 and phase 2 can be conducted using the inclusion-exclusion principle as shown in [101]. For example, the probability of failure up to the end of phase 1, Q_1, can be calculated by

$$
\begin{aligned}
Q_1 = Pr(ASCS_1) + Pr(LNS_1) + Pr(Battery_1) - Pr(ASCS_1.LNS_1) \\
- Pr(ASCS_1.Battery_1) - Pr(LNS_1.Battery_1) \\
+ Pr(ASCS_1.LNS_1.Battery_1) \\
= q_{ASCS_1} + q_{LNS_1} + q_{Battery_1} - q_{ASCS_1} \cdot q_{LNS_1} - q_{ASCS_1} \cdot q_{Battery_1} \\
- q_{LNS_1} \cdot q_{Battery_1} + q_{ASCS_1} \cdot q_{LNS_1} \cdot q_{Battery_1}
\end{aligned}
\tag{4.4}
$$

The three minimum cut sets for phase 1 are $ASCS_1$, LNS_1, and $Battery_1$, respectively. To analyse the fault trees quantitatively, the probability of failure of basic event *A* in all phases from i to j (i.e. $q_{A_{i,j}}$) is calculated using the equation:

$$q_{A_{i,j}} = e^{-\lambda_A t_{i-1}} - e^{-\lambda_A t_j} \tag{4.5}$$

where λ_A refers to the failure rate of a basic event *A*, t_j is the length of phase j.

The unreliability or failure probability of phase j (P_j) can be determined using:

$$
\begin{aligned}
Pr(P_j\ Failure) = 1 - \frac{Success\ up\ to\ end\ of\ P_j}{Success\ up\ to\ end\ of\ P_{j-1}} \\
= 1 - \frac{1 - Q_{1,j}}{1 - Q_{1,j-1}}
\end{aligned}
\tag{4.6}
$$

where $Q_{1,j}$ refers to the unreliability in all phases from 1 to j. It should be noticed that the probability of failure is calculated using the exponential distribution as it is assumed that the AGV fails when the components are in the period of their useful life.

In the FTA calculation, a component will be considered only when it is involved in the completion of a phase mission. It will not be considered if it contributes nothing to the phase mission. Applying the aforementioned method, the component failure probability, mission reliability, and phased unreliability of the AGV within MFOP can be calculated. The results are given in Table 4.8 and Table 4.9.

Table 4.8 Subsystem failure probability at the end of whole mission obtained by FTA

Description	Failure Probability at mission end
AGV Software Control System	0.00034925
Attachments	0.00009360
Drive Unit	0.00008725
Batteries	0.00007277
Laser Navigation System	0.00005094
Safety Systems	0.00002183
Steering System	0.00001455
Brake System	0.00001164

Table 4.9 The resultant mission reliability and phase unreliability obtained by FTA

Phase	Mission reliability at phase end	Phase unreliability
1. Mission Allocation & Route Optimisation	0.99998	0.00001855
2. Dispatch to Station	0.99974	0.00024386
3. Loading of Item	0.99967	0.00007266
4. Travelling to Storage	0.99945	0.00021915
5. Unloading	0.99942	0.00002243
6. Travelling Back to Base	0.99930	0.00012527

Usually, the importance measures are used to evaluate the contribution of each subsystem failure to the occurrence of the failure of the whole system. The ranking of their calculation results can indicate the key subsystems. However, the problems considered in this thesis belong to a kind of non-coherent FTA problems consisting of multiple phases, which are difficult to be assessed via the commonly-used importance measures described in Section 2.7.4.

From the results shown in Table 4.8, it is seen that the ASCS, attachments, drive unit and battery have the largest failure probability at the end of the whole mission. That implies these four components are most vulnerable to failure.

From Table 4.9, it is found that the mission reliability at the end of the 6th phase is 0.99930, which is based on the success of all six phases. This means that the AGV has more than 99% probability to complete the mission successfully. This value, in fact, indicates the overall reliability of the AGV in accomplishing the whole mission. In addition, Table 4.9 shows that phase 2 'dispatch to station' and phase 4 'travelling to storage' show the largest phase unreliability values. This means that the AGV is more likely to fail in the completion of these two phases.

In this Section, the FTA is employed to investigate the reliability issues existing in the AGVs that are being increasingly used for intelligent transportation and material distribution. Moreover, with the aid of the FMECA, the critical AGV components and the crucial mission phases of AGVs can be identified at the design stage. From these studies, it is found that the reliability issues of the AGVs can be investigated more effectively if the mission and the AGV subsystems can be considered simultaneously. However, it is difficult to use the FTA to study the impact of the AGV failure on the system performance if there are more than one AGVs running in the system. This is because the problems related to the interactions between AGVs (such as deadlock and conflicts caused by failed AGVs) cannot be shown and included in the FTA. In addition, the phase lengths could vary dynamically because the AGVs in a larger and more complex system may take different routes for completing different missions. The FTA is not capable of modelling these kinds of attributes. For these reasons, an alternative method should be adopted to overcome these issues.

4.7 PN Simulation

Dynamic simulation is well known for studying the dynamic time varying behaviour of a system. In this Section, Petri Net (PN) simulation is adopted to investigate the reliability of the aforementioned AGV mission. The development of the PN simulation model involves a three-tiered approach, i.e. subsystem Petri Net (SPN) will be fed to phase Petri Net (PPN), and then the PPN will be used as the information fed to master mission Petri Net (MPN).

4.7.1 Subsystem Petri Net (SPN)

Assume any failure mode can lead to subsystem failure and thus system failure, then the modelling for the failure modes of AGV subsystems can be simplified. Given the modularity of the subsystems, this is chosen as the starting point for the lower tier of PN models, called the subsystem Petri Net (SPN) model, as shown in Figure 4.5.

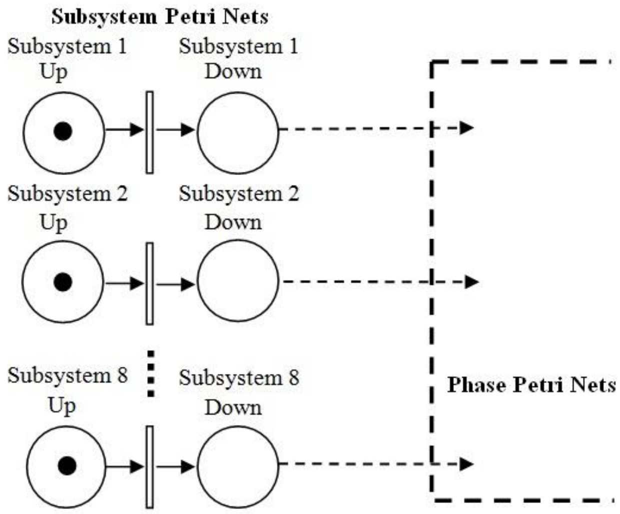


Figure 4.5 Subsystem Petri Net

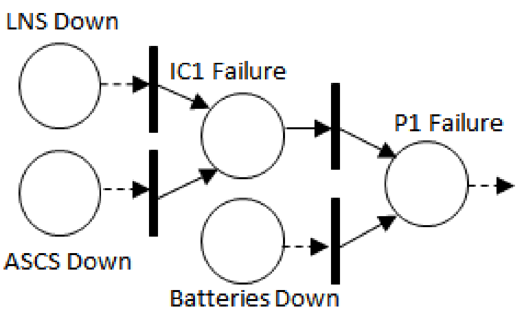
The subsystem labels 1–8 correspond to the subsystems listed in the FMECA table. These PN models are used to model the health states (i.e. working state and failed state) of each AGV subsystem. For more complex architectures, this tier can have a preceding tier represented by component models. As the mission has been modelled as a MFOP, the repair of subsystems will not be considered in this study. Therefore, the SPN will show only two kinds of health states, i.e. ‘subsystem up’ and ‘subsystem down’. Once a subsystem fails after working for a certain time period, the token in the ‘subsystem up’ place will be transferred to the ‘subsystem down’ place. The time for this failure transition can be computed based on the component failure rate data given in [17] by using the random sampling and exponential distribution method. The exponential probability distribution is selected to describe the time between events occurring continuously and independently at a constant average rate. The cumulative distribution function F is defined as

$$F(t;\lambda) = \begin{cases} 1 - e^{-\lambda t} & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{4.7}$$

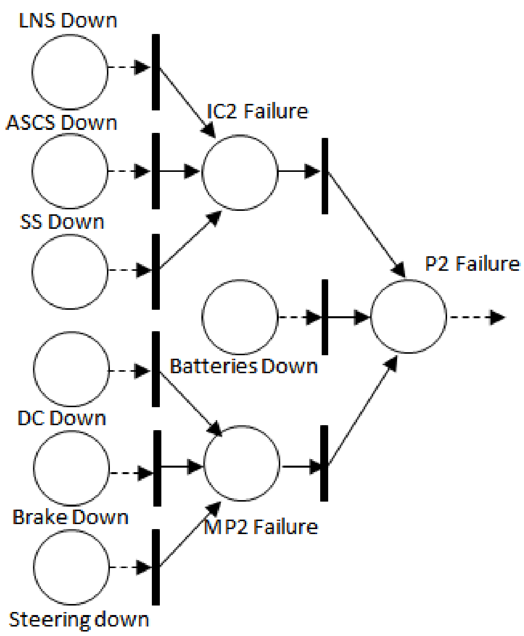
where λ is failure rate, and t is time. The information about subsystem failures can then be fed into the phase Petri Net (PPN) models using linking-arcs that are indicated by the dashed lines in Figure 4.5.

4.7.2 Phase Petri Net (PPN)

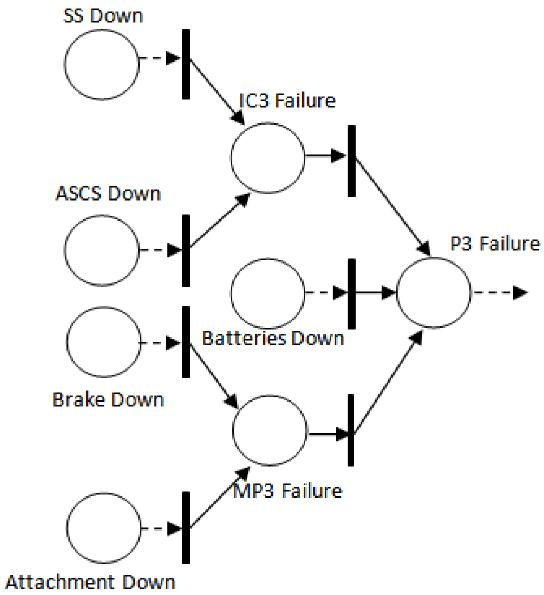
The PPN presents the interrelated subsystem failure mechanisms that correspond to failure in the phase. The logic used for implementing the FTA can be used again for constructing the PPNs. For this reason, the PPNs constructed for phases 1 to 6, which correspond to the fault trees in Figure 4.3, are shown in Figure 4.6. The transitions are instantaneous and represented by solid rectangular bars. Through comparing the fault trees in Figure 4.3 with the corresponding PPNs in Figure 4.6, it can be found that there is no place in the PPNs that can indicate the logic between the failed event and the previous phases that have been successfully completed in the fault tree. This will be dealt with using the Master Petri Net (MPN) described in the following Section. Tokens are absent from all places in Figure 4.6, indicating that the whole AGV system is in a good health condition. In other words, the presence of a token in a place will mean the presence of a failure in either a subsystem or a phase.



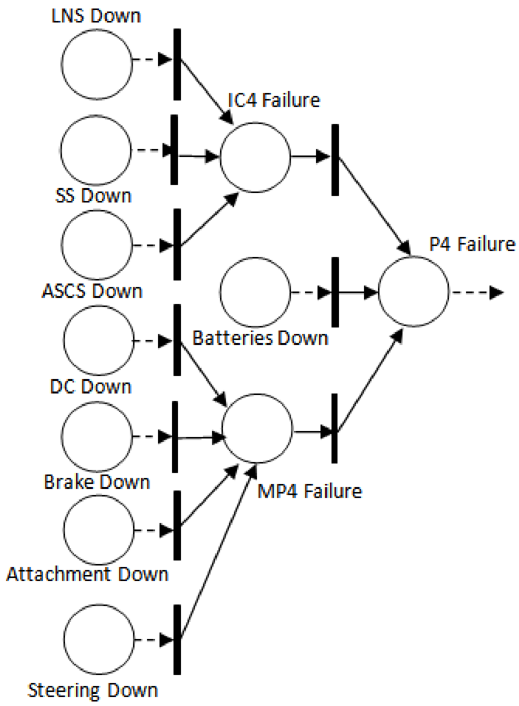
(a) Phase 1



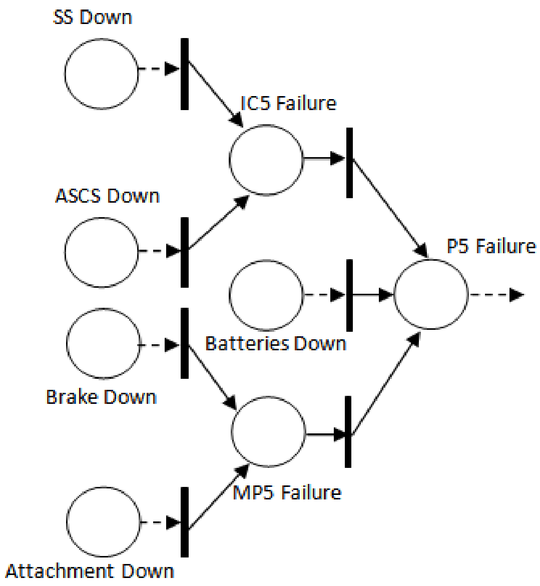
(b) Phase 2



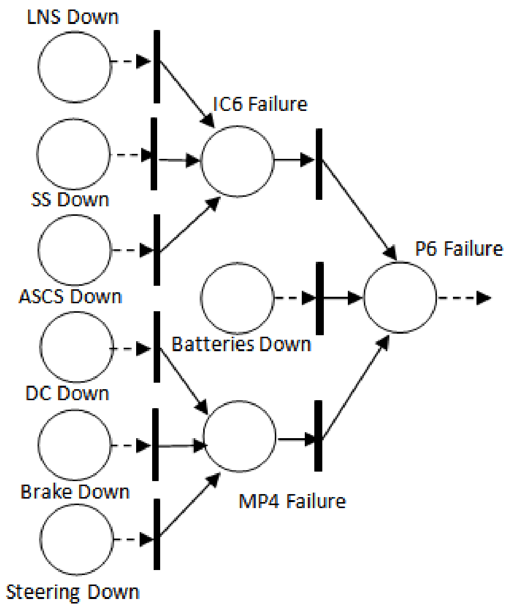
(c) Phase 3



(d) Phase 4



(e) Phase 5



(f) Phase 6

Figure 4.6 Phase Petri Nets

4.7.3 Master Petri Net (MPN)

The MPN is used to govern the change of phases from the beginning of the mission, phase 1, to the successful completion of the whole mission, at the end of phase 6. Figure 4.7 shows the structure of the MPN, where a token in the phase place is used to indicate the phase that the AGV is operating in. The system failure happening in each phase, i.e. the top event of the PPN for that phase, will directly result in the failure of the whole mission. Hence, if the AGV is operating in phase *i* so that a token resides in place 'phase *i*' and the AGV fails in that phase, so a token is in place 'P*i* failure' then a token will be transferred to the system failure place, so that the mission fails. The switching time of transition between two neighbouring phase places is the length of the preceding phase. Likewise, the switching time of transition between phase 6 and mission finish is the length of phase 6. If the AGV completes all six phases without failure, then a token will be placed in the 'simulation success' place.

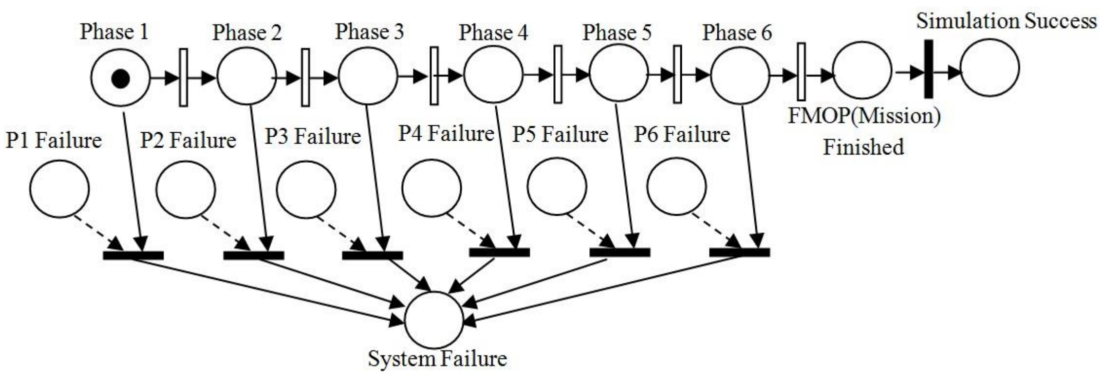


Figure 4.7 Master Petri Net

4.7.4 Simulation Model

In order to calculate results about how reliable the operation of the AGV mission is, the PN model has been embedded in a simulation model. The failure rates of all AGV subsystems are given in Table 4.6. To implement FMECA, FTA and PN simulations, the length (i.e. time duration) of each identified phase is assigned a value as listed in Table 4.1. The total time duration to complete the whole mission is 0.51 hours (i.e. 30.6 minutes). It is worth noting that the data presented in Table 4.1 is empirical data based on the consultation with an AGV operator. Hence, the values of time duration would be different when considering different AGV applications such as distribution centres, dock terminals, flexible manufacture systems and so on [2, 42, 56]. Then, the simulation is programmed in Python. The relevant calculations are conducted on a personal computer with Window 10 operation system. The specification of the computer is Intel(R) Core(TM) i7-7500U CPU @ 2.70GHz, 16GB RAM. The calculations are implemented using the following steps that are established based on the logic illustrated in Figure 4.8.

Step 1: Import the phase lengths into the MPN and in parallel, generate the switching time of the transitions of each subsystem in the CPN's by using the random sampling and exponential distribution method;

Step 2: Find the transition with the minimum switching time and then switch it;

Step 3: Search through the immediate transitions that are directly connected to the present place. If any are found enabled, switch them;

Step 4: Repeat Step 3 until no more immediate transition are enabled;

Step 5: Test for any of the following conditions and log them:

a) if system has failed, begin next simulation;

b) if mission has completed, begin next simulation. If not, go back to Step 2.

Step 6: Iterate the above simulation for *n* times based on the assumption that the reliability of the AGV system can be obtained by repeating the simulation.

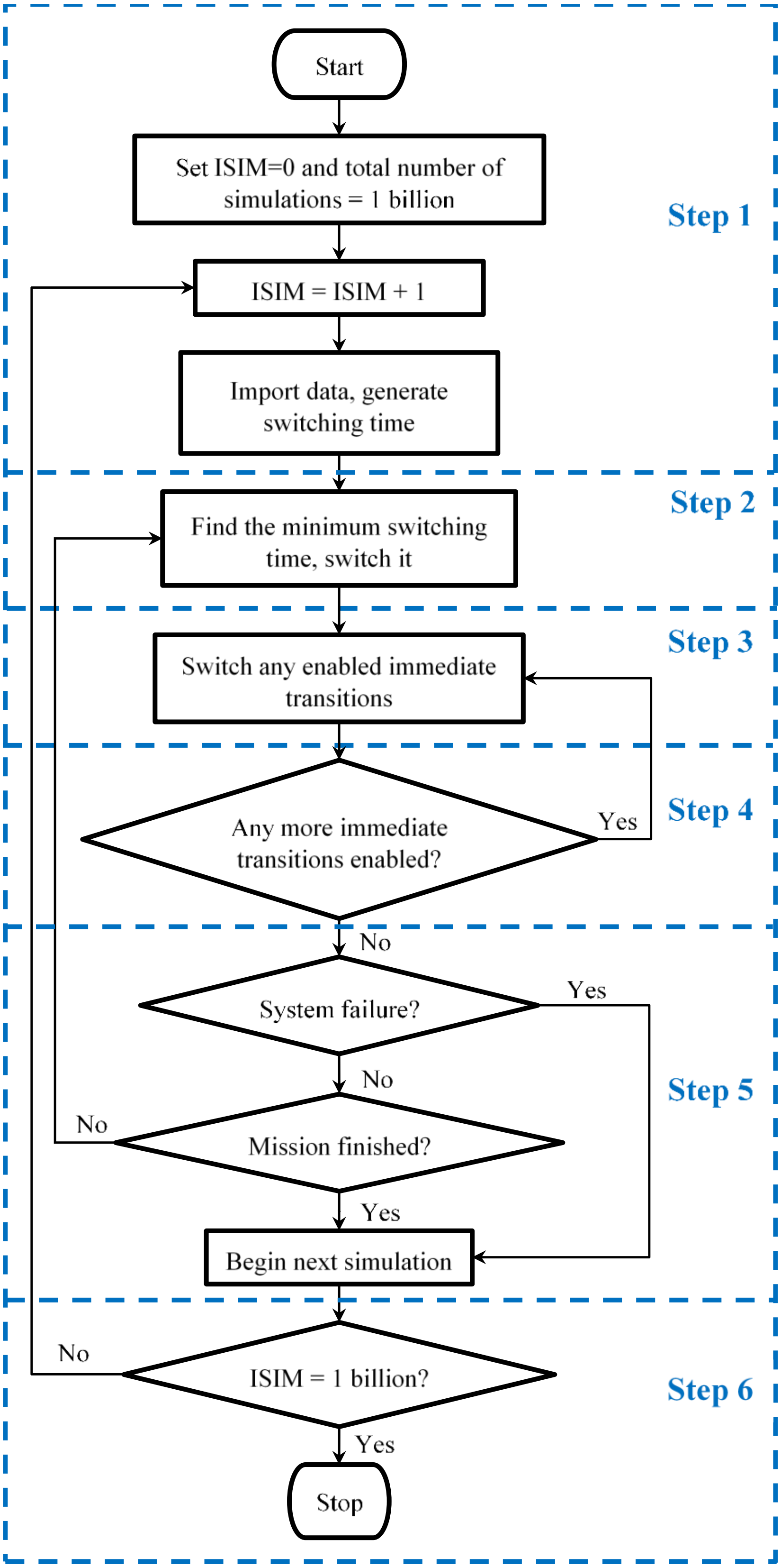


Figure 4.8 Simulation flowchart

According to the simulation flowchart shown in Figure 4.8 and the corresponding description from Steps 1 to 6, the PN simulation of a single-AGV system can be programmed as the pseudo code given in Figure 4.9. It should be noted that the program can be readily adapted for 'AND' gates. Firstly, the MCSs should be obtained. Then, the subsystem or component with the longest surviving time (T_{LS}) in each MCS can be identified. Hence, after the system operation time is greater than any of T_{LS}, it means at least one MCS has failed, which will immediately lead to a system failure.

```
Single-AGV System PN Simulation (MFOP=n missions)
Input: Phase time, failure rate, MFOP=n
While j< Max Iteration:
Generate: Time of each transition
Time=0
Mission=0
        while mission<n:
                i=0
                For i< number of phases:
                        if Time <= minimum (Failure time):      # for OR gates only
                        [if Time <= minimum (maximum (MCS1), maximum
                (MCS2), ..., maximum (MCSn)):      # for AND gate (n Minimum Cut Sets
                (MCSs))]
                                Time = Time + Phase i Time
                                i+=1
                        else:
                                Count number of mission failed
                                Count number of failure in phase (i+1)
                        if i== number of phases:
                        Count number of mission completed
                        break
                end for
                mission = mission +1
        end while
        j=j+1
end while
Postprocess results and visualisation
```

Figure 4.9 Pseudo code of single-AGV PN simulation

4.7.5 *Simulation Results and Validation*

Through embedding the PN into a simulation, the phase unreliability and mission reliability are calculated. The results are listed in Table 4.10. In order to ensure the reliability of calculation results, one billion simulations are performed to reach a good convergence of the computing result, which takes about 1.5 hours. The calculation results are validated by comparing them with the phase and mission reliability results obtained using the FTA (see Table 4.9). The comparison has shown that the simulation results obtained from the PN model are very close to the analytical solutions derived from the FTA. The simulation errors of both the unreliability of each phase and the mission reliability at the end of each phase are below 1% as shown in Table 4.11. This demonstrates that the PN method is as accurate as the FTA in the reliability assessment of AGVs.

Table 4.10 PN simulation results

Phase	Phase failures	Phases started	Phase unreliability	Mission reliability at phase end
1	18449	1000000000	0.00001845	0.999982
2	244863	999981551	0.00024486	0.999737
3	72843	999736688	0.00007286	0.999664
4	218911	999663845	0.00021898	0.999445
5	22488	999444934	0.00002250	0.999422
6	125509	999422446	0.00012558	0.999297

Considering the convergence of the results, Figure 4.10 shows the comparison of the analytical and simulation results of the unreliability of phase 1 against the number of simulations. From the figure, it is seen that the value of the unreliability of phase 1 obtained from the simulation has converged to the analytical result after performing approximately 100 million simulations. Similar results were found for the other phases. Hence, performing one billion simulations should be enough to guarantee the reliability of the calculation results.

Table 4.11 Comparison of analytical and simulation unreliability results

Phase	FTA Analysis	PN Simulation	Average error %
1	0.00001855	0.00001845	0.545
2	0.00024386	0.00024486	0.412
3	0.00007266	0.00007286	0.282
4	0.00021915	0.00021898	0.077
5	0.00002243	0.00002250	0.309
6	0.00012527	0.00012558	0.243

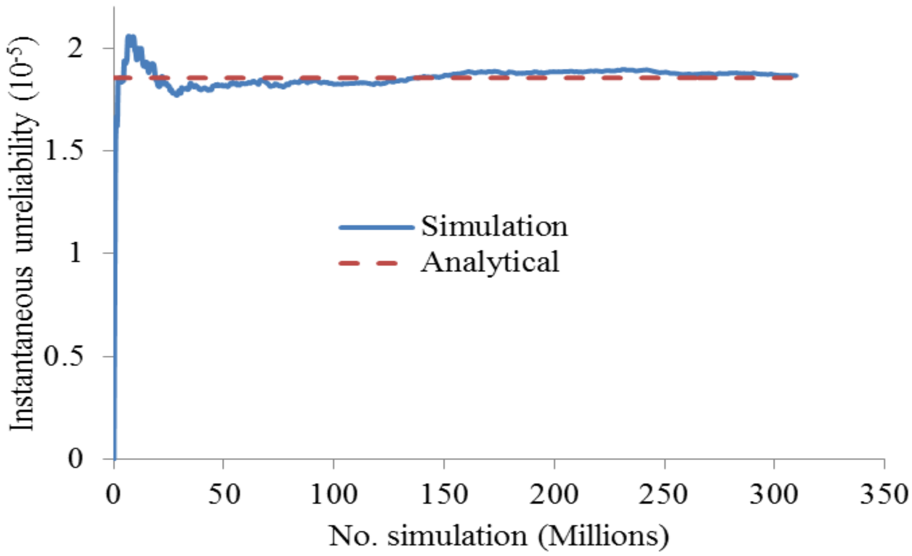


Figure 4.10 Convergence of phase 1 unreliability

From the results in Table 4.10, it is found that phase 2 ‘dispatch to station’ and phase 4 ‘travelling to storage’ show the largest phase unreliability values. This means that the AGV is more likely to fail when it undertakes the tasks in these two phases. Additionally, it is found that the mission reliability at the end of the 6th phase is 0.999297, which is based on the success of all six phases. Therefore, this value also indicates the overall reliability of the AGV in accomplishing the whole mission. This means that the AGV has more than 99% chance to complete the mission successfully. Based on these calculation results, it can be concluded that the AGV studied here is a very reliable material distribution vehicle in the warehouse. However, these results are for only one mission. In practice, the AGV is expected to perform numerous missions.

So, how its reliability evolves with the increasing number of missions becomes an interesting question. The answer for this question can be inferred from Table 4.10. From the table, it is seen that the mission reliability at the end of each phase decreases gradually with the increase of the number of phases that the AGV has successfully completed. This suggests that if without maintenance service, the more missions are completed, the more unreliable the AGV system will tend to be.

To further demonstrate this tendency, the PN model has been run to simulate the AGV system that performs continuous consecutive missions without receiving any maintenance. The results for 600,000 MFOPs and each MFOP contains 500 consecutive missions are shown in Table 4.12, in which the unreliability for each phase is shown. The number of simulations, failures, and reliabilities for each mission and overall MFOP are listed in Table 4.13. It is seen that the reliability of the AGV for completing the MFOP with 500 missions is 0.69547667. Obviously, such a method is very helpful for determining the optimal inspection interval for performing the maintenance of the AGV.

Table 4.12 Phase failures during 600000 MFOP simulations

Phase	Phase started	Failures in				Total failure	Phase unreliability
		Mission 1	Mission 2	…	Mission 500		
1	251755556	7	12	…	7	4667	0.00001854
2	251750889	162	138	…	101	61589	0.00024464
3	251689300	41	54	…	47	24193	0.00009612
4	251665107	115	132	…	82	55059	0.00021878
5	251610048	11	9	…	10	5654	0.00002247
6	251604394	69	75	…	66	31552	0.00012540

Following this logic, the reliability of the MFOPs that have different numbers of consecutive missions is calculated via simulation. The simulation results are shown in Figure 4.11.

Table 4.13 MFOP and mission failure results

MFOP/mission	Starts	Failures	Reliability
Mission 1	600000	405	0.99932500
Mission 2	599595	420	0.99929953
⋮	⋮	⋮	⋮
Mission 500	417599	313	0.99925048
MFOP	600000	182714	0.69547667

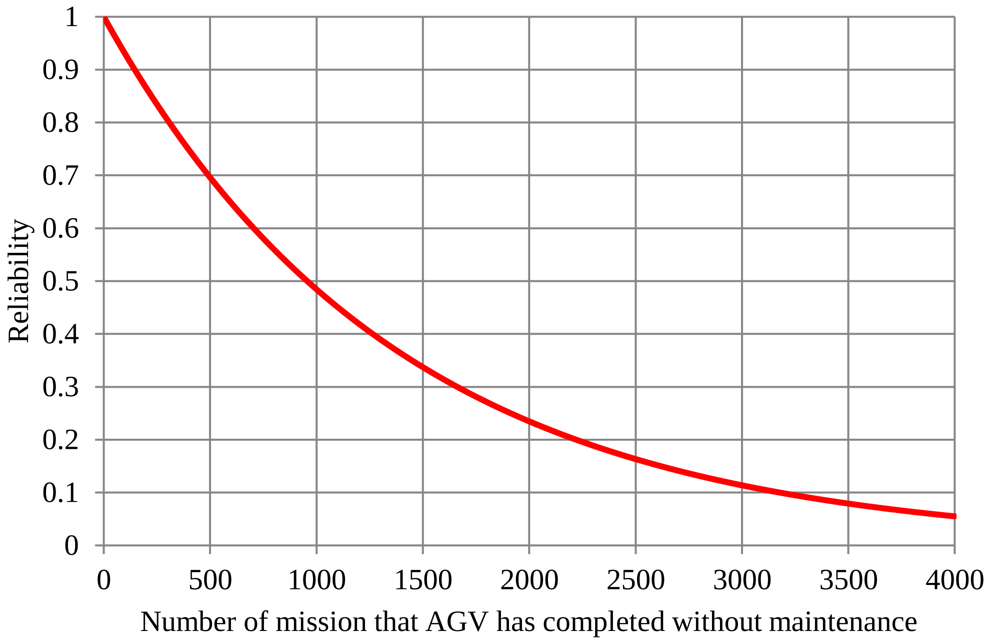


Figure 4.11 Reliability of the AGV verses the number of missions

From Figure 4.11, it is interestingly found that the success probability shows a monotonous decreasing tendency with the increase of the number of missions that the AGV can complete without requiring any maintenance. From such a decreasing tendency, the optimal inspection and maintenance time can be inferred so that the availability of the AGV can be kept above the desired level defined by the users based on concrete requirements. For example, when maintaining the AGV's reliability above 0.7, the inspection and maintenance should be conducted once when every 500 missions are completed.

4.8 Conclusions

In order to investigate the reliability issues existing in a typical AGV that is being increasingly used for intelligent transportation and material distribution in warehouses and/or manufacturing facilities, the FMECA, FTA, and PN modelling are conducted in this Chapter. It has been shown that these methods can help to identify the critical AGV components and the crucial mission phases of the AGVs early at design stage. From the research depicted above, the following conclusions can be reached:

1. The key AGV components can be successfully identified based on the criticality rank that is obtained through performing the FMECA of the AGV. The calculation results presented has shown that almost all AGV components except the manual button, are critical components. These critical components are driving, operating, control and power supply units of the AGV.
2. The calculation results of the PN model are very close to these obtained from the FTA. This demonstrates that PN method is an effective approach to performing the system reliability assessment in this application area.
3. The FTA results have shown that among the identified critical components, the ASCS, attachments, drive unit and battery are more vulnerable to failure because they are found having the largest failure probability at the end of the whole mission.
4. Both PN simulation and FTA calculation have suggested that the AGV is more likely to fail when completing the phase 'dispatch to station' and the phase 'travelling to storage'. It is worthy to note that such a judgement is only based on the empirical data listed in Table 4.1 and Table 4.6. It would be different for a practical application because the PN simulation and FTA calculation results are dependent on the actual environmental, loading and operational conditions of the AGVs. All these factors can be considered within the modelling approach thus enabling more complex AGV systems to be modelled.
5. As opposed to the FTA, the PN method provides a more convenient approach to predicting the reliability of complex systems. This is attributed to the merit of the PN method, which does not require the calculation of analytical equations that are often difficult to establish particularly for complex systems. Also, the PN approach can account for dependencies which may occur, however the FTA cannot.

6. Although the research presented in this Chapter is preliminary, the results have shown that the PN approach can be adopted to help the AGV operator to assess the reliability of AGVs and thus assure normal production with higher efficiency and lower maintenance cost.

It is worth noting that the FTA is applicable to those simple AGV systems without involving any dependencies and moreover their mission does not involve multiple tasks. However, if any complexity is involved or the maintenance needs to be considered, the combined use of the FTA with PN simulation is probably an efficient approach. The research has shown that the combined use of them can bring new analysis capabilities to this domain area.

In the following Chapters, the research will be expanded to further consider the routing problems in the scenarios when an AGV fails in a multi-AGV system. The mission and route will be analysed simultaneously.

5 Reliability Evaluation of Multi-AGV Systems

5.1 Overview

In Chapter 4, the reliability of a typical AGV was analysed qualitatively, quantitatively and computationally in detail. The critical AGV subsystems and operational phases were identified and the PN simulation method has been demonstrated effective in simulating the reliability and operation of AGVs. This Chapter aims to extend the application of the PN model to simulate an AGV system with multiple AGVs. This kind of AGV system is more frequently used in the modern industries and warehouses. Hence, the interactions between the AGVs can be investigated. In addition, not only the missions of the AGVs but also the routing problems of the AGVs will be studied.

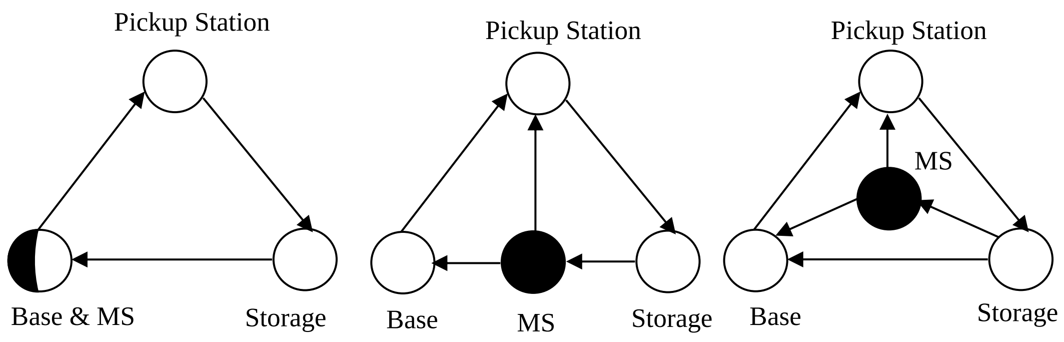
This Chapter will also discuss the availability of AGVs and its influence on the efficiency and performance of the AGV system. It is well known that the availability of a system can be guaranteed via conducting appropriate maintenance, either major or minor, to repair or replace defective components. At present, preventive, corrective and predictive maintenance are the primary maintenance strategies that are popularly adopted in engineering practice. In the application of AGV systems, preventive maintenance is usually conducted periodically despite the actual health condition of the AGVs. In contrast to the former, corrective maintenance is conducted only when a failure is present in the AGV; predictive maintenance determines the maintenance time based on the actual health state of AGV components/subsystems. Different from preventive maintenance, predictive maintenance uses big data and relies on the actual health condition of the equipment, rather than using the average or expected life time statistics, to predict the time of conducting maintenance. These maintenance strategies, their merits and constraints, as well as their influences on system availability, have been studied before in other industries [58, 59]. For example, different maintenance policies for manufacturing production lines were simulated in [60] and the maintenance cost and the availability of an aircraft system were optimised in [61]. However, the relevant research on the maintenance of AGVs has received little attention since most of the AGV maintenance activities are provided by the manufacturers or suppliers. Most of them have 24/7 global help desks to receive any AGV failure and maintenance enquires. In addition, these companies provide different maintenance services to their clients. In view of the insufficient research on the impact of maintenance activities on the availability of AGV systems, two different maintenance strategies, i.e. preventive and corrective maintenance, for multi-AGV systems will be considered in this research. The reason for selecting these two types of maintenance strategies is due to their popularity in other fields and the fact that they have been commonly used by the AGV suppliers. Their different influences on the system efficiency and availability will be investigated. Predictive maintenance is not considered in this research because it has not been a proven technology in the application of AGVs due to the difficulty of obtaining reliable remaining life prediction of the AGV components in different applications. However, with the aid of the approaches outlined in this Chapter, predictive maintenance can be readily built into the model once the relevant data, techniques, and operating conditions are available in the future.

In the practical application of an AGV system, the failed AGV will be recycled as soon as possible to prevent deadlock and conflict. This is usually done manually by the workers or operators in most AGV systems. In this research, the automatic recycling of a failed AGV will be considered when modelling the multi-AGV system. In other words, once an AGV fails it will be collected immediately by an additional AGV and transported to an appropriate site along an optimised travelling path, so that the human's intervention in the operation of the system can be reduced. A specific area for storing the failed AGV and the corresponding maintenance plan will be considered during modelling the multi-AGV system. In this way, not only the automation of the AGV system can be further improved, but also the influences of the location of the maintenance site and maintenance plan of the failed AGV on the system efficiency can be investigated. In the research, the system will be modelled using coloured Petri Nets (CPNs). Such comprehensive research paves the way to achieve more successful layout design, operation, and maintenance of multi-AGV systems. In addition, to the best of the author's knowledge, the reliability, operation, mission, and maintenance of AGVs and AGV systems have never been studied simultaneously in the previous research. Another unique contribution of this research is that an innovative approach is developed to use five different types of CPNs, which interact with each other, to provide the overall availability of the multi-AGV system. This is a versatile approach that can be easily modified if the requirements or missions change.

5.2 Configuration of the AGV System & Mission of Interest

To demonstrate the complexity in modelling an AGV fleet, a multi-AGV system consisting of three AGVs is modelled first. The modelling method developed here can be further applied to modelling the fleets of any number and the different system layout problems as described in later Chapters. Different from a single-AGV system, a multi-AGV system requires to consider the interactions between different AGVs and the influences of the failure of one or more AGVs on the operation of the others in the same system. By using the modelling method developed in Chapter 4, it is possible to consider the structure of the individual AGVs and model the subsystems. However, as the main purpose of this work is to model the maintenance and operation of multi-AGV systems, especially with the focus on the interactions between AGVs, the AGV will be treated as a whole system with an assumed failure rate of 12 failures per year which is the sum of the subsystems' failure rates given in Chapter 4, and no longer consider its subsystems separately. It is necessary to note that the failure rate here is the total number of failures per year of all the critical subsystems in an AGV. It is deduced also from Table 4.6. Likewise, the mission of the AGVs is also divided into six phases as in Chapter 4. They are (1) mission allocation and route optimisation, (2) dispatch to station, (3) loading of item, (4) travelling to storage, (5) unloading and (6) travelling back to base, respectively.

To demonstrate the significant influence of layout configuration on the efficiency of recycling failed AGVs on a multi-AGV system, three different layout configurations of a three-AGV system are considered, see Figure 5.1. In a typical AGV mission, the journey of an AGV will be started by travelling from its base to a pickup station to collect materials, then to its destination, storage, to unload the material, and finally back to base to complete the mission. Hence, every example considered here will consist of an AGV base, a pickup station, a storage site, a maintenance site, and several transport paths. The base is for storing and recharging the AGVs; the pickup station is the place where items are collected; and storage is the destination for unloading the items. Every place is assumed allowing to park more than one AGVs. In Figure 5.1, MS indicates the location of the maintenance site. Although the configurations shown in Figure 5.1 are simple with only 3 or 4 places, they do contain all the essential elements of a typical AGV mission. They should have been sufficient enough for clearly describing the development process of the methodology. The developed methodology can be extended to consider larger and more complex configurations, which will be further studied in later Chapters.



(a) Configuration 1 (b) Configuration 2 (c) Configuration 3

Figure 5.1 Layout configurations of the AGV system

From Figure 5.1, it is seen that different layout configurations are distinguished by different locations of the maintenance site and extra paths required to deliver recycling tasks. For example, the maintenance site shares the same space with the base in Figure 5.1(a); the maintenance site is located between the base and the storage in Figure 5.1(b); the maintenance site is located in the centre of the system in Figure 5.1(c) and moreover, an extra path between the pickup station and the maintenance site is designed in the figure to prevent deadlock due to failure. Accordingly, three extra paths are designed to assure the accessibility to failed AGVs wherever it is in the system. The time required to travel on the extra paths can be obtained geometrically by neglecting the size of the stations.

To facilitate the research, the length of each phase has been assumed and listed in Table 5.1. Herein, the assumed values for phases 2, 4, and 6 are different from those in Table 4.1 because these values are dependent on the route lengths that the AGVs need to travel. In Figure 5.1, the main three paths connecting the three stations are assumed to have the same length. The operating time of the AGV systems is set to be 10 hours per day based on the consideration that the operation of the AGVs must be under the supervision of the operators and the operators will work 10 hours per day. The failure decay of AGVs is zero if they are not in operation. Though it is expected that natural decay occurs in reality. Due to a lack of data on known distributions, this is omitted in this research.

In the model, it is assumed that the failed AGV will be removed as soon as possible from the system to prevent deadlock and conflicts, and therefore minimise the downtime of the system due to the failure of the AGV. To meet such a requirement, it is essential to optimise the location of the maintenance site, from where a recycle vehicle (i.e. the vehicle used to collect the failed AGV and tow it to the maintenance site) is sent out and able to recycle the failed AGV in the shortest time.

Table 5.1 The assumed phase lengths

Phase	**Phase Length** (Hours)
Phase 1: Mission Allocation & Route Optimisation	0.02
Phase 2: Dispatch to Station	0.2
Phase 3: Loading of Item	0.02
Phase 4: Travelling to Storage	0.2
Phase 5: Unloading	0.02
Phase 6: Travelling Back to Base	0.2

5.3 Modelling a Multi-AGV System

To maintain the desired availability of individual AGVs and the reliability of a multi-AGV system, both the maintenance strategy of the AGVs and the location of their maintenance site should be optimised. To explore a solution for this problem, the CPN models of a multi-AGV system and the associated AGV maintenance strategies are developed in the following. They will be used to investigate the influences of AGV maintenance strategies and the location of maintenance sites on the operation performance of the whole AGV system.

In a multi-AGV system, every AGV should be distinguishable as they are located at different positions in the system and could fail at different times. Attributing to the powerful capability of CPN's in describing such kind of problem [107, 108], the CPN is employed in the following research.

To accurately describe the operation and maintenance activities in a multi-AGV system, the following five novel CPN models are developed:

- Path Petri Nets (PaPNs) – for describing the layout configuration of the system;
- Master Petri Nets (MPNs) – for governing the mission progress or phase change of individual AGVs in the system;
- Recycle Petri Nets (RePNs) – for describing the recycle process of failed AGVs;
- Corrective maintenance Petri Nets (CMPNs) – for defining the corrective maintenance of failed AGVs in the system;
- Periodic maintenance Petri Nets (PMPNs) – for defining the periodic maintenance of all AGVs in the system.

Although the 5 CPNs are described separately, they are closely linked to each other as illustrated in Figure 5.2. The PaPNs and MPNs are linked together so that the flow of AGVs in the system and their allocated missions are correlated simultaneously. Both the MPNs and PaPNs feed information to the RePNs to enable the recycling process. In addition, the CMPNs and PMPNs obtain the information about the failed AGVs that are recycled from the RePNs and feed their responses to the MPNs.

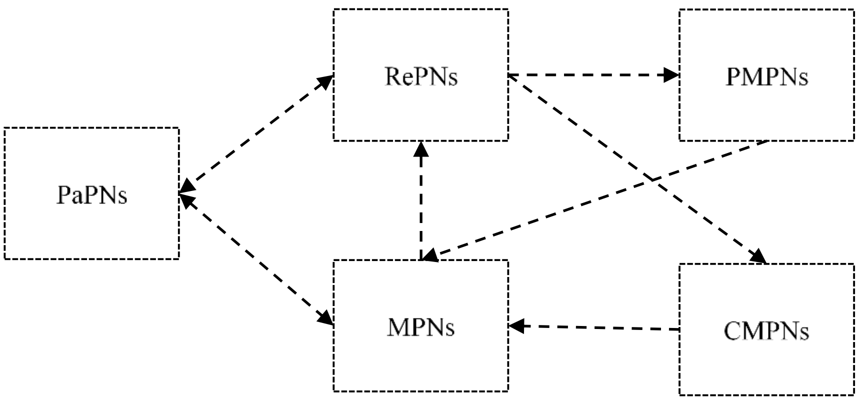
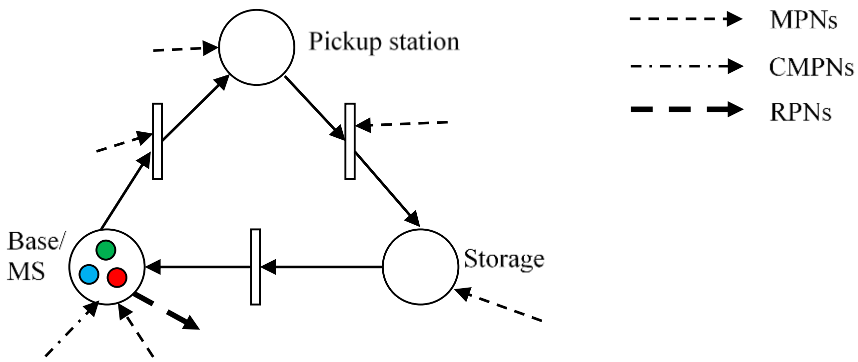


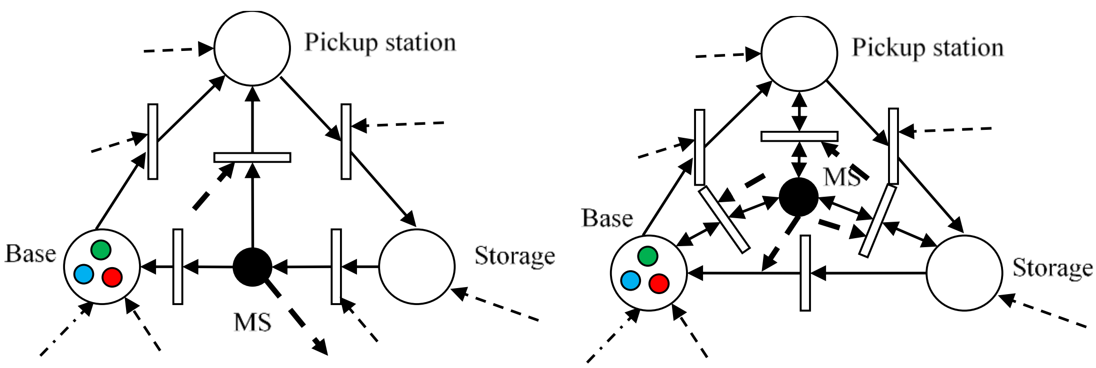
Figure 5.2 Overview of CPN connections

5.4 Path Petri Net (PaPN)

The PaPNs for the configurations shown in Figure 5.1, with one direction of movement enabled only, are shown in Figure 5.3. In the figure, the dotted arrows represent information flows from three different PNs. The MPN links the path with the mission; and the RePN is connected to locate the failed AGVs and find the optimal route for recycling them. The CMPN is connected to the 'Base' place to send the repaired AGV back to the system. The place for the maintenance site is painted in black to indicate its different positions in different configurations.



(a) PaPN for Configuration 1



(b) PaPN for Configuration 2 (c) PaPN for Configuration 3

Figure 5.3 PaPNs for the configurations in Figure 5.1

5.5 Master Petri Net (MPN)

The MPN model is developed to govern the change of phases from the beginning of the mission, Phase 1, to the end of Phase 6, i.e. the successful completion of the whole mission. The structure of the MPN is shown in Figure 5.4. The coloured tokens in the

MPN represent different AGVs and they are initially in the 'Base' place in the PaPN models. Once a mission of an AGV starts, its token will move into the phase 1 place. If the token representing an AGV resides in place 'Phase *i*', it indicates that the AGV is in the phase *i* of its mission. The failure of an AGV in any phase will result in the failure of the mission.

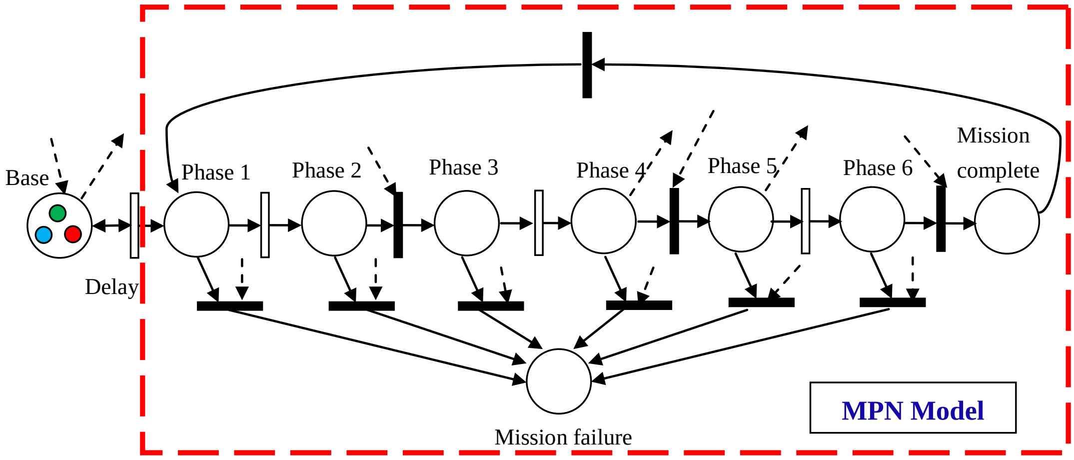


Figure 5.4 MPN model

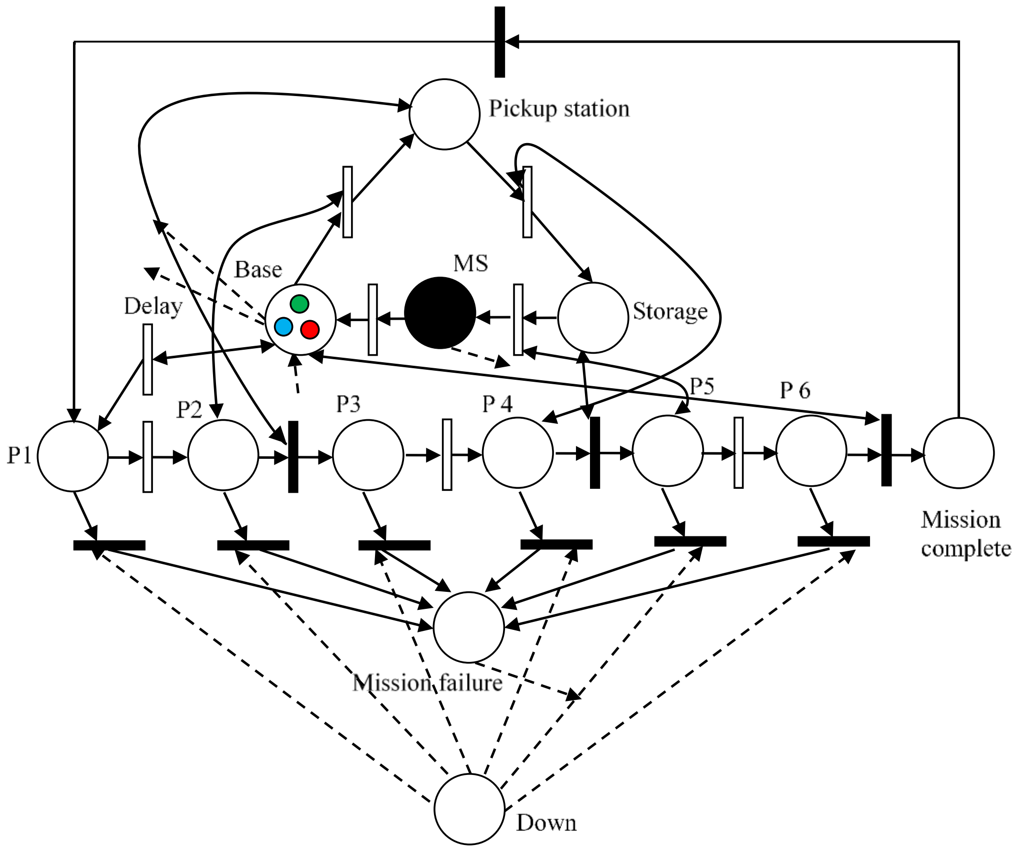


Figure 5.5 PaPN-MPN model

The MPN model and the relevant PaPN model will be used in combination to describe the mission and the AGV routing problem. As an example, the combined PaPN-MPN model adopting layout 1 from Figure 5.1(b) is shown in Figure 5.5.

From Figure 5.5, the integration of the two nets is clearly exhibited. The tokens inside the 'Base' place indicate that the AGVs are available to be allocated to missions. Both nets share the same 'Base' place so that the nets are linked together. The AGVs in the 'Base' have the same chance to be selected to commit a particular mission. It is worth noting that only the same coloured tokens in the places of both the PaPN and MPN can enable the transitions. Hence, the movement of the AGVs and their working phases can be correlated together.

Initially, three tokens representing the AGVs are in the 'Base' place. Once an AGV starts its mission the corresponding token will move from 'Base' into P1 in the MPN after the delay associated with this phase. Also, the same colour token will be returned to the 'Base' as indicated by the bidirectional arrow between the place 'Base' and the transition 'delay' in the MPN because the AGV has not started to move physically. Once the token flows to the 'P2' phase place in the MPN, the transition between the 'Base' and the 'pickup station' in the PaPN will be enabled. After the delay associated with travelling between the 'Base' and the station has expired, this transition will be enabled, and the appropriate token will move into the 'pickup station' place. A token will also be returned to the 'P2' place. The transition between the places 'P2' and 'P3' in the MPN is now enabled and hence the token will move between 'P2' and 'P3' modelling the progression of the phases. The tokens in the network will flow continuously until the mission is completed and the AGVs come back to the 'Base' for starting new missions. Once an AGV fails, the corresponding token for that AGV will reside in the place 'Down'. This will enable the transition to the 'Mission failure' place in the MPN, indicating the termination of the mission for that AGV. The 'Mission failure' place is connected to the RePN, so that the token given to this place can enable the RePN to start the recycling process. The switching time of a transition between two neighbouring phase places is the length of the preceding phase. Likewise, the switching time of a transition between two places in the PaPN is the travel time between the two stations. If the AGV completes all 6 phases without failure, then a token will be placed in the 'Mission complete' place.

Each AGV is assumed to be activated in random order one by one with a time delay of 0.22 hours. This time gap is greater than the time to complete a single path between 2 sites. Hence, each path will have at most one AGV running on it throughout the mission. Such timings can help to successfully prevent deadlock and conflicts caused by failed AGVs in the system. It worth noting that the deadlock and conflicts caused by the failed AGVs are investigated in later Chapters.

5.6 Recycle Petri Net (RePN)

Once an AGV fails, the recycling of the failed AGV will be activated immediately. First of all, the position of the failed AGV will be located. A new place called 'Failure location' is defined to locate the position of the failed AGV. Hence once an AGV fails, a new place for failure location will be generated based on the time that the AGV has already travelled since it left its last place. For example, when an AGV fails between the pickup station and the storage, a place of failure location will be generated as shown in Figure 5.6.

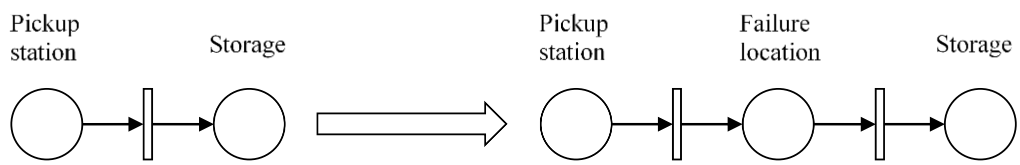


Figure 5.6 Generation of failure location

Then, the route for the recycle vehicle is optimised. As shown in Figure 5.7, during the process of route optimisation if any AGV is found running on the optimised route, the recycle vehicle will not leave the maintenance site until that AGV reaches its next station. After that AGV reaches the station, it will park there and be off the route until the failed vehicle is recovered. In this way, the recycle route will never be blocked. Any AGVs that are not on the optimised route will stop and stay at their current positions to avoid causing the blockage of the optimised recycling route. After the recycle vehicle reaches the failed AGV, it will tow the failed AGV to the maintenance site. The token in 'stop all AGVs' produced due to the AGV failure will be removed as soon as the failed AGV reaches the failure location, so that the system can be reactivated again. Since the maintenance site can be reached by following the flow of working AGVs, the system will resume operation and all the other AGVs will resume their tasks immediately once the failed AGV is collected by the recycle AGV. The transition between the places, 'maintenance site' and the 'failed AGV's recycled' can be enabled only after the token representing the recycle vehicle that tows the failed AGV arrives at the maintenance site place.

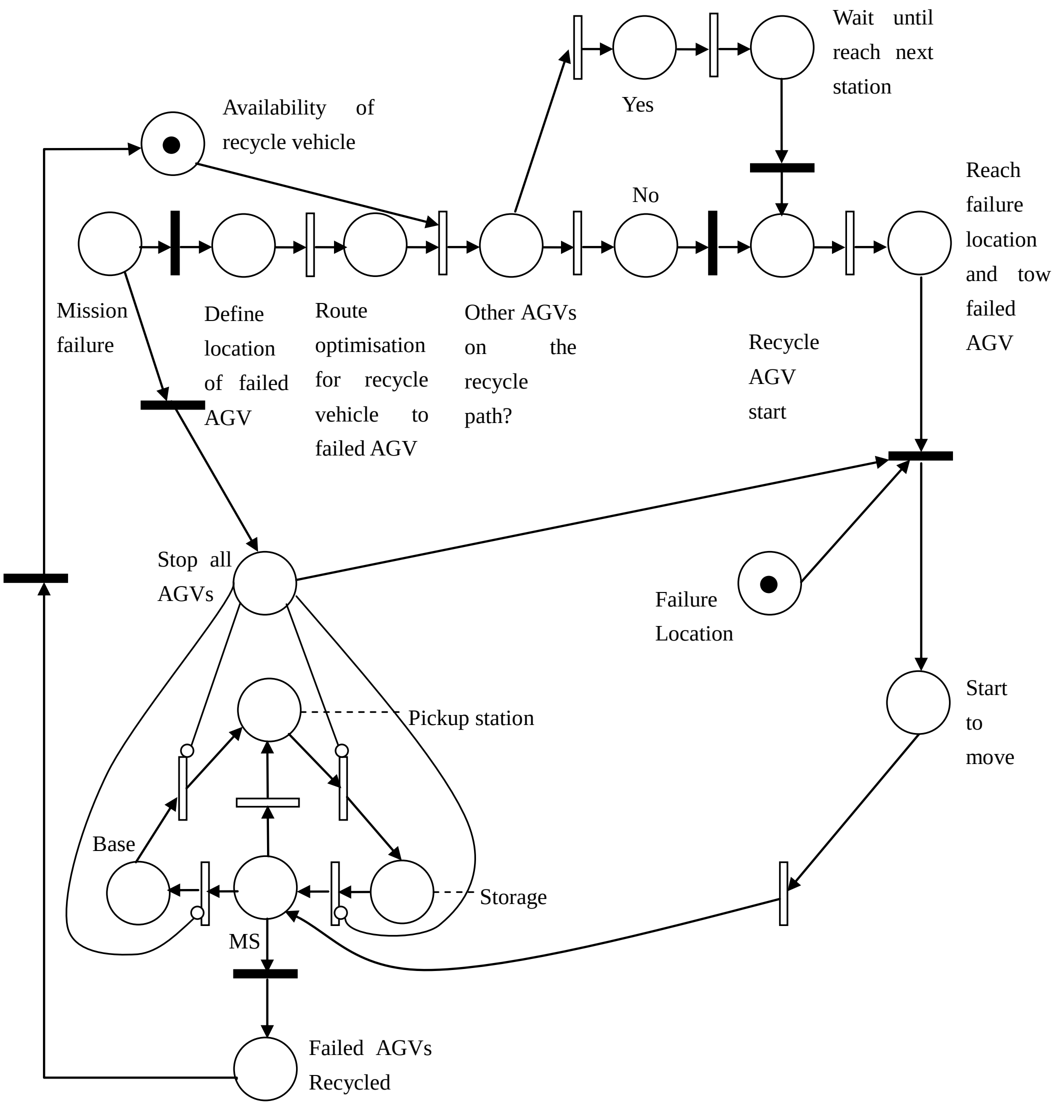


Figure 5.7 RePN model

As mentioned above, the recycling of the failed AGVs will disturb the normal operation of other AGVs running on both the recycling route and non-recycling routes, to plan the recycling route in advance is critical to guarantee the performance of the whole multi-AGV system. So, it is very important to optimise the recycling route to ensure the availability of AGVs and the operation efficiency of the multi-AGV system.

In order to demonstrate the identification of the optimal recycling route, the layout configuration shown in Figure 5.1(b) is expressed using a matrix as shown in Equation (5.1). The variables in the matrix are defined in Figure 5.8.

$$\begin{array}{c} \\ S1 \\ S2 \\ S3 \\ S4 \end{array} \begin{array}{c} \begin{array}{ccccc} A1 & A2 & A3 & A4 & A5 \end{array} \\ \begin{bmatrix} 1 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix} \end{array} \tag{5.1}$$

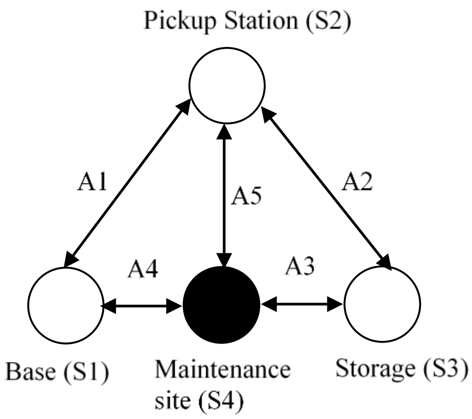


Figure 5.8 Definition of variables in matrix

In the matrix, the rows and columns respectively represent the stations and the paths in the system. The number '1' indicates the availability of direct connection between a station and a path, while the number '0' indicates the unavailability of direct connection between a station and a path. With the aid of a brute-force based searching algorithm [109], the recycling routes passing through the least number of stations can be obtained. For example, starting from maintenance site, S4 in Figure 5.8, its connectivity to route A3, A4 and A5 can be identified using the matrix in (5.1). By repeatedly searching the connectivity of stations and routes and eliminating those already searched, the location of the failed AGV can eventually be reached. In the example shown in Figure 5.8, routes A3, A4 and A5 are directly connected to the 'Maintenance site' place. Therefore, they will be checked first to see whether the failed AGV is on any of them. If the failed AGV is found, define the closest station to the failed AGV. If the failed AGV is not on any of these 3 routes, the algorithm will check the columns in the matrix corresponding to A3, A4 and A5 and determine the other stations on the routes and check if the breakdown is at any of these stations. The algorithm will repeat the check until the breakdown is located. This is a typical application of a linear brute-force forward-tracking search algorithm. This method is relatively simple and can be easily implemented compared with other algorithms such as stochastic search and tree search. However, it is worthy to note that this method could get computational expensive once the system size becomes very large. If the obtained recycling routes pass through the same number of stations, further searching needs to be conducted to identify the recycling route with the shortest distance. To ease understanding, an example is given in Figure 5.9, where possible recycling routes are shown for the case when an AGV is assumed failed during Phase 2. To facilitate the description, RT is defined as the actual operation time before the failure of the AGV during the mission, P1L the time for completing the actions of Phase 1, P2L the time for completing the actions of both Phase 1 and Phase 2, and L4 and L5 are respectively the time that the AGV will take to complete routes A4 and A5. In Phase 2, the AGV travels from the 'Base' to the pickup station and from Figure 5.9, it is found that two recycling routes passing through the same number of stations have been identified from the matrix. As the route, S4→A4→S1→'Failure Location', requires shorter time to travel than the route, S4→A5→S2→'Failure Location', the route S4→A4→S1→'Failure Location', is regarded as a better recycling route.

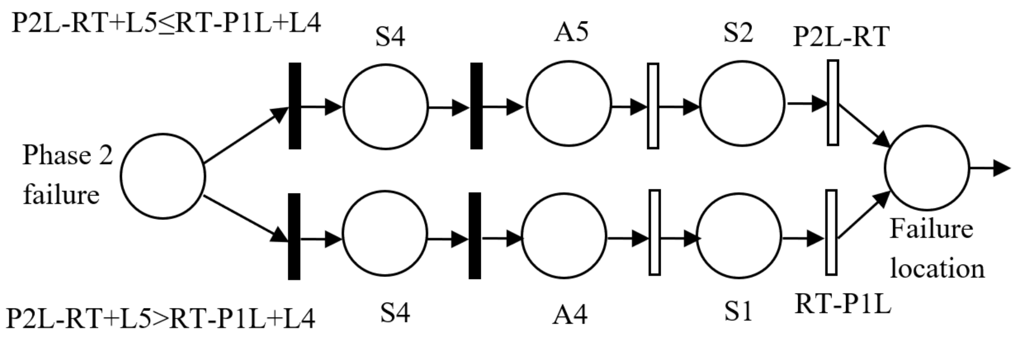


Figure 5.9 Search of the shortest distance

5.7 Corrective Maintenance Petri Net (CMPN)

On arriving at the maintenance site, the failed AGVs will immediately enter the process of corrective maintenance. It will be repaired as soon as a maintenance engineer is available. However, if no maintenance engineer is available, the failed AGVs will have to wait in a queue. After the corrective maintenance, the health condition of the recovered AGV will be assumed to be as good as that of a new vehicle. At that time, the maintenance engineer who undertakes the repair of that AGV will be released and will become available again. Considering the fault occurring in the faulty AGV may be either major or minor that needs different time to repair, in the model it is assumed that the time for repairing the failed AGVs is randomly distributed in the range of 10 to 20 hours. The CMPN model that is developed in this thesis for describing such corrective maintenance process is shown in Figure 5.10.

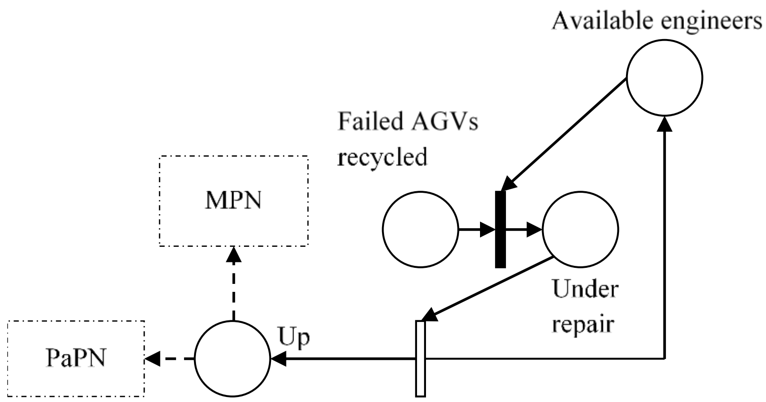


Figure 5.10 CMPN model

5.8 Periodic Maintenance Petri Net (PMPN)

Considering that periodic maintenance is being popularly adopted in industrial practice to prevent catastrophic failure, a PMPN model is further developed in this thesis to simulate the periodic maintenance of the AGVs in the multi-AGV system and is shown in Figure 5.11. In the PMPN model, all AGVs in the system will be treated as new following the periodic maintenance.

From Figure 5.11, it is worth noting that in the PMPN model, the three transitions with different colours correspond to the failure time of the three AGVs in the system. All the AGVs in the system will accept periodic maintenance despite their present health conditions. In the research, it is assumed that the periodic maintenance will last for 2 days. For example, in Figure 5.11, m AGVs are in good health state and n AGVs are faulty, so a total of m+n AGVs will receive the periodic maintenance for 2 days.

After 2 days of periodic maintenance, the system will be put back into operation.

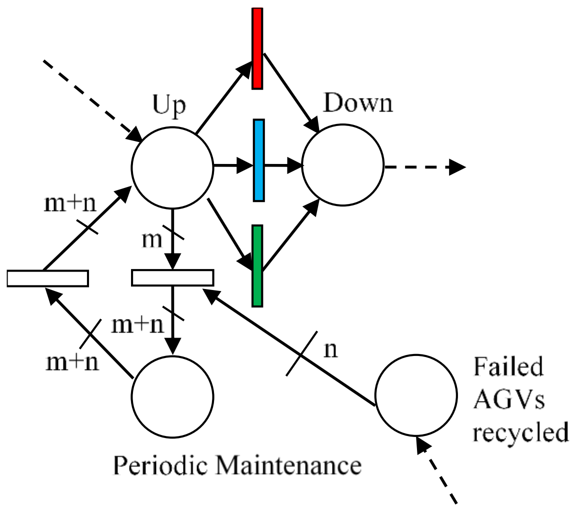


Figure 5.11 PMPN model

5.9 Simulation Model

By integrating the aforementioned five different CPN models, a comprehensive model for describing the layout configuration, recycling and maintenance processes of a multi-AGV system can be readily obtained. To facilitate the simulation of the maintenance process, in this work all five models are fully coded in Python. The failure rate and repair rate of all AGVs, the time spent on performing the periodic maintenance, and the phase lengths are used as the inputs of the model. Here, it is worth noting that the values of these parameters presented in this thesis are used only for demonstration purposes. Their values would be different in different applications. Finally, the simulation of the integrated CPN model can be implemented by using the following steps:

Step 1: Initialise the model by:

a) defining the values of the timed transitions representing the phase lengths in the MPN and the PaPN using Table 5.1;

b) generating the switching times of the transitions for each AGV in the PMPN by using the random sampling and the exponential distribution method;

c) setting the time interval of the periodic maintenance in the PMPN; and

d) placing three colourful tokens in the 'Base' place initially, and one token in each 'AGV up' place to show that all AGVs are assumed to be in 'healthy' state at the start.

Step 2: Identify and switch the transition with the minimum switching time in the whole model;

Step 3: Search through the immediate transitions that are directly connected to the present output place switched. If any are found enabled, switch them;

Step 4: Repeat Step 3 until no more immediate transition is enabled;

Step 5: Check the condition of 'Is corrective maintenance adopted?'. If 'Yes', only check whether the required operation time T_o between periodic maintenance is expired or not, log it and start next simulation; if 'No', check both the required time T_o and the health condition of all AGVs. If either the given time is expired or all AGVs have failed, log it and start the next simulation. If not, go back to Step 2.

Step 6: Iterate the above simulation until the iteration number reaches 10,000.

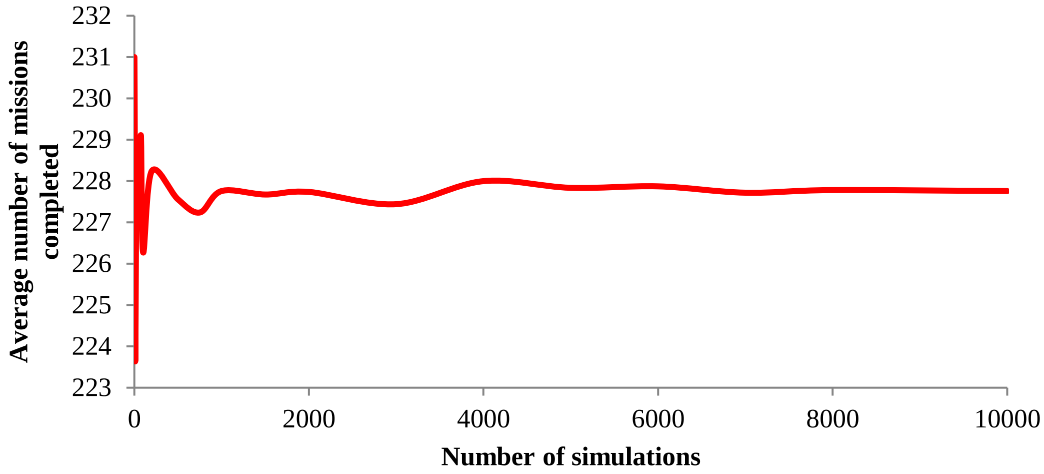
These steps are programmed as described by the pseudo code in Figure 5.12.

In order to validate the convergence of the model, the average number of completed missions, in the layout shown in Figure 5.1(b) with only corrective maintenance, are calculated. The maintenance interval is the time between each periodic maintenance. The results obtained respectively for the maintenance intervals of one week, one month and three months are shown in Figure 5.13. From the results, it is found that the calculated average number of completed missions fluctuates at the beginning. Then, it starts to converge gradually with the increasing number of simulations and finally reaches a saturated value after performing 6000, 2500 and 1500 simulations when the maintenance interval is respectively one week, one month and three months. It is also interestingly found that the longer the maintenance interval, the faster the convergence tends to be. As one week is the shortest period considered, 10,000 simulations are taken in the following calculations to guarantee the reliability of the simulation results. On average, it takes about 5 minutes to run 10,000 simulations for each maintenance interval. But the calculation will take as long as about 30 minutes when the maintenance interval is set to be one year.

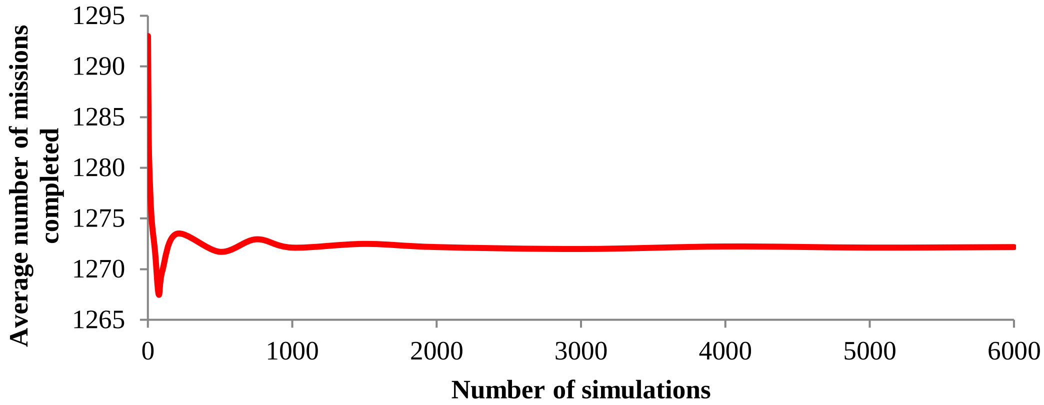
```
Input: Phase time, failure rate, layout of AGV system, total operation time
        Planned period of Periodic Maintenance
        Number of AGVs=3, corrective maintenance, Time=0
Define Function recycleTime: #RPN #PaPN
    Find the path or station AGV failed
    If not in station:
        If time the AGV travelled on path <path time length/2:
            Station near failure = previous station
        Else:    Station near failure = next station
    Calculate the time required for recycling the failedAGV in the layout

While j< Max Iteration:
    Generate: Time to failure for each AGV, dispatch order
    While time <=total operation time/number of period maintenance: #PMPN
        To =max (running time of functioning AGV)
        If AGV i has failed:     #MPN
            Remove that AGV from dispatch order
        For i in AGV:
            If AGV i running time < time to failure of AGV i:
                AGV i running time += phase length
            If AGV i running time ≥ time to failure of AGV i:
                FailedAGV.append(i)
            If there is corrective maintenance:
                Generate repair time
                AGV i running time+= (repair time+ recycleTime)
                Other AGVs running time+= recycleTime
                Time to next failure of AGV i+= time to failure
        If AGV i running time< To:
            Add AGV i back to order
    end while
end while
Postprocess results and visualisation
```

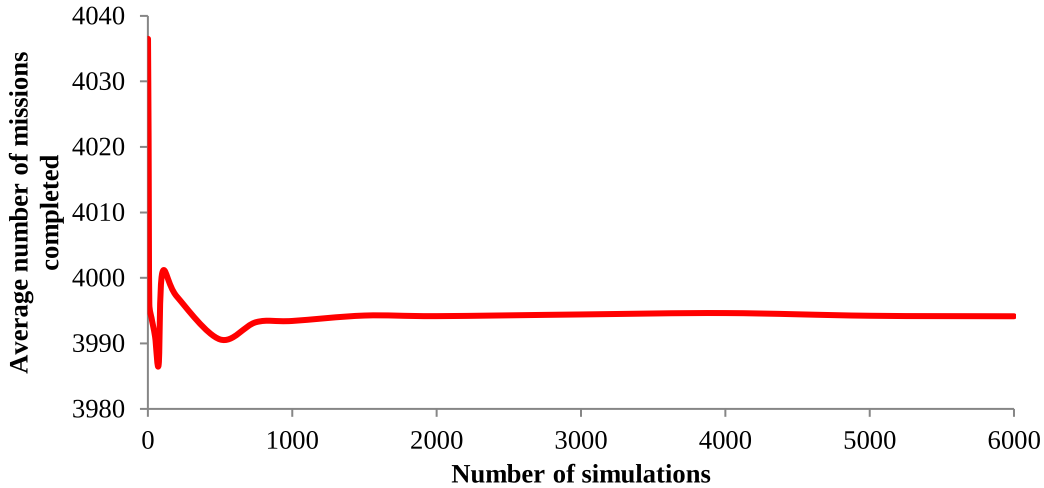
Figure 5.12 Pseudo code of multi-AGV system



(a) One week



(b) One month



(c) Three months

Figure 5.13 The average number of missions completed in one week, one month, and three months without periodic maintenance

5.10 Factors Influencing the Performance of a Multi-AGV System

Firstly, the influence of the different layout configurations considered on the recycle time of failed AGVs is investigated in this Section. It is deemed that the use of a separate maintenance site (see Figure 5.1(b) and (c)) is helpful to reduce conflict and deadlock, thereby increasing the efficiency of the recycling, although more space and extra routes will be needed to accommodate the separate maintenance site. This is because the separate maintenance site will require extra space to conduct corrective maintenance, and it needs to be connected to other stations via extra paths, as illustrated in Figure 5.1. The length of the extra paths will be normalised with the ratio to the equivalent path length between the stations. The average recycle time in the scenarios of using the 3 different layout configurations in Figure 5.1 is calculated and the calculation results are listed in Table 5.2. where the existence of the separate maintenance site is indicated by 1.

Table 5.2 Recycle time

Location indicated by	**Average recycle Time** (hours)	**Extra Space** (unit)	**Length of extra route required** (unit)
Figure 5.1(a)	0.13162	0	0
Figure 5.1(b)	0.12851	1	$\sqrt{3}/2$
Figure 5.1(c)	0.10075	1	$3\sqrt{3}/4$

From Table 5.2, it is found that when the maintenance site is placed in the centre (see Figure 5.1(c)), the shortest recycle time can be achieved, but at the cost of extra space and the longest extra route length. When the maintenance site shares the same site with the AGV base (see Figure 5.1(a)), the system does not require extra space and extra routes, however such a layout configuration will lead to the longest recycle time. The reason for the increased recycle time is because it is assumed that the recycling process can be started only when there is no AGV running on the recycle path. When the maintenance site is placed between the AGV base and the storage (see Figure 5.1(b)), extra space is required with the compromised values of recycle time and the length of an extra route. From these simulation results, it can be concluded that the location of the maintenance site will directly affect the recycling, space, and route. Therefore, the maintenance site location will have significant influence on the performance and cost of a multi-AGV system and should be considered early in the design.

The influence of different maintenance strategies on the performance of the multi-AGV system is also investigated in this Section. Assume the operation time of the system is 10 hours every day and the layout configuration illustrated in Figure 5.1(b) is adopted, the number of completed missions obtained when using different maintenance strategies is calculated and the calculation results are listed in Table 5.3. In the table, *T* is the time interval of periodic maintenance; *P* is the percentage of AGVs failed within the time interval if there is no maintenance (%); *N1* is the number of missions completed per year with periodic but without corrective maintenance; *N2* is the number of missions completed per year with both periodic and corrective maintenance; *DT1* is the percentage of downtime per year with periodic but without corrective maintenance (%); *DT2* is the percentage of downtime per year with both periodic and corrective maintenance (%). In the calculation, the operation time of the system per day is assumed based on the average working hours of workers as the operation of AGVs is usually supervised by human. A fully automated system can run up to 10 hours a day. But this would be different in different applications.

Table 5.3 Number of completed missions

T	***P***	***N1***	***DT1***	***N2***	***DT2***
7 days	0.03	11518	30.58	11840	28.64
20 days	1.10	13213	20.36	14709	11.34
1 month	3.93	12840	22.61	15264	8.00
2 months	18.06	11028	33.53	15792	4.82
3 months	36.32	9372	43.51	15972	3.73
4 months	53.37	7983	51.88	16059	3.21
6 months	77.34	6084	63.33	16142	2.71
12 months	98.06	3280	80.23	16234	2.15

From Table 5.3, it is found that more than 98% of AGVs will fail within 12 months or after completing 3280 missions if without conducting any maintenance. This highlights the importance and necessity of conducting appropriate maintenance of the AGVs during their service. It can be imagined that the number of completed missions will increase if the AGVs can receive periodic maintenance service. This has been proved by the simulation results listed in Table 5.3. But there must exist an optimal interval for conduct periodic maintenance. In other words, both a too long and too short maintenance interval will not lead to the maximum productivity of the system. This is because too many AGVs would fail during the period if the maintenance interval is set to be too long, while the frequent periodic maintenance may cause long downtime if the maintenance interval is set to be too short. From Table 5.3, it is found that 20 days may be the best value of the periodic maintenance interval, which leads to the maximum number of completed missions (i.e. 13213) in a year. In reality, the AGV manufacturers and suppliers usually provide 2 to 6 times of planned maintenance every year. For the system analysed in this example, only 6084 missions can be successfully completed if 2 periodic maintenances are arranged in a year. This means that more than 7,000 missions cannot be completed.

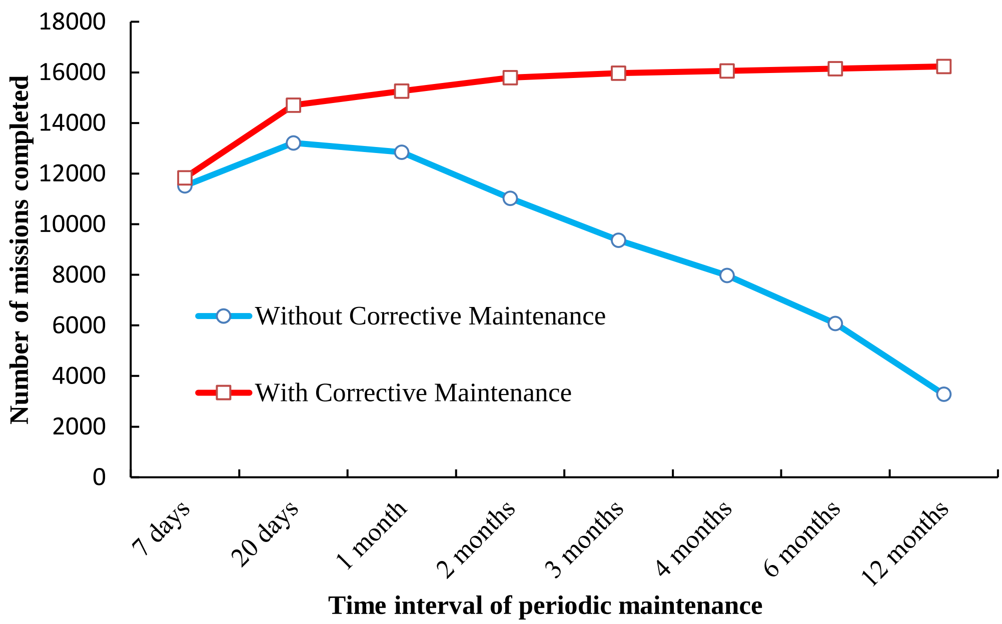


Figure 5.14 Missions completed per year

Furthermore, the comparison of the corresponding values of *N1* and *N2* has shown that the long-term system efficiency can be further improved by using both periodic maintenance and corrective maintenance strategies in combination to take care of the AGVs in the multi-AGV system, although this could induce additional financial and labour costs. The advantage of using both maintenance strategies can be readily observed from the two curves in Figure 5.14, which are plotted using the *N1* and *N2* data listed in Table 5.3.

In summary, from the above discussion of the simulation results it can be concluded that both the location of the maintenance site and maintenance strategies have a significant influence on the performance of a multi-AGV system. Therefore, they should be optimised early at the design stage of the system.

5.11 Conclusions

This chapter has presented the methodology using CPN models to simulate the design, operation, and maintenance strategies of a multi-AGV system. From the research results described above, the following conclusions can be drawn:

1. The CPN modelling is a valid approach to simulate the design, operation, and maintenance of a multi-AGV system. The simulation results are very helpful for assessing the mission performance, evaluating routing, and planning the maintenance strategies in a particular design of multi-AGV system.
2. In the CPN models, both tokens and transitions can be allocated specific properties using different colours. Such a unique feature of the CPN makes it more powerful and flexible in performing simulation, thereby greatly simplifying the development of CPN models.
3. The application of the CPN facilitates the investigation of the influences of the location of maintenance site and the optimal interval for conducting periodic maintenance on system performance. It has been demonstrated that they do have a significant influence on the performance of a multi-AGV system and should be optimised early at the design stage of the system.
4. Long-Term high efficiency of a multi-AGV system can be achieved by using the periodic and corrective maintenance strategies together to take care of the AGVs. When only periodic maintenance strategy is adopted, the system

performance is very sensitive to the time interval for conducting periodic maintenance. It has been proved that both a too long and too short time interval will lead to low productivity of the system.

It should be noted that all of the assumed values, such as path lengths and working hours, can be modified for different applications. The AGV system considered above is relatively simple and the loading capacity of individual AGVs in the system is not considered either. For these reasons, the CPN models will be further improved in the next Chapter to investigate the operation of multi-load AGVs in a larger AGV system with more stations and bidirectional paths.

6 Performance Evaluation of Multi-load AGV

6.1 Overview

With the rapid development of the modern industries, the productivity of the AGV systems is increasing gradually. More AGVs and larger space will be required by individual AGV systems. Accordingly, besides the system efficiency, the cost of individual AGV systems also becomes a matter of concern. However, the research conducted in the previous Chapters is mainly focused on typical single-load AGVs as they are being widely used today in a variety of applications. The application of them to constructing large-scale AGV systems will require large space and a large number of AGVs. This will not only increase the difficulty of system design but will also increase the cost of the project inevitably. Therefore, it motivates the study of multi-load AGVs in this Chapter as the application of multi-load AGVs has potential to reduce the number of AGVs in the system of the same capacity. In addition, the efficiency of a large-scale single-load AGV system could be low because more conflicts and deadlocks between AGVs may occur in the system, particularly when the route paths are bidirectional paths. This factor can significantly affect the system efficiency as well and should be taken into account in developing the simulation models.

In fact, much effort has already been made before in order to improve the efficiency of single-load AGV systems. For example, a new deadlock recovery strategy was proposed in 2010 in [110] to reduce handling time and cost. In order to enable the synchronous operation of a larger number of AGVs, a genetic algorithm was employed in [111] to minimise the unloading time of an AGV system that involves 200 containers and 10 AGVs in a container terminal. In addition, the minimum number of AGVs for guaranteeing the on-time completion of prescribed tasks was also investigated in [46]. But despite these early efforts, the efficiency improvement of the large-scale AGV systems is still limited due to the application of single-load AGVs, which have the limited load-carrying capacity and are able to take only a single item in one mission.

To overcome the issue caused by the limited load-carrying capacity, a new concept AGV, called multi-load AGV, was proposed. As compared to single-load AGVs, a multi-load AGV possesses more powerful load-carrying capacity. Moreover, it is able to pick up more loads at each station or even from multiple stations. The comparison of multi-load and single-load AGV systems has been conducted by some scholars in order to demonstrate the advantage of multi-load AGVs [47, 49, 11]. However, there are still some issues that have not been fully understood:

(1) The influence of the multi-load capacity of individual AGVs on addressing the conflict and deadlock issue has not been investigated.

(2) The influence of the load-carrying capacity of individual multi-load AGVs on the efficiency of the AGV system has not been systematically studied since most available research about multi-load AGVs is focused on investigating the AGVs that are able to carry less than 4 units. Thus, it is difficult to understand the influence of the AGV's load-carrying capacity on the system performance from these previous researches.

Also, most of the previous research on both single-load and multi-load AGV systems was conducted using mathematical programming. However, with the further scaling up of AGV systems, it will become difficult to simulate large-scale AGV systems by the approach of mathematical programming [112]. Even if the large-scale AGV system is successfully modelled, the long-time simulation calculation will put the method at a great disadvantage. Hence, in this work, a simulation modelling approach will be developed in this Chapter to efficiently simulate large-scale multi-load AGV systems. This new modelling approach is identified by:

(1) Application of Coloured Petri Nets (CPNs) to simulate the operation of large-scale multi-load AGV systems;

(2) The ability to evaluate the efficiency and performance of the AGV systems that consist of different numbers of AGVs and the AGVs have different load-carrying capacities;

(3) The ability to simulate conflict and deadlock in the operation of AGV systems.

Due to the dynamic property and the unique intuitive graphic presentation feature of CPNs [83], the models developed in this Chapter will be able to simulate the operation and movement of AGVs as well as the deadlock and conflict in the AGV systems practically.

6.2 System Layout

The simulation of a large-scale AGV system is difficult and computational expensive [113]. In order to simplify the kind of simulation, it is necessary to identify a basic system layout that consists of all key elements in a real AGV system so as the performance of the large-scale AGV system can be inferred. The key elements should include stations for different purposes, paths connecting stations together, and a number of AGVs running on the system. Herein, for facilitating the development of the simulation model, a basic AGV system that consists of 9 stations (S1 to S9) and 12 bidirectional paths is considered which is shown in Figure 6.1. The size of the stations and the lengths of the paths are assumed to be the same. These settings are commonly used in large automated warehouses such as a Shentong (STO) Express sorting centre in Hangzhou, China, which is illustrated in Figure 6.2 [114]. More complex systems that consist of more AGVs, more stations, and differing length of paths are studied in later Chapters.

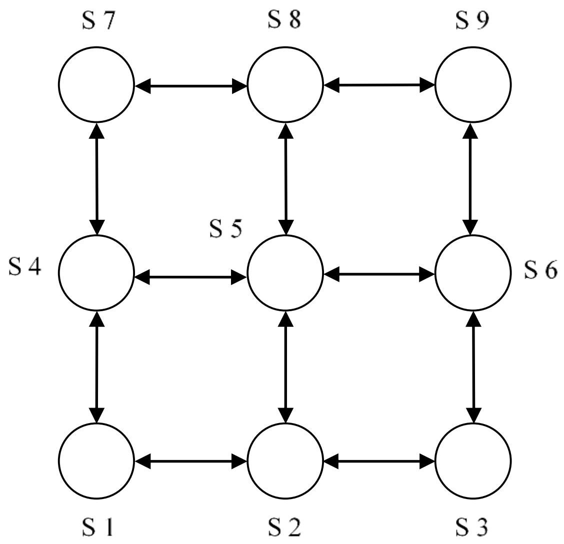


Figure 6.1 System layout

In the system layout shown in Figure 6.1, it is assumed that two different types of AGVs, i.e. single-load and multi-load, are able to operate in the system. However, it is assumed that only those AGVs with the same load-carrying capacity are allowed to run in the same system because using the same type of AGVs can ease management. A typical mission of the single-load AGVs is assumed to consist of five phases, i.e. (1)

mission allocation and route optimisation, (2) dispatch to the targeted pick-up station, (3) collect one item, (4) travel to the corresponding unload station, and (5) unloading. Different from the mission described in Chapter 4, the AGVs are not required to return to the 'Base' after unloading because it is assumed that the new mission will be allocated immediately after the completion of the previous mission. So, they can start their next mission directly. The time durations for phases 1, 3 and 5 are assumed based on expert knowledge as listed in Table 6.1.

Figure 6.2 Shentong (STO) Express sorting centre in Hangzhou

It is worth noting that compared to the phase length for phase 1 that was defined in Chapter 4 and 5, a different phase length is defined here for phase 1, which indicates that the system must use more advanced computer and software to achieve a more powerful central control and management system. The time for completing phases 2 and 4 is dependent on the distance or the paths used by the AGVs.

Table 6.1 Assumed phase lengths

Phase	**Phase Length** (hour)
Phase 1: Mission allocation & route optimisation	0.005
Phase 3: Collect one item	0.02
Phase 5: Unloading	0.02

The mission of the multi-load AGV is similar to the single load AGV but there would be more than one pickup and unload stations. The time taken to complete the movement from one station to a directly connected station is assumed to be 0.1 hours. The loading capacity of the multi-load AGV is defined as the maximum number of items it can load. This means the multi-load AGVs will pick up items from different stations and then transport them to the corresponding unload stations. Station S1 is defined as the AGV's base where the AGVs are stored and charged. Therefore, pickup and unload will not happen at station S1. In every mission, the pickup and unload stations are randomly selected from stations S2-S9, thereby guaranteeing the actual operation of the AGV system can be simulated as closely as possible, and thus the added value of this research for optimising and managing the future AGV systems. The 12 bidirectional paths that connect the stations are assumed to have the same length so that the AGVs will take the same time when travelling on any of them. But for different applications, the layout of the system can be easily modified by varying the length of the paths, the number of stations, and the connectivity between them if necessary. In addition, the bidirectional paths are defined in the system layout, but their width only allows the AGVs that travel in the same direction to go through. As a consequence, all AGVs travelling on the same path must move in the same direction to prevent deadlock. Those AGVs that are going to travel in opposite direction have to wait in the station until the path is evacuated. This will lower the efficiency of the system to certain extent, but today it is still commonly used in practice due to the use of magnetic tape for navigation. The further discussion of this issue is conducted in later Chapter.

Finally, the capacity limit of the 9 stations in the defined system layout is not considered in this research, so that the AGVs that are already parked in the stations will not prevent other AGVs from entering the same station and perform tasks. But this is not true in reality. So, the impact of the station capacity on the system performance will be further investigated in Section 9.2.

6.3 Development of AGV Models

As the aim of the study in this Chapter is to develop a model that enables the investigation of the superiorities of multi-load AGVs over single-load AGVs, all AGVs in the system are assumed to be reliable for simplifying the simulation. Considering the AGV system to be investigated consisting of multiple AGVs, all AGVs should be distinguishable as they are located at different positions in the system.

The comprehensive model for simulating the operation activities of the AGVs in the prescribed system layout is composed of three CPNs. They are Route Petri Nets (RoPNs), Master Petri Nets (MPNs), and Conflict Detection and Avoidance Petri Nets (DAPNs). RoPNs are used to describe the routes that the AGV will travel along; MPNs are used to govern the phase changes in the missions of AGVs; and DAPNs are used to detect and avoid the conflicts in the operation of the AGVs. More details of these nets are described in the following Sections.

6.3.1 Mission Generation

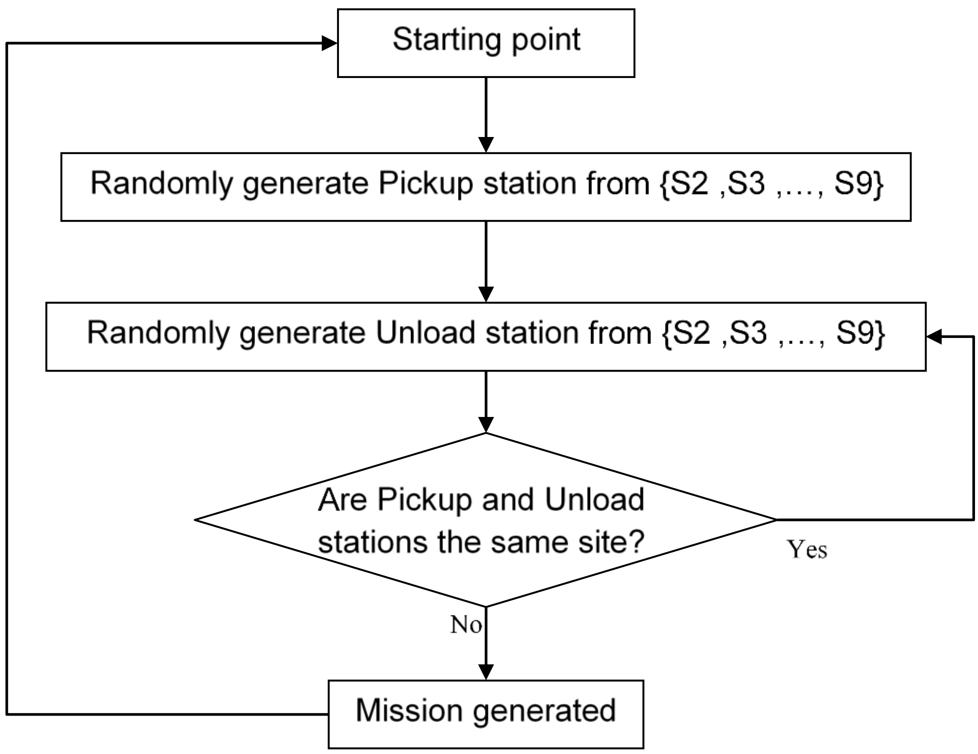


Figure 6.3 Mission generation for a single-load AGV

Firstly, the missions for the AGVs are generated in the model. In a typical AGV system there are usually three types of stations, namely starting point, pickup and unload stations. Therefore, in the system layout shown in Figure 6.1, station S1 is defined as the starting point of the initial mission for all AGVs. The starting points of the AGVs in all subsequent missions will be their end points in the last mission. In the research, the mission specification is generated in a random manner, every station in the system layout except S1 will have an equal chance to be selected as either pickup or unload station. This means that the AGVs will be allocated random transportation missions. By contrast, in the modelling of single-load AGV systems it is necessary to set a rule in order to ensure that the single-load AGV is not assigned the same station as both pickup and unload in one mission. The mission generation process for single-load AGVs is shown in Figure 6.3.

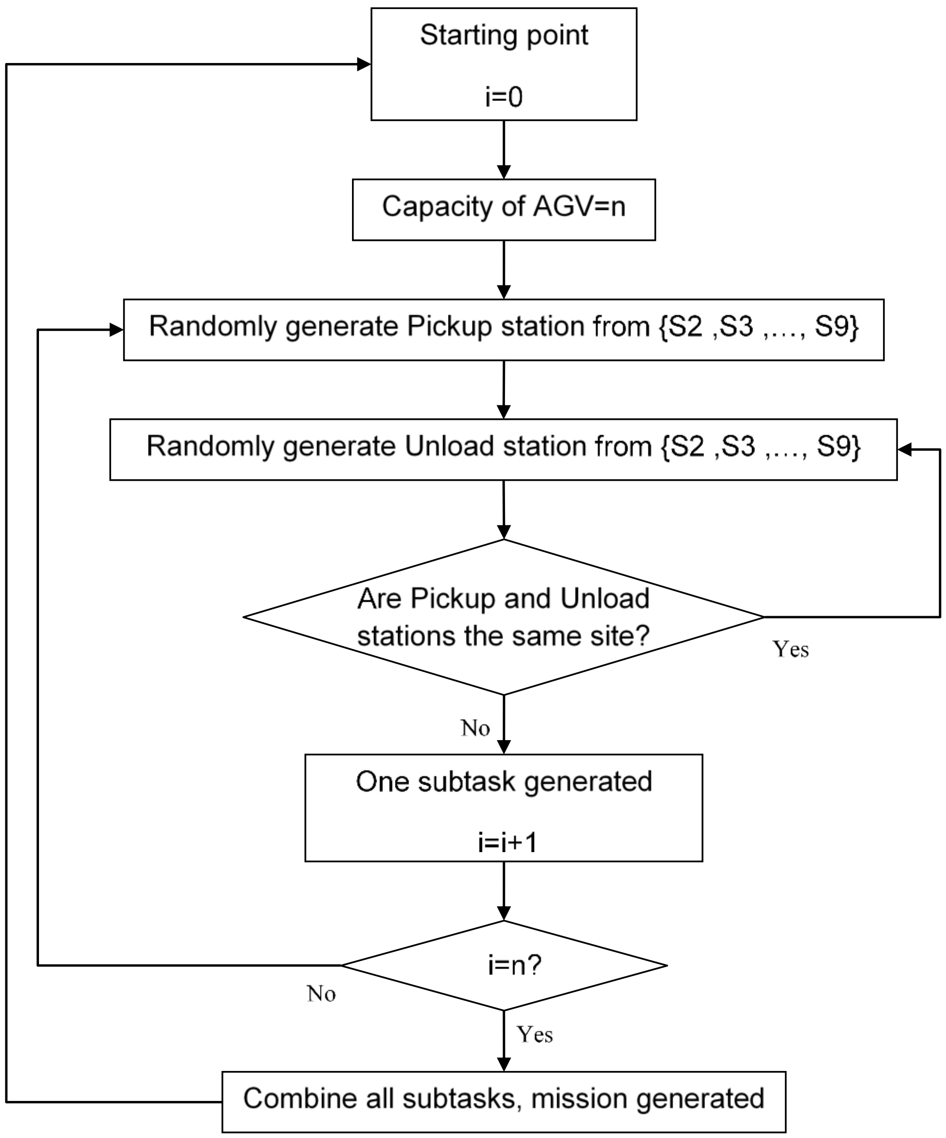


Figure 6.4 Mission generation for a multi-load AGV

Since a mission of a multi-load AGV consists of several tasks that the vehicle will deliver continuously, the mission generation process for a multi-load AGV system is illustrated in Figure 6.4. In the figure, 'n' indicates the load-carrying capacity of the multi-load AGV system. The capacity is defined as the maximum number of items that the AGV can carry at the same time. The weight and packed size of each item is assumed to be the same in this research for simplifying the simulation.

From Figure 6.4, it is seen that different from the mission generation process for single-load AGVs, the random generation process for multi-load AGVs must be repeated in order to generate a complete specification of the mission. Each subtask allocates one item located in one station which needs to be delivered to another. This is the same as the mission of a single-load AGV. Again, the pickup station and the paired unload station should be different in a subtask. The repeating process is finally ended only when the total load-carrying capacity of the multi-load AGV is fully utilized by the planned tasks, i.e. when $i = n$.

6.3.2 Route Petri Net (RoPN)

Once the target stations in an AGV mission are known, the route to these target stations needs to be optimised to guarantee the shortest distance that the AGVs will travel for delivery of all tasks. To facilitate route optimisation, a coordinate system is defined in the research and is shown in Figure 6.5. The following 5 rules are developed to define the priority of the direction of movement of AGVs between stations:

Rule 1 – Prior to reaching a station that has the same x-coordinate as that of the target station, AGV's move in a horizontal direction.

Rule 2 – Once the AGVs reach a station that has the same x-coordinate as that of the target station, its priority movement will be in the vertical direction.

Rule 3 – When the x-coordinate of the target station is larger than that of the current station visited by the AGV, it will take the path on the right as the priority route. Otherwise, it will take the path on the left as the priority route.

Rule 4 – When the y-coordinate of the target station is larger than that of the current station visited by the AGV, it will take the top vertical path as the priority route.

Otherwise, it will take the bottom vertical path as the priority route.

Rule 5 – When the AGV reaches a station that has the same x and y-coordinates as the defined x and y-coordinate values of the target station, it is assumed that the AGV has reached the target station in the present mission.

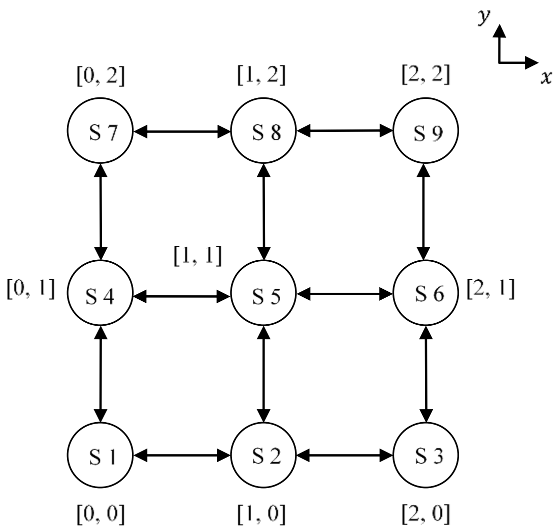


Figure 6.5 The coordinate system for route optimisation

To demonstrate the application of these rules, an example is considered. In the example, the AGV is expected to start from station S1, and the target station is S9. The optimal route that the AGV will take is shown in Figure 6.6. Here, it is worth noting that these rules can be modified for different layouts. If the paths are staggered or have different lengths, the shortest route searching algorithm, e.g. Dijkstra's algorithm [115], should be employed, which will be discussed in Chapter 9.

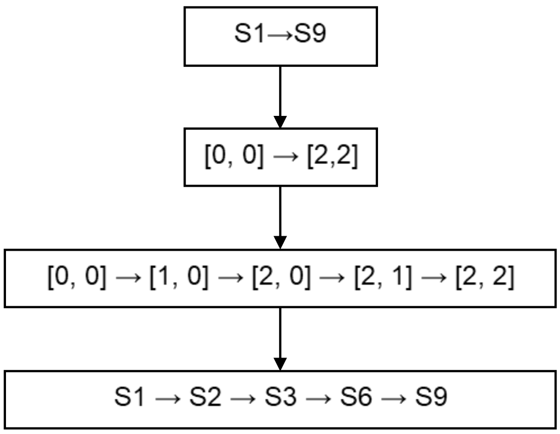


Figure 6.6 The optimal route from station S1 to station S9

Since different AGVs will be assigned different tasks, their target stations will be different from each other. For this reason, the RoPN for every AGV must be generated separately. The RoPN for the example shown in Figure 6.6 is illustrated in Figure 6.7.

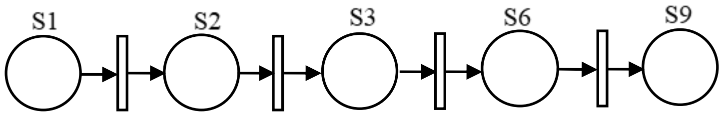


Figure 6.7 The RoPN for the example in Figure 6.6

In the application of multi-load AGVs, it is particularly important to optimise the visiting order to target stations, as different visiting order arrangements may lead to significantly different travelling distances for the mission. For example, if a three-load AGV is asked to visit 3 target stations S4, S7 and S9, this could be achieved by several routes. For example, the AGV could travel along the route S1→ S4 → S5→ S6→ S9→ S8→ S7, passing a total of 7 stations, or it could travel along the route S1→ S4 → S7→ S8→ S9, passing only 5 stations. Therefore, the visiting order to target stations should be optimised to ensure the shortest travel time or distance [116]. To facilitate the optimisation, a specific matrix is created using Dijkstra's algorithm [115] to describe the path distances corresponding to different pairs of stations. The matrix is expressed as:

$$
\begin{array}{c}
\\
\mathbf{S1}\\ \mathbf{S2}\\ \mathbf{S3}\\ \mathbf{S4}\\ \mathbf{S5}\\ \mathbf{S6}\\ \mathbf{S7}\\ \mathbf{S8}\\ \mathbf{S9}
\end{array}
\begin{array}{c}
\begin{array}{ccccccccc}
\mathbf{S1} & \mathbf{S2} & \mathbf{S3} & \mathbf{S4} & \mathbf{S5} & \mathbf{S6} & \mathbf{S7} & \mathbf{S8} & \mathbf{S9}
\end{array}\\
\begin{bmatrix}
0 & 1 & 2 & 1 & 2 & 3 & 2 & 3 & 4\\
1 & 0 & 1 & 2 & 1 & 2 & 3 & 2 & 3\\
2 & 1 & 0 & 3 & 2 & 1 & 4 & 3 & 2\\
1 & 2 & 3 & 0 & 1 & 2 & 1 & 2 & 3\\
2 & 1 & 2 & 1 & 0 & 1 & 2 & 1 & 2\\
3 & 2 & 1 & 2 & 1 & 0 & 3 & 2 & 1\\
2 & 3 & 4 & 1 & 2 & 3 & 0 & 1 & 2\\
3 & 2 & 3 & 2 & 1 & 2 & 1 & 0 & 1\\
4 & 3 & 2 & 3 & 2 & 1 & 2 & 1 & 0
\end{bmatrix}
\end{array}
\qquad (6.1)
$$

where the [i, j]-th element is the minimum number of path segments between station Si and station Sj. For example, any shortest route between S1 and S9 involves 4 path segments. The larger the number, the longer the distance between the stations. It is worthy to note that this matrix can be extended and modified to adapt to different layouts as discussed in Chapter 9. Considering the example of a three-load AGV visiting 3 target stations S4, S7 and S9, when S1 is the start point, the shortest distances to S4, S7 and S9 are 1, 2 and 4 path segments, respectively. This suggests that the first station that the AGV should visit is S4. Then from S4, the shortest distances to S7 and S9 are 1 and 3, respectively. Therefore, the AGV should then visit S7, and finally S9.

6.3.3 Master Petri Net (MPN)

As mentioned in Section 5.5, the MPN model is developed to govern the change of phases, from the beginning of the mission, Phase 1, to the successful completion of the whole mission, at the end of Phase 5. For example, the structure of the MPN for 3 single-load AGVs is illustrated in Figure 6.8.

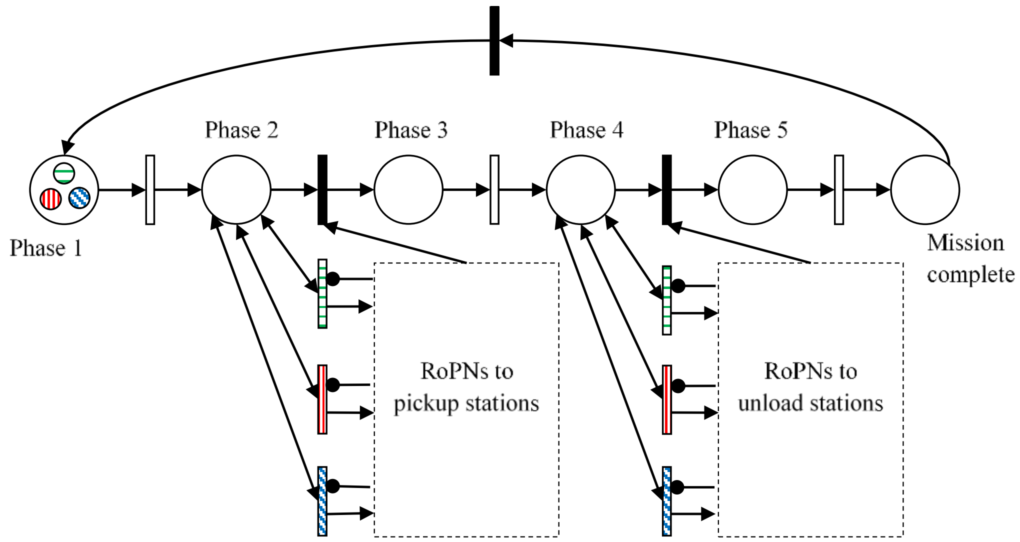


Figure 6.8 The MPN for 3 single-load AGVs

Once the travelling route of the AGVs is determined through optimisation, the MPN will be developed to define the phase changes for the operation of different AGVs. It is worth noting that in the MPN, the AGVs are represented by different coloured tokens. Only the same coloured tokens in the places of both the RoPN and MPN can enable the transitions. In this way, the movement of AGVs and their working phases can be modelled together.

In the scenario of using single-load AGVs as shown in Figure 6.8, there are 3 single-load AGVs in the system. They are initially at place ‘Phase 1’. Once an AGV in ‘Phase 1’ is assigned a mission, the corresponding token will move from ‘Phase 1’ to ‘Phase 2’. After the token is transferred to place ‘Phase 2’, modelling the dispatch to the pickup station, the transitions between ‘Phase 2’ and the places in RoPNs will be enabled. As the arcs connecting the transitions and the place ‘Phase 2’ are double ended, a token of each colour will be placed back into place ‘Phase 2’ as well as the corresponding RoPN’s. The arc with a solid circle end is known as an ‘inhibitor arc’, which stops the token firing once a token is present in the corresponding RoPN. Following the movement of the tokens in the corresponding RoPNs, the transition between ‘Phase 2’ and ‘Phase 3’ is enabled and the corresponding token will move into place ‘Phase 3’ initiating the travel to the unload station. Since the route of every AGV is different, the AGVs will spend different amounts of time in their RoPNs. The similar movement of the AGVs and their transitions will continue until the mission is completed. Then, the AGVs will be assigned new missions and they will start from ‘Phase 1’ again.

In the scenario of using multi-load AGVs, as there are multiple pairs of pickup and unload stations in the operation of multi-load AGVs, the MPN developed in this scenario will be different from that shown in Figure 6.8. In the operation of multi-load AGVs, after picking up items the AGV does not necessarily go directly to the unload station for those items as a multi-load AGV is usually asked to deliver multitasks that are generated and packed together, as shown in Figure 6.4. For example, if the multi-load AGV passes a station on its way to the target unloading station and it happens to carry some items that need to be unloaded there, the multi-load AGV will be expected to unload those items at that station before continuing to the target station. To ease understanding, an example of the MPN for a two-load AGV is shown in Figure 6.9. Where, it is assumed that the AGV is asked to deliver two tasks. The first is to transfer item A from station S2 to station S8, and the second is to transfer item B from station S6 to station S8.

From Figure 6.9, it is seen that the AGV will visit all pickup stations first. So, the

AGV will pass through the paths in the order S1→S2→S3→S6. It is worth noting that the transition for pickup or drop off is always enabled first since the transition time is shorter. The token in S6 will be transferred to 'pick up item B' place but a new token will be produced in S6 simultaneously due to the double-head arrow. Then the token in 'pick up item B' will disable the transition, and the newly produced token in S6 will be transferred to S5. Then, the AGV will travel to the unload station and S8. Once both items A and B are unloaded at the target unload station S8, the mission is successfully completed. Therefore, the RoPN and MPN of the multi-load AGV are not separable.

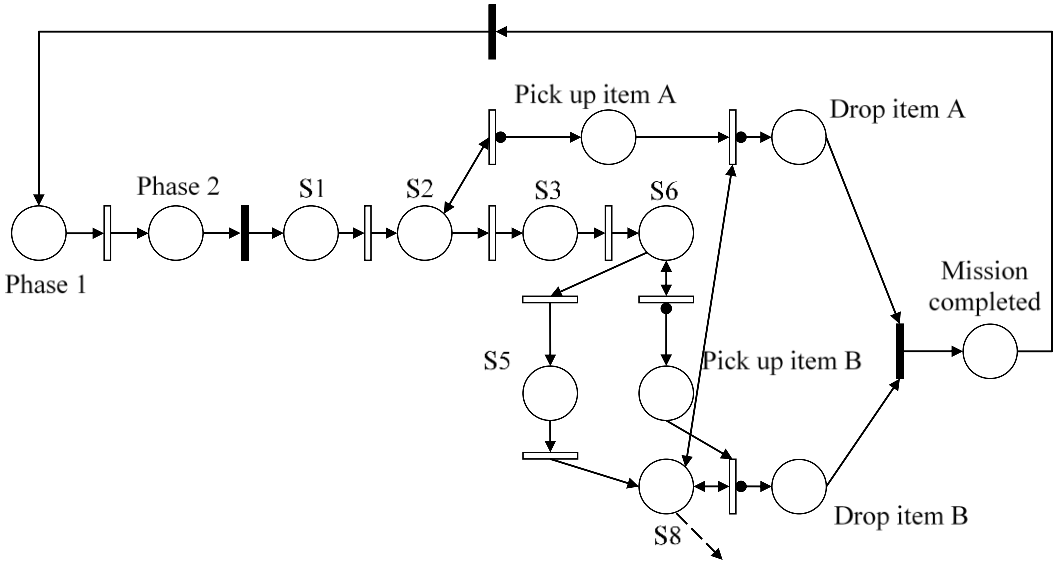


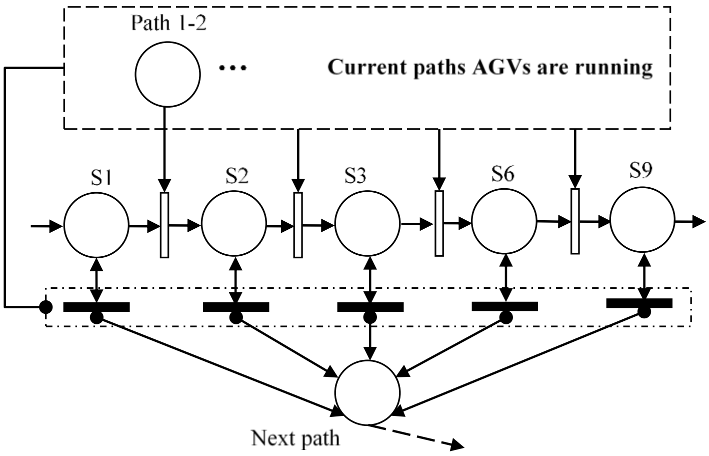
Figure 6.9 The MPN for a two-load AGV

6.3.4 Conflict Detection and Avoidance Petri Net (DAPN)

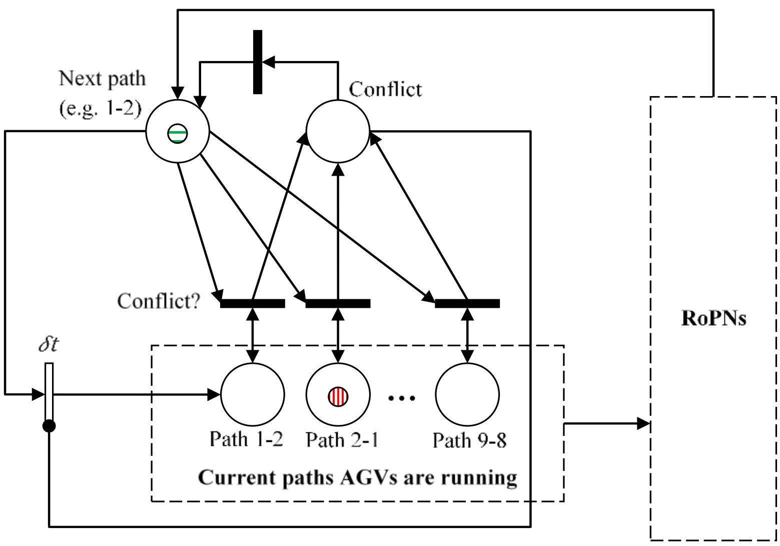
It is well known that traffic conflict is inevitable in the transportation of multi-AGV systems [10, 23, 25]. To facilitate the detection and avoidance of potential conflicts, the paths that all AGVs are travelling on must be identified and compared. To clearly explain this method, an example is given in Figure 6.10.

Figure 6.10(a) defines the next path that an AGV will travel on. Once a token is transferred into a new station place in the RoPN, a new token that carries the information about the next path and travel direction will be produced in the places for 'Next path'. For example, if the AGV is currently in S1 and going to travel to S2, the 'Next path' will be '1-2'. Here, the first digit in the 'Next path' indicates the start station and the second digit represents the next station that it is planning to travel to. Figure

6.10(b) illustrates the detection of the conflicts between the AGVs. Once the next path of an AGV going to travel is identified, the process of conflict detection will be activated. If there is no conflict with other AGVs, the coloured token in the 'Next Path' place will be transferred to the place that is labelled with the path and direction information. It means the AGV can start travel on the path according to the information. Otherwise, the token will stay in the 'Next Path' place so that the token cannot flow in the corresponding RoPN. It means that the AGV has to stay in the current station until the conflict is absent. Once a coloured token is produced in the places of the current paths, the next path check will be stopped by the inhibit arc connected to all the transitions from the places of the stations to 'Next path' place.



(a) Example for identifying next path using RoPN



(b) Avoid conflict

Figure 6.10 The example of DAPNs

For example, if ‘AGV 1’ is travelling on ‘path 2-1’ while ‘AGV 2’ is going to travel on ‘path 1-2’, a conflict will occur. Then, the corresponding ‘conflicts?’ transition will be enabled. It should be noted that this kind of instant transition can be enabled by the tokens with different colours and will not change the colour property of the tokens been transferred. The token in the ‘Next path’ place will be transferred and produced simultaneously through the ‘Conflict’ place. This process will be repeated continuously. It is worth noting that the token in the ‘Conflict’ place always has the same colour as the token in the ‘Next path’ place. Since there is a small time delay, δt, for transferring the token to the place indicating the path being occupied, the token cannot move to its next place in the RoPN. This means ‘AGV 2’ will have to wait in station S1 until ‘AGV 1’ reaches S1. Once ‘AGV 1’ reaches S1, the token in the place indicating ‘path 2-1’ will be transferred to the RoPN of ‘AGV 1’ so that the token in ‘Next path’ will be transferred to the ‘path 1-2’. Thus, the token in the ‘path 1-2’ place can enable the corresponding transition in the RoPN of ‘AGV 2’. Therefore, the DAPNs are able to control the movement of tokens in the RoPNs.

6.4 Performance Research of Multi-load AGV

As illustrated in Figure 6.11, with the aid of the three different CPN models described in Section 6.3, a simulation model is developed in Python to simulate the mission, routing and conflict detection and avoidance that often occurs in both single-load and multi-load AGV systems.

Figure 6.11 CPN model integration

The corresponding programming pseudo codes are given in Figure 6.12. The MPNs govern the phase change of the AGVs’ missions, where the actions (e.g. route optimisation, item pickup and drop off) are performed. The RoPNs are automatically generated based on the algorithms of mission generation and route optimisation. It receives information from the MPNs and knows when the AGVs are going to move.

On the other hand, the RoPNs are able to generate information about the net paths that the AGVs are going to travel on. These paths are then compared in the DAPNs for detecting potential conflicts.

```
Input: Phase time, failure rate, layout of AGV system,
        total operation time/ total number of missions
        Number of AGV, Time=0, capacity of AGV, distance between stations
Define Function MissionGeneration:      # mission generation algorithm
    Knowing the capacity of the AGV. The target stations are generated randomly
    from S2 to S9.
    For each pair of Pickup and drop stations:
        While they are the same:
            Replace the drop station by another one randomly
    Reorder if required

While j< Max Iteration:
    Initialise parameters

    While missions <=Total number missions required to complete:      # MPN
        Generate Missions for each AGV
        AGV with lowest running time (random one if they are the same) is chosen
        Knowing the current position of AGV and its next target
        optimise the route      # RoPN

        If current position≠ next target:      # DAPN
            Define the path going to use
            If the path is not in using paths:
                Import the path into using paths for the AGV
                current position = next station
                time of the AGV += the time travel on the path
            Else: # it means there are more than one AGV on the same path
                If the travelling directions are the same:
                    Move as usual
                Else:
                    time of the AGV= max (time of the AGVs travelling opposite)-δt
                    # hence the AGV will move first after the path is clear

        If current position= next target:      #target reached
            current position = current position
            time of the AGV += the time for pickup or drop item
    j=j+1
end while
Postprocess results and visualisation
```

Figure 6.12 Pseudo code for the AGV system with multi-load AGVs

6.5 Model Development

To verify the simulation models developed above and investigate the influences of the number of single-load AGVs, and the load-carrying capacity of a multi-load AGV, on the performance of an AGV system in the same system layout, the number of single-load AGVs, the load-carrying capacity of multi-load AGV, and the time spent on each path are used as the inputs of the model. The simulation procedure is implemented using the following steps:

Step 1: Initialise the model through

(1) defining the values of the timed transitions. These times are based on the phase lengths assumed in Table 6.1 and the time required to complete travel on each single path.

(2) placing coloured tokens that represent different AGVs into Phase 1.

Step 2: Identify and switch the transition with the minimum switching time in the whole model. It should be noted that the transitions for pickup and unloading always have priority over the transitions to 'next path' places. Hence, the AGVs will perform the pickup and unloading operations before they start to move to the next stations.

Step 3: Search the immediate transitions that are directly connected to the present place. If any is found enabled, switch it.

Step 4: Repeat Step 3 until no more immediate transitions are8 enabled.

Step 5: Iterate the above simulation until the predefined iteration time is reached.

In order to investigate the convergence performance of the developed model, the total operation time that is taken for completing 15,000 missions with three single-load AGVs is calculated. Each AGV is allocated 5000 missions. The total operation time is defined as the sum of the operational time of all AGVs in the system. The calculation results are shown in Figure 6.13.

From Figure 6.13, it is found that the oscillation of the total operation time taken by the AGVs decays quickly with the increase of the number of simulations, and finally converges to a stable value after the number of simulations exceeds 1,500. To guarantee the reliability of the calculation results, 3,000 simulations are adopted to calculate the total operation times of the AGVs in different configuration scenarios of the AGV system.

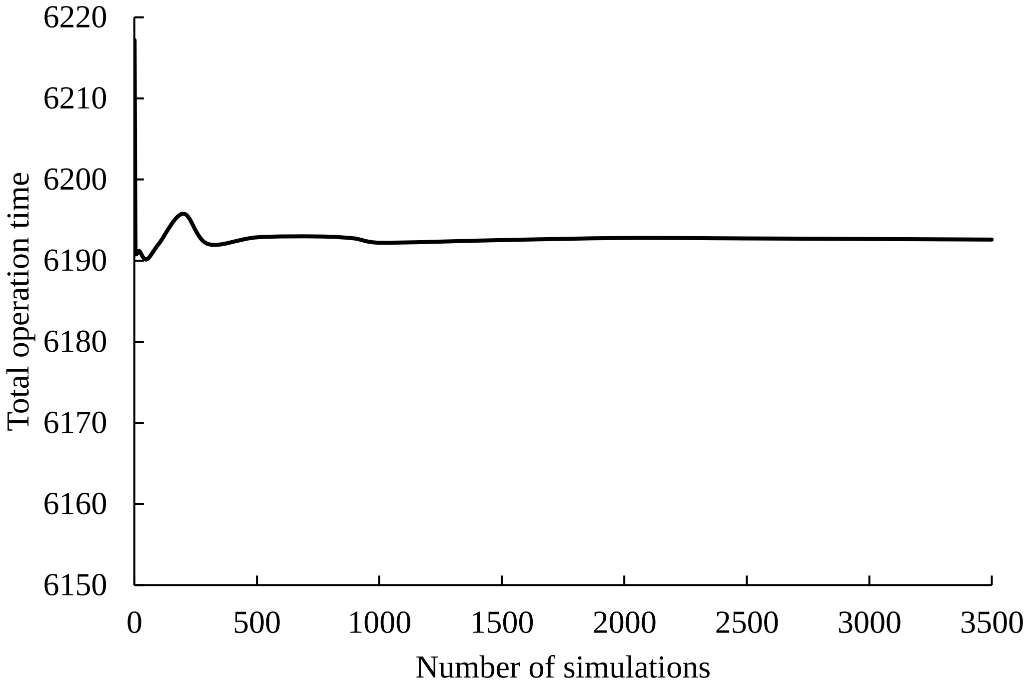


Figure 6.13 Convergence performance of the developed model

6.6 Performance Prediction of AGV Systems

The influence of the number of single-load AGVs on the performance of the AGV systems is investigated first. The total operating time that is taken by the system to complete 15,000 missions for the layout in Figure 6.1 was calculated for systems containing 1 to 10 AGVs. It is assumed that the AGV is always saturated with tasks, which means there is no time gap between the tasks of each AGV. The calculation results are listed in Table 6.2. In the table, the second column is the time taken to complete all missions by the AGV system. The third column is the sum of operation time by all AGVs in the system during the process. The fourth column is loss in operational efficiency due to the increase in the number of AGVs. The efficiency loss η can be calculated by using the following equation

$$\eta = \frac{OT_i - OT_1}{OT_1} \times 100\% \tag{6.2}$$

where OT_i represents the total operation time of the i-th single-load AGV. The last column is the number of conflicts that happen during the period of completing the required number of missions.

Table 6.2 Total operation time taken by the systems consisting of different numbers of single-load AGVs

Number of single-load AGVs	**Time taken to complete 15,000 missions**	**Total operation time of all single-load AGVs**	**Loss in operational efficiency**	**Number of conflicts in the process**
1	6099.6060	6099.6060	0.00%	0
2	3075.6296	6151.2593	0.85%	1755.9603
3	2064.2229	6192.6688	1.53%	3396.8913
4	1556.8209	6227.2837	2.09%	4922.8177
5	1251.0290	6255.1448	2.55%	6340.2453
6	1046.6469	6279.8813	2.96%	7666.1243
7	900.0698	6300.4888	3.29%	8885.5333
8	789.7964	6318.3717	3.59%	10064.1040
9	703.7405	6333.6648	3.84%	11153.4090
10	634.7416	6347.4161	4.06%	12183.7830

From Table 6.2, it is found that the more single-load AGVs are used, the less time will be taken by the system to complete the missions (see the results listed in the second column). However, the total operation time of all AGVs listed in the third column increases with the increase of the number of AGVs, due to the increased chance of traffic conflict as shown in the fourth column. This implies that the operational efficiency of the AGV system will decrease when more AGVs are employed in this application. But different tendencies could be observed from other AGV applications, which are characterised by different values of the predefined parameters (such as the time taken for pickup or drop items).

In addition, as the total operation time of all AGVs can directly reflect the operational cost of the AGV system, the increasing tendency of the total operation time of all AGVs versus the number of AGVs means that the operational cost of the AGV system will monotonically increase with the increasing number of AGVs.

Subsequently, an AGV system that contains only one multi-load AGV is considered in order to investigate the influence of the load-carrying capacity of multi-load AGV on the performance of the system. It is assumed that the multi-load AGV always travels at a constant speed and its load-carrying capacity varies from 1 to 10 items, the corresponding total operation time that the system will take to complete 15,000 missions in the system layout shown in Figure 6.1 is calculated. Also, as the orders of the stations to be visited are important for the multi-load AGV, the importance of reordering and predefining missions is investigated through assuming 4 possible scenarios. As both mission allocation and the routing problem of multi-load AGVs in an actual AGV system layout have never been studied before, these four scenarios are proposed as initial setups to the area. They are:

1. First Come First Served (FCFS) scenario – as described in [117], the order of target stations is not optimised. The route the vehicle travels is based on the order of the subtasks received;
2. Optimise the order of target stations – the order of target stations is optimised to ensure the shortest journey;
3. If all the missions were known in advance, the missions sharing the same stations can be grouped together for completion. Given the order of the target stations is still optimised, the unload station is fixed in each mission – in other words, there is only one unload station in each mission;
4. In addition, given the order of target stations is still optimised, both pickup and unload stations are fixed– there is only one pair of pickup and unload stations in each mission.

The calculation results of the time of completing 15,000 missions by a multi-load AGV in all the above 4 scenarios are listed in Table 6.3 and graphically displayed in Figure 6.14.

Table 6.3 Time (hours) to complete 15,000 missions by a multi-load AGV

Load-carrying capacity (items)	**Scenario1**	**Scenario 2**	**Scenario 3**	**Scenario4**
1	6099.6060	6099.6060	6099.6060	6099.6060
2	5295.9048	4972.8478	4314.6740	3349.9406
3	4681.1233	4291.8075	3543.6099	2433.6573
4	4202.7873	3809.4410	3072.6713	1975.3732
5	3822.9014	3443.2901	2742.1501	1700.2785
6	3514.1916	3152.1014	2493.1356	1517.0789
7	3258.9378	2913.2522	2296.5783	1385.8178
8	3045.2775	2713.3601	2137.6648	1287.9843
9	2863.0643	2542.4237	2005.0836	1211.2480
10	2706.6132	2396.0947	1893.5317	1150.6632

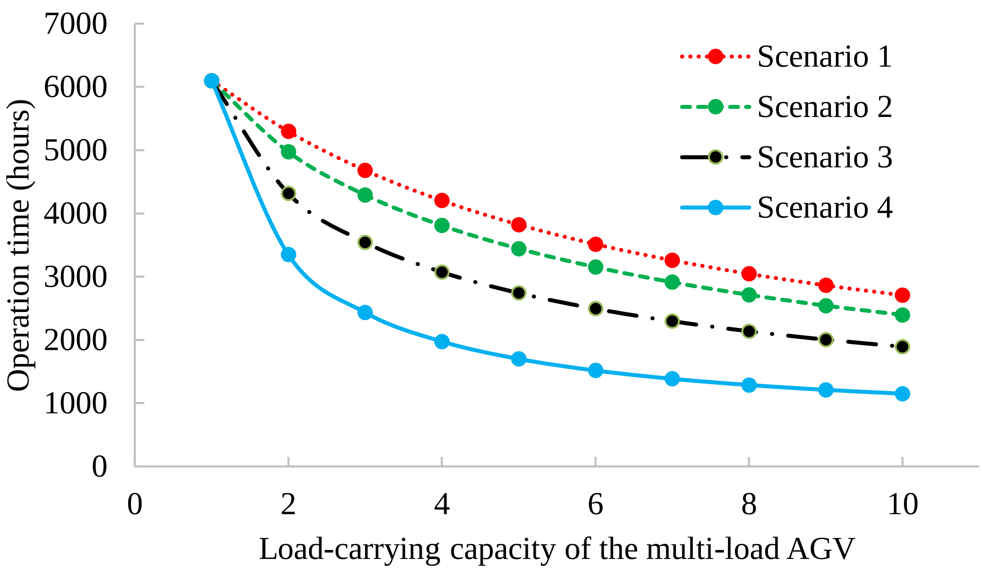


Figure 6.14 The tendencies of operation time versus the capacity of multi-load AGV

From Table 6.3 and Figure 6.14, it is found that

1. The operation time shows a gradually decreasing tendency in all four scenarios

with the increase of the load-carrying capacity of the multi-load AGV. This further proves that the operation efficiency of the AGV system can be improved by increasing the capacity of the multi-load AGVs;

2. In Figure 6.14, the line representing the operational time for scenario 2 is always below the line representing the operational time for scenario 1 under all AGV load-carrying capacity conditions except when the capacity is '1'. This suggests that optimisation of the order of target stations is able to increase the performance of the multi-load AGV system;
3. Further observation of Figure 6.14 has shown that based on the optimised order of target stations, the system efficiency can be further improved if the pickup and unloading stations in a mission are fixed, although investigation should be conducted to see whether this is achievable in real applications such as a good distribution centre.

Using the data listed in Table 6.3, the improvement of system efficiency in all scenarios can be calculated using the following equation

$$\Delta Eff = {(T_{FCFS} - T)}/{T_{FCFS}} \times 100\% \tag{6.3}$$

where ΔEff indicates the improvement of system efficiency, T_{FCFS} is the operation time of the multi-load AGV in the FCFS scenario, T is the operation time of the multi-load AGV in the other scenarios considered. The values of ΔEff are graphically shown in Figure 6.15.

From Figure 6.15, it is seen that efficiencies increase rapidly when capacity increases from 1 to 3 but the increase levels off with further capacity increase. After the loading capacity of the AGV is greater than 6, the efficiency improvement tends to be constant. In other words, after a capacity of approximately '6', the efficiency improvement by increasing the load-carrying capacity of the multi-load AGV is limited. This implies that there is an 'optimal capacity' of the multi-load AGV, 6 for this research system, which is important to the future scaling up the design of multi-load AGV systems. In addition, from Figure 6.15 it is also found that the effect of increasing the capacity of the AGV on the efficiency improvement is the greatest in Scenario 4.

This suggests that the shorter the route in a mission, the more the efficiency will be improved by the approach of increasing the capacity of the AGV.

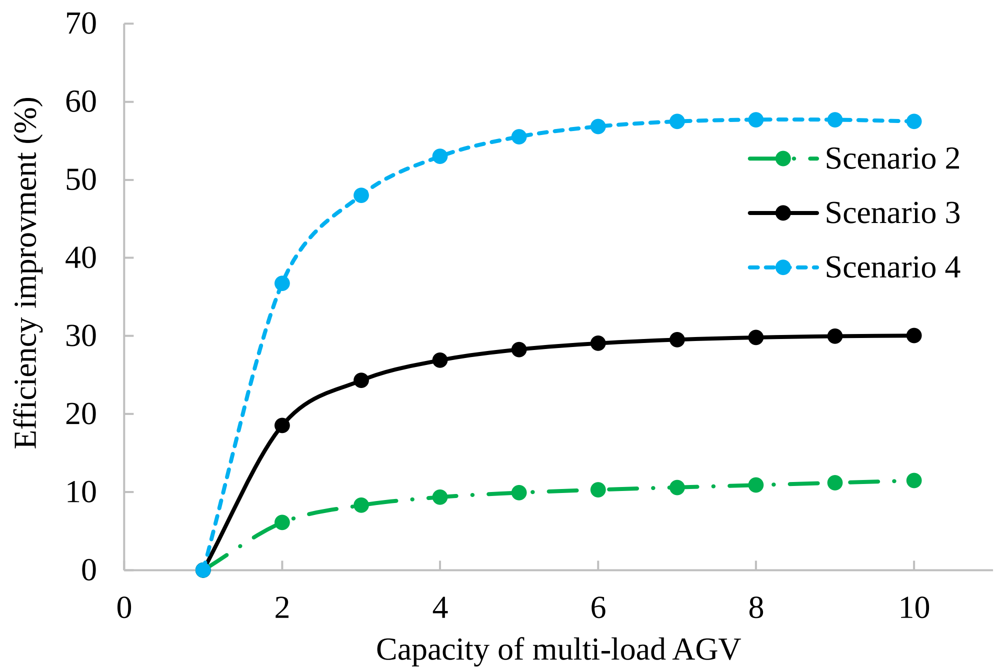


Figure 6.15 Efficiency improvement in different multi-load AGV scenarios

To demonstrate the superiority of multi-load AGV over single-load AGV in the application, a comparison is made between the operation time obtained in the most inefficient FCFS scenario, Scenario 1, in Figure 6.14 and those operation times listed in Table 6.2. The comparison results are shown in Figure 6.16. Three curves representing the operation time obtained in the FCFS scenario using one multi-load AGV, time taken by single-load AGVs, and total operation time of all single-load AGVs are plotted, respectively.

From Figure 6.16, it is found that except at capacity ‘1’, the curve representing ‘Time taken by the multi-load AGV to complete missions’ is always above the one for ‘Time taken by single-load AGVs to complete missions’. This indicates that in contrast to using a multi-load AGV, to use multiple single-load AGVs does reduce the time required to complete missions. However, the solid line representing ‘Total operation time of all single-load AGVs’ is always found to lie above the curve representing ‘Time taken by the multi-load AGV to complete missions’ with the exception of capacity ‘1’. This suggests although using multiple single-load AGVs can reduce the system operation time, it leads to a much higher system operational time than that obtained by a multi-load AGV. This demonstrates the superiority of multi-load AGV over single-load AGV in practical applications.

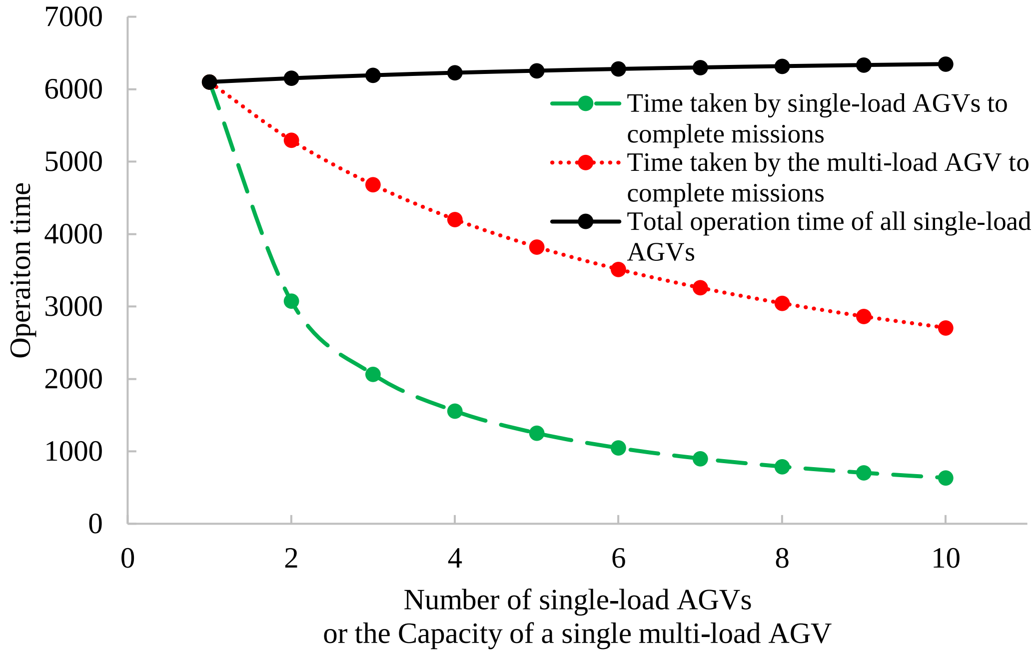


Figure 6.16 Performance comparison of multi-load and single-load AGVs

6.7 Conclusions

In order to investigate the performance of multi-load AGVs and demonstrate their advantages over single-load AGVs in applications, the CPN method is applied to simulate a multi-load AGV system in this Chapter. Moreover, the CPN models of a number of single-load multi-AGV systems are also developed for comparison. Through performing a series of simulations, the following important conclusions can be drawn:

1. As opposed to the conventional mathematical programming methods, the CPN does provide a powerful tool to simulate and address the traffic conflict issues that are often encountered in the operation of AGV systems;
2. Increasing the number of single-load AGVs in a system can reduce mission completion time. However, it increases the total operation time of all single-load AGVs. So, it can be concluded that the operation efficiency of AGV systems will decrease when more single-load AGVs are employed;

3. Compared to employing multiple single-load AGVs, the use of a multi-load AGV does lead to a longer mission completion time. However, the total operation time when using a multi-load AGV is much lower than that taken by all single-load AGVs. Since the total operation time determines the operating cost of the system, it can be said that the application of a multi-load AGV will bring the operator more economic benefit than using multiple single-load AGVs;
4. The research has shown that after the load-carrying capacity of the multi-load AGV exceeds a certain value, to further increase its load-carrying capacity will no longer improve the system efficiency significantly. As that value indicates the ‘optimal capacity’ of the multi-load AGV, it is of great significance to scaling up the design of the future multi-load AGVs.

The application of the simulation model developed in this Chapter can be further extended to study more complex AGV applications, such as the multiple multi-load AGVs that will be considered in Chapter 7. In addition to this, more complex operational conditions, such as AGV failures, maintenance etc., have not been considered in the research of this Chapter. They will be studied in the following Chapters.

7 Impact of AGV's Reliability on the Performance of AGV Systems

7.1 Overview

In Chapter 6, the advantage of using a multi-load AGV has been studied by comparing it with the application of multiple single-load AGVs. In this Chapter, the research will be extended furthermore to study the application of multiple multi-load AGVs, in which the inevitable interactions between the vehicles will be considered. The system simulation in this Chapter is still based on the same system layout described in Section 6.2. It is necessary to note that in the practical application of AGVs, only those AGVs with the same load-carrying capacity are allowed to run in the same system, because using the same type of AGVs can ease management. Otherwise, the complexity of the AGV control will increase enormously in actual applications. Such a principle is also adopted in the study of this Chapter. In addition, the reliability of the AGVs will be taken into account when evaluating system performance. In the simulation model developed, the failed AGVs are recycled by an automatic recycle vehicle to prevent blockage. In Chapter 5, all AGVs are required to stop at their current positions once the recycle process is trigged. They will stay there until the recycle vehicle reaches the failed AGV. Considering such a recycling policy may negatively influence the performance of the system, a new recycling policy will be adopted in this Chapter. According to the new policy, when an AGV fails, the AGVs running on other paths will continue to operate normally, and the AGVs that are blocked by the failed AGV will be redirected to their target stations. Such an improvement will increase the operational efficiency of the AGVs in the system, and will be adopted in the new simulation models developed in this Chapter. To reduce and prevent failure of the AGVs yielding unplanned downtime, different maintenance strategies and backup AGVs ensuring availability of the system will be simulated and the corresponding system performance will be evaluated. To facilitate the research, several different new CPN models will be constructed to simulate the activities in the AGV systems. The CPNs are linked together and share information about the movements, operations and health states of the AGVs in the systems.

7.2 Assumptions

The assumptions to formulate the problem are given as follows:

- The lengths of the paths are equal, requiring 0.1 hours of travelling time from one station to another by an AGV. Since modern AGV control systems allow flexible routing of the AGVs, the symmetrical distance is a reasonable assumption [49].
- The AGVs are either in a working or a failed health state. Once an AGV fails, it will stop its movement or action immediately, preventing further damage to the whole vehicle.
- After maintenance has been performed, the recovered AGV will be assumed to be as good as new. It should be noted that this cannot be guaranteed in real applications.
- The weight of each item is the same. In warehouse handling the standard products are often the same, hence this can be seen as a valid assumption creating negligible difference.
- No capacity limits at stations. This factor will be further discussed in Chapter 9.
- The operation of an AGV will not stop the operation of other AGVs in the same station. This assumption depends on the application of the AGV. For example, if the operations of the AGVs in the same station are independent, then the assumption is true. However, if a specified machine is required to support an AGV activity, other AGVs needing the same support have to wait. This factor will be further discussed in Chapter 9.
- An AGV failed at a station will not cause a blockage at the station. This is assumed to simplify the modelling and focus on the failure on paths. This factor will be further discussed in Chapter 9.
- The speed of AGVs is assumed to be constant.

7.3 Development of AGV Models

The overall model to describe the operation activities of multiple multi-load AGVs in the prescribed system layout consists of eight CPNs. These are described as the following:

- Route Petri Nets (RoPNs) - to describe the optimised routes that the AGV will travel to complete a mission.
- Master Petri Nets (MPNs) - to govern the phase changes in the missions of AGVs.
- Conflict Detection and Avoidance Petri Nets (DAPNs) - to detect and avoid the conflicts in the operation of the AGVs.
- AGV Health State Petri Nets (AHSPNs) – to simulate the change of health state of AGVs.
- Recycle of Failed AGV Petri Nets (RFAPNs) – to recycle the failed AGV in the system back to the base.
- Reroute Petri Nets (RTPNs) – to reroute the AGVs due to the blockage of the path by a failed AGV.
- Corrective Maintenance Petri Nets (CMPNs) – to define the corrective maintenance of the failed AGVs in the system.
- Periodic maintenance Petri Nets (PMPNs) – to define the periodic maintenance of the failed AGVs in the system.

These PNs connect and share information to simulate all of the operations in the AGV systems. These nets will be described in more detail in Sections 7.4 to 7.9. An overall CPN connection diagram is shown in Figure 7.1. The MPNs, RoPNs and DAPNs link together to simulate the normal operation of the AGVs in the system. Once the AHSPNs diagnose an AGV failure, this information will be fed to the RFAPNs to activate the recycling process. The RTPNs are also activated simultaneously to prevent blockage due to the failure, before the failed AGV is recycled. After the failed AGV has been towed back to the 'Base', corrective maintenance to this failed AGV will be simulated by the CMPNs if onsite repair is available. After repair, the health state of the AGV in the AHSPNs will be 'working' again and a new mission can be started. It should be noted that the DAPN has been discussed in Section 6.3.4 and not been modified in this chapter.

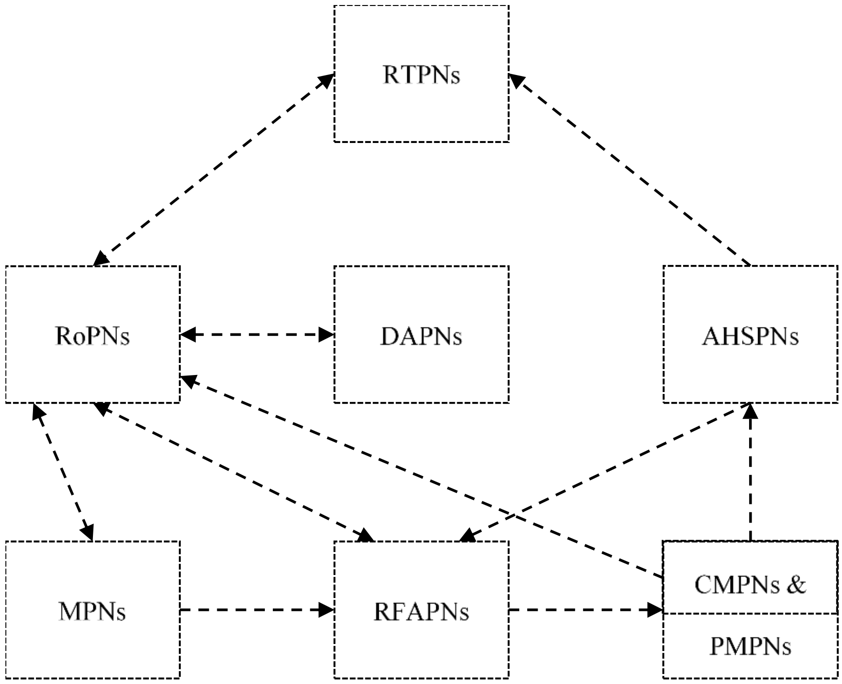


Figure 7.1 CPN connections

7.4 Master Petri Net (MPN)

The MPN model is developed to govern the change of phases from the beginning of the mission, Phase 1, to the successful completion of the whole mission as described in Section 6.2. Once the travelling route of the AGVs is determined through optimisation, the MPN will be developed to define the phase changes between the RoPNs of different AGVs. This has been developed in Section 6.3.3.

However, due to the increase in the number of multi-load AGVs and the failure factor are included, the MPN has to be extended and modified. To ease understanding, an example of the MPN for 2 two-load AGVs is shown in Figure 7.2, where, one of the two-load AGVs is shown in detail. Firstly, two AGVs are assigned tasks. The AGV, represented by  in Phase 1, is assigned a mission consisting of two delivery tasks. The first task of the AGV is to transfer item A from station S2 to station S6, and the second is to transfer item B from station S3 to station S7. After the mission allocation process is completed, the corresponding token will move from Phase 1 to Phase 2. Once the token is transferred to place ‘Phase 2’, the transitions between Phase 2 and the places in respective RoPNs will be enabled.

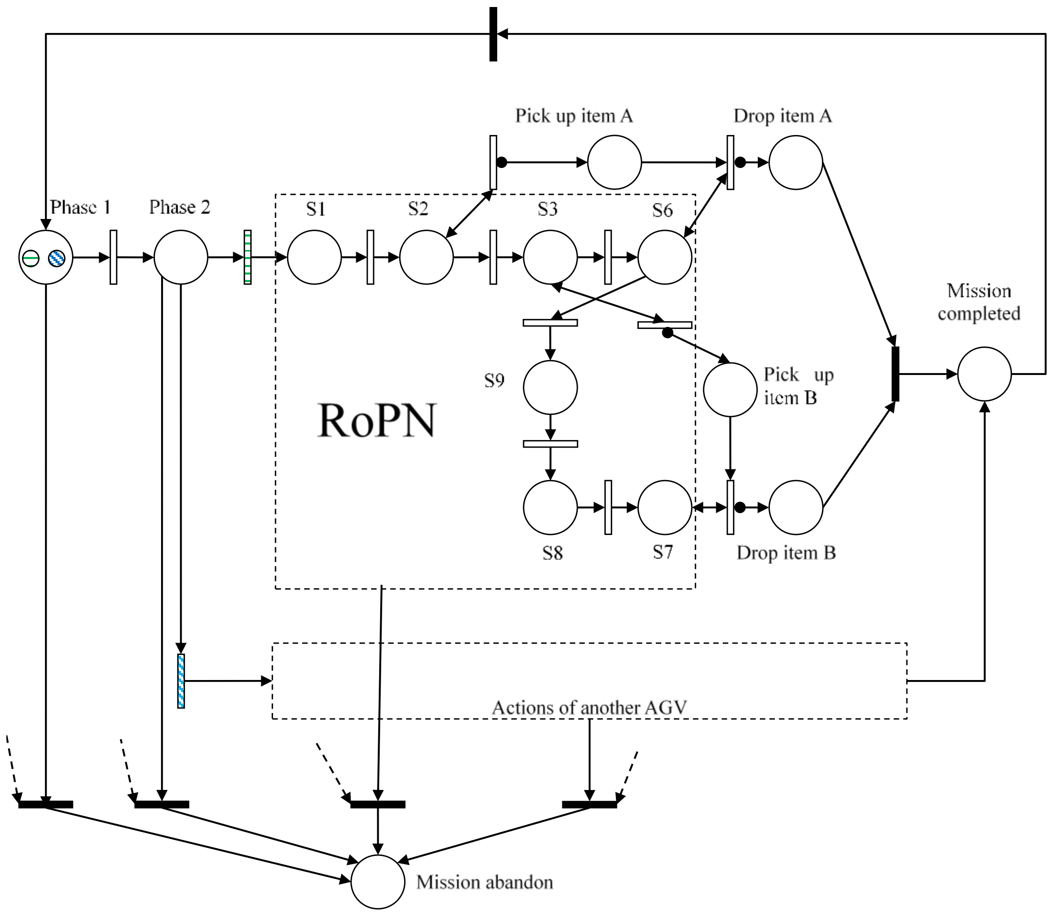


Figure 7.2 Master Petri Net (MPN) for a two-load AGV

From Figure 7.2, it is seen that the AGV will visit all the pickup stations first. So, the AGV will pass through the paths in the order S1→S2→S3. The AGV will pick up item A in S2 and then travel to S3 to pick up item B. As the arcs connecting the transitions and places representing the pickup stations are double ended, a token will be placed in these places representing S2 and S3 as well as the corresponding 'Pick up item' and places. By doing this, these pickup actions can be performed and 'memorised' while the token representing the AGV can still move in the RoPN. After a token is transferred to the places representing pickup of an item, the inhibitor arc connected back to the transition will inhibit the pickup transition. The transition in the RoPN is then activated so that the AGV can move to the next station. Then, the AGV will travel to the unloading stations S6 and S7. Similar movement of AGVs and their transitions will continue until both items A and B are unloaded. The transition connecting the output place representing unloading an item can only fire if the corresponding tokens exist in both the places representing the unloading station and the corresponding items picked up. Once both items are unloaded, the mission can be considered as being completed successfully. Finally, the AGVs will be assigned a new mission and they will start from 'Phase 1' again. Therefore, the RoPN and MPN of the multi-load AGV are not separable. They can be generated automatically for different missions. On the other hand, once an AGV failure information is received from the AHSPNs, the corresponding token in the MPN will be transferred to 'Mission abandon' place. That means the failed AGV will not be able to move or take any further action until its health state is back to working.

7.5 AGV Health State Petri Net (AHSPN)

The AHSPNs are created to model the change of AGVs' health states from working to failure. The AGVs are assumed to be in the 'perfect' health state at the start. With the increase of the service life of the AGVs, the components in the AGV degrade gradually and eventually leading to a failure in the end. In addition, once an AGV fails, it is assumed to stop operation. To demonstrate the AHSPNs, an example with *n* AGVs is illustrated in Figure 7.3.

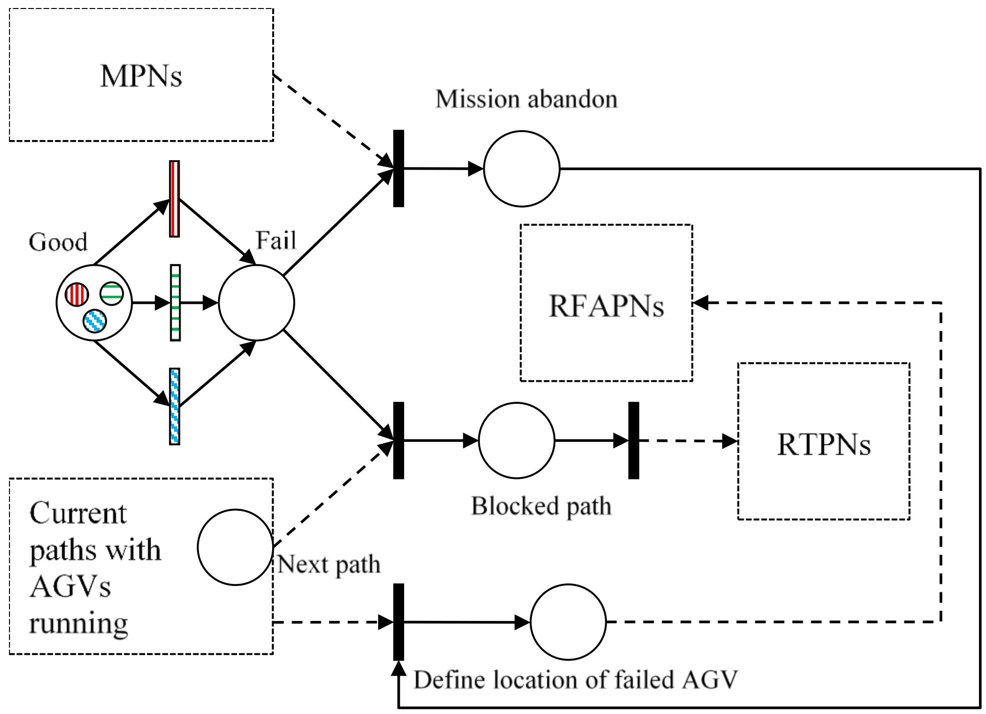


Figure 7.3 AGV health state Petri Net (AHSPN)

In Figure 7.3, there will be *n* tokens with different colours to represent all AGVs in the ‘Good’ place. This means there are *n* healthy AGVs and they are able to work normally. In addition, there are *n* transitions with the corresponding colours to define the failure time of the AGVs. Once an AGV fails, then the corresponding token in the ‘Good’ place will be transferred to the ‘Fail’ place. Due to lack of data and reliable model of actual ageing issues of the AGV's, the time for this failure transition is computed by using random sampling and a Weibull distribution with a characteristic life of 730 hours and shape factor 3. The Weibull distribution is able to reflect that the AGVs’ failure rate is assumed to increase with time. That means that the longer the AGVs operate, they will be more likely to develop fault. The 730 hours of the characteristic life mean that 63.2% of the AGVs are assumed to fail after an actual service time of 730 hours. Herein, it is necessary to note that the above values of the parameters for the distribution are assumed only for demonstration purposes. They could be different in practice. The probability density function (PDF) of the distribution based on these presumed values is plotted in Figure 7.4, where the density indicates the probability that an AGV may fail in the scenario indicated by ‘Time to failure’. It is found that the AGVs are most likely to fail when the service time is around 730 hours.

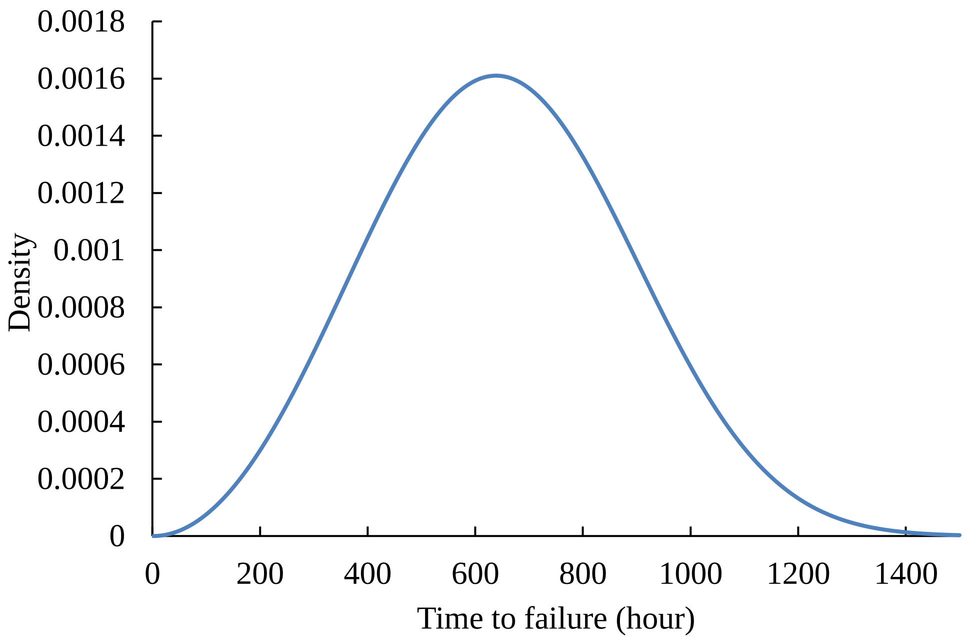


Figure 7.4 Probability density function of the Weibull distribution

The information about AGV failures is fed into the MPNs, which will lead to the abandonment of the AGV mission. Once a token is transferred to the ‘Fail’ place due to the failure of an AGV, the token with the same colour in the MPN will be transferred to 'Mission abandon' place, as shown in Figure 7.2. The RFAPNs will be activated simultaneously to recycle the failed AGV as soon as a token is transferred into the 'Define location of failed AGV' place in the net. The failure information will be also fed to appropriate RoPNs to identify the location of the failed AGV and the possible path blockages caused by the failed AGV.

In Figure 7.5, the location of the failed AGV can be identified according to its activities and the time when it fails. There will be a token in the 'Using path' place to define the path that the AGV is travelling on. Once the AGV fails, the token in the 'Fail' place from the AHSPN of the AGV and the token in the 'Station' place from the RoPN will be transferred to the 'Blocked path' and 'Mission abandon' places. Then, the position of the failed AGV can be identified by calculating the time that it has travelled on the path. However, if the AGV fails in a station, there will be no token in the 'Using path' place. The station that an AGV fails can be identified successfully by transferring the token in the 'Station' place.

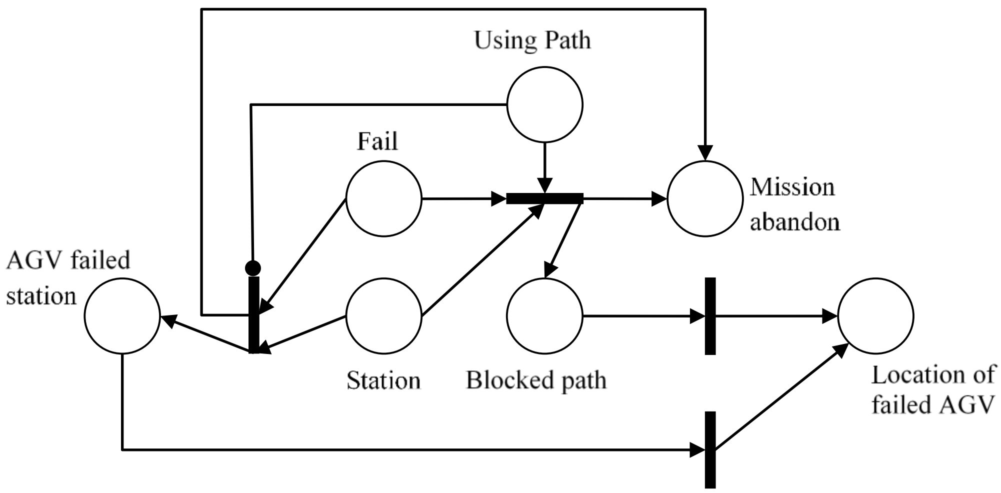


Figure 7.5 Locating failed AGV

7.6 Recycle of Failed AGV Petri Net (RFAPN)

The recycling process of failed AGVs is shown in Figure 7.6. Once the information about mission abandonment is received from the MPN, the recycling process will be activated. Firstly, the location of the failed AGV is identified followed by the route optimisation from the base S1 to its location. There is only one special vehicle parked in the 'Base', whose only role is to recycle failed AGVs. If it is available, it will be despatched to the failure location following the RoPN generated using the route optimisation described in Section 6.3.2. It will be seen as unavailable until it tows the failed AGV back to the 'Base'. Hence, if another AGV fails during the unavailable time, the recycle task will be queued and it will have to wait at its failed location. After the recycle vehicle reaches the position of the failed AGV, it will tow the AGV back to the 'Base'. On arriving in the 'Base', the decision will be made on whether the repair should be started immediately, which is dependent upon the availability of corrective maintenance engineer. If the engineer is available or the off-site maintenance strategy is adopted, the CMPNs will be activated to enable the repair process. Otherwise, the failed AGV will stay in the 'Base' awaiting repair.

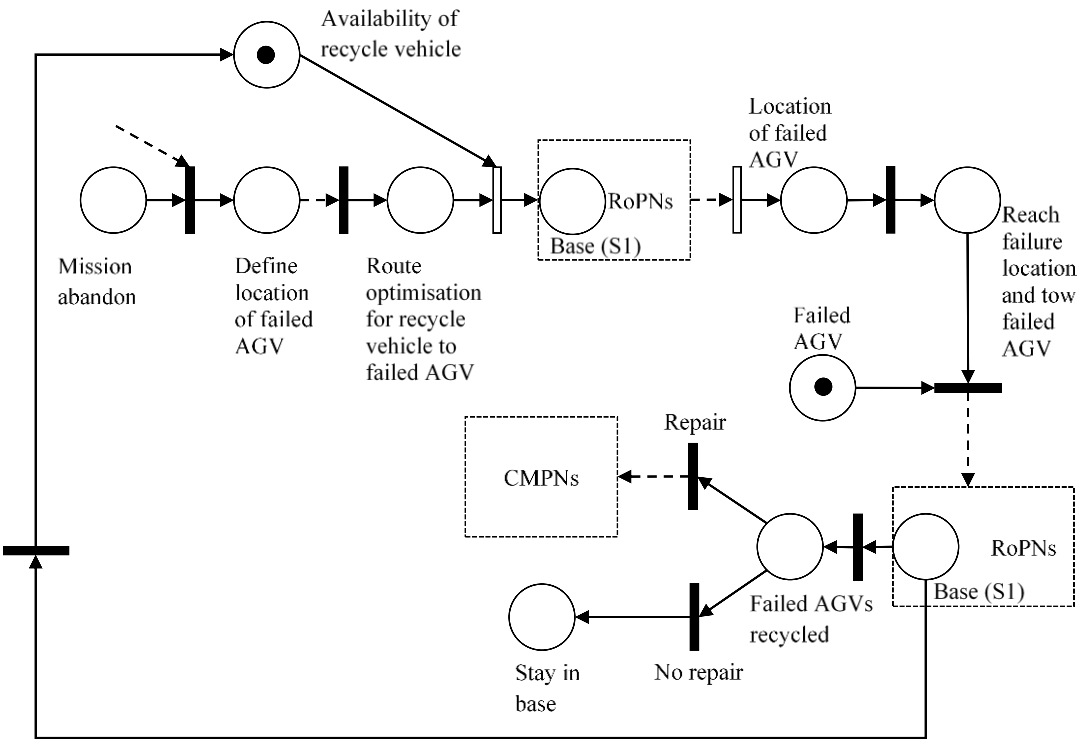


Figure 7.6 Recycle of failed AGV Petri Net (RFAPN)

7.7 Reroute Petri Net (RTPN)

Once an AGV fails when it is moving on a path, the path will be blocked until the failed AGV is towed by the recycle vehicle. During the period of blockage, those AGVs that intend to travel on that blocked path must be redirected. This process is illustrated in

Figure 7.7.

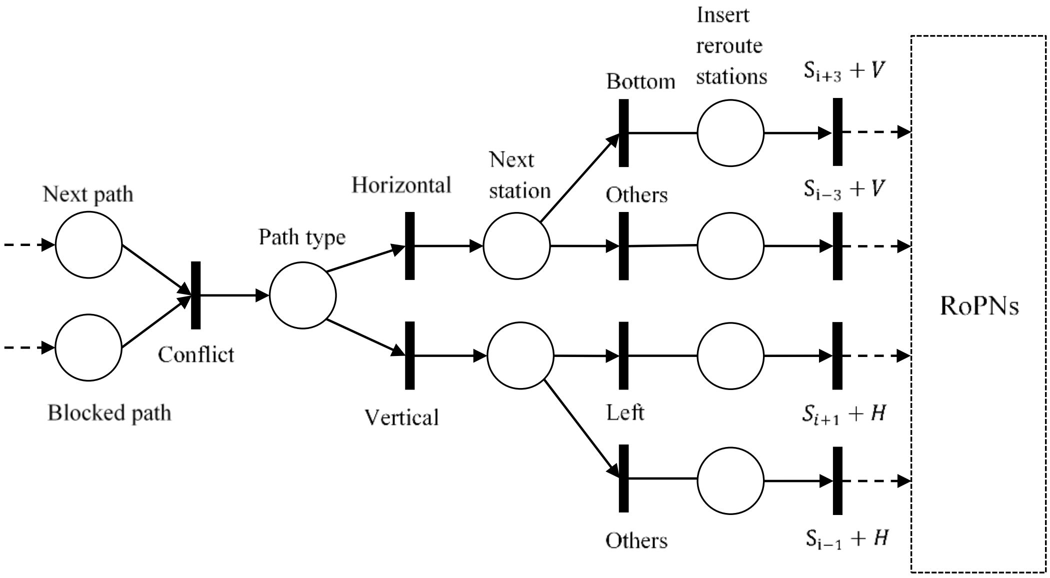


Figure 7.7 Reroute Petri Net (RTPN)

From Figure 7.7, it is seen that the RTPNs will be activated when the path that the AGV is going to travel on is a blocked path defined by the PN for locating the failed AGV. Firstly, the type of this path will be identified, i.e. is it a horizontal or vertical path? Then, the target station will be defined, e.g. an AGV is going to travel from Station Si to Sj, where Sj is the target station. Following this logic, there will be four different scenarios. Every scenario will have a unique rerouting strategy as described in Table 7.1.

Here, an example is given below to ease the understanding of the rerouting method. When an AGV intends to travel from station S2 to S3 via the path '23', the path will be checked whether it is blocked by a failed AGV. If it is blocked, the reroute process will be activated. Since it is a horizontal path on the bottom edge as shown in Figure 6.5, an intermediate station, S6(=S(3+3)), will be inserted before the target station S3 in the list of target stations'. The AGV will change its moving direction from horizontal to vertical. Then, the AGV can travel following the new RoPN which has been modified from S2→S3 to S2→S5→S6→S3.

Table 7.1 Reroute strategy

Path Types	**Target Stations**	**Reroute Methods**
Horizontal	On the bottom edge	1. Insert a station with the $station\ number = S_{i+3}$ in front of the target station; 2. Change the movement direction to vertical (shown by $+V$ in Figure 7.7); 3. Use the current station as the starting point, compute route optimisation again to create a new RoPN.
	Others	1. Insert a station with the $station\ number = S_{i-3}$ in front of the target station; 2. Change the movement direction to vertical; 3. Use the current station as the starting point, compute route optimisation again to create a new RoPN.
Vertical	On the left edge	1. Insert a station with the $station\ number = S_{i+1}$ in front of the target station; 2. Change the movement direction to horizontal (shown by $+H$ in Figure 7.7); 3. Use the current station as the starting point, compute route optimisation again to create a new RoPN.
	Others	1. Insert a station with the $station\ number = S_{i-1}$ in front of the target station; 2. Change the movement direction to horizontal; 3. Use the current station as the starting point, compute route optimisation again to create a new RoPN.

7.8 Corrective Maintenance Petri Net (CMPN)

As shown in Figure 7.8, in the CMPN once a failed AGV is recycled and towed back to the ‘Base’ (S1) and moreover, a decision has been made to repair it immediately, it will enter the corrective maintenance process. Different from the CPMN shown in Figure 5.10, two different corrective maintenance strategies, namely repair onsite and send back to the supplier for repair, are considered here. This is closer to the realistic situation than the case considered in Section 5.7. The two corrective maintenance strategies will take different repair times and have considerably different costs. The transitions for activating two different corrective maintenance strategies will be removed respectively if the corresponding strategy is abandoned. If the onsite repair strategy is chosen, a maintenance engineer, extra test space and repair equipment will be expected on site. The failed AGVs will be repaired as soon as a maintenance engineer is available. After the corrective maintenance has been performed, the maintenance engineer who undertook the repair will be released and become available again. In the model, the repair time (T_r) of the failed AGV is assumed to increase with the increase of the load-carrying capacity (L_A) of the AGV. This relation between the repair time and the load-carrying capacity of the AGV is formulated in Equation (7.1) based on empirical engineering knowledge. The 20 working hours are the average time taken to repair a single-load AGV. As the capacity of the AGV increases by 1, the average time will increase by 4 hours.

$$T_r = 20 + 4L_A \quad (hours) \tag{7.1}$$

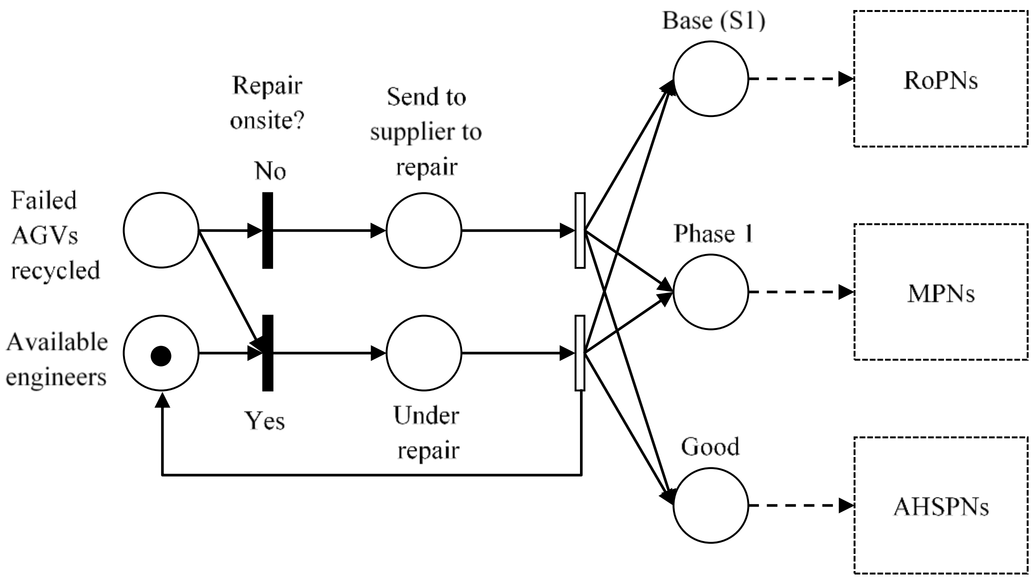


Figure 7.8 Corrective maintenance Petri Net (CMPN)

However, if the failed AGV is sent to the AGV supplier for repair, the average repair time is assumed to be 10 days (100 working hours), which include the time spent on transferring the failed AGVs between the warehouse and the AGV supplier, as well as the actual repair time. This value could vary a lot for different cases as it is highly dependent on the delivery distance and the efficiency of the AGV supplier. After the repair, the health state of the AGV will be transferred to the ‘Good’ place in the AHSPNs and start its new mission from the ‘Base’.

7.9 Periodic Maintenance Petri Net (PMPN)

The PMPN models shown in Figure 7.9 are developed for simulating periodic maintenance in the systems. In this net, all the AGVs, despite their health state, will be inspected and repaired if necessary during the maintenance period. The duration is assumed to be two days here, but it would be different for different service suppliers.

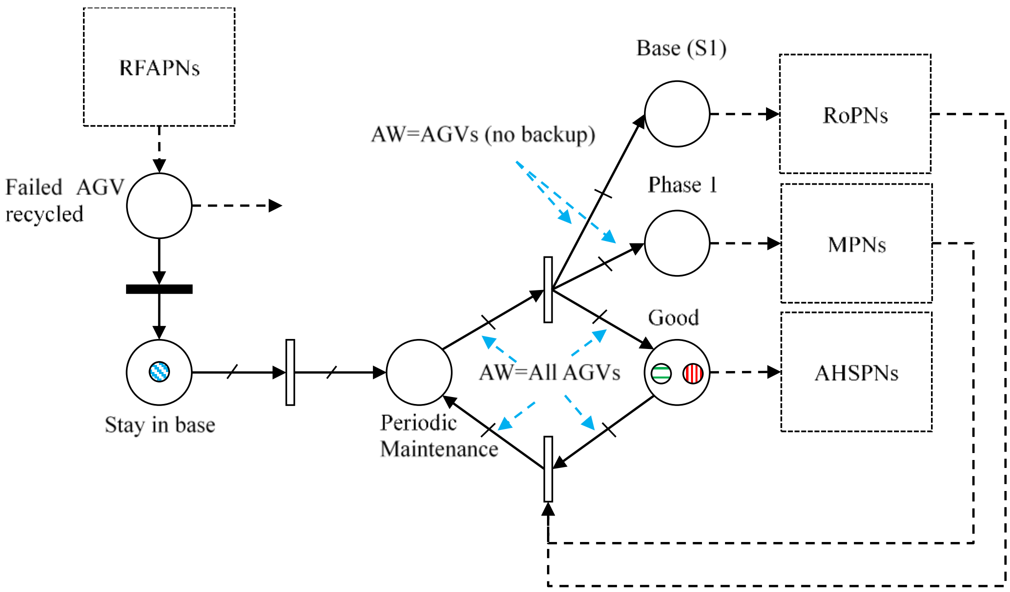


Figure 7.9 Periodic maintenance Petri Net (PMPN)

All the AGVs including both failed and functional ones, will undergo the periodic maintenance process. In the example, there are two healthy AGVs and one failed AGV represented by the tokens in the PN. The tokens in the RoPNs and MPNs will be transferred to ‘Periodic maintenance’ place so as the working AGVs will stop operation as soon as the periodic maintenance process is activated. After the maintenance has been performed, it is assumed that the health state of all AGVs in the system is as good as new. The appropriate tokens will be respectively fed to the RoPNs, MPNs, and AHSPNs so that all the AGVs can start new tasks again. It is worth noting that the number of tokens transferred to the RoPNs and MPNs is equal to the number of AGVs allowed to operate in the system, so that the backup AGVs in the system will not be used to perform any task.

The failed AGVs will be parked in the 'Base' after they are recycled. Different from the periodic maintenance model developed in Section 5.8, a new method, using backup AGVs, is adopted to maintain the performance of the system. The backup AGVs are usually parked in the 'Base'. Once an AGV fails, a backup AGV will be selected randomly to perform new tasks. This process is shown in Figure 7.10. However, such a strategy will inevitably increase the capital and maintenance costs because the backup AGVs can be seen as a waste of resources, which will be further studied in Chapter 8.

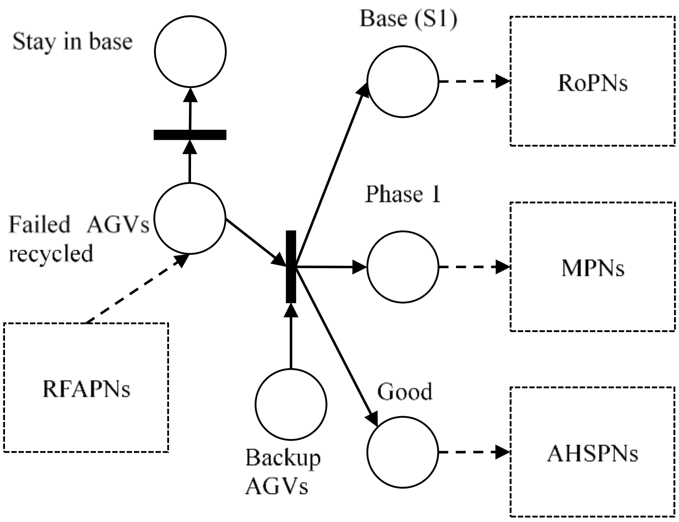


Figure 7.10 Activation of backup AGVs

7.10 Simulation Model

In order to assess the performance of the AGV systems in the same system layout but consisting of different numbers of AGVs that have different load-carrying capacities, and investigate the influence of AGV failures on the system performance, 7 different CPN models mentioned above are assembled to be in one simulation model. The number of AGVs, their load-carrying capacity, the phase lengths, the failure rates and repair time of failed AGVs, and the required working period of the systems are used as the inputs of the simulation model. Then, the simulation is conducted by using the following steps and its corresponding pseudo code is shown in Figure 7.11.

```
Input: Phase time, failure rate, layout of AGV system, maintenance strategy
       total operation time/ total number of missions
       Number of AGV, Time=0, capacity of AGV, distance between stations,
Define Function MissionGeneration: # mission generation algorithm
    Knowing the capacity of the AGV. The target stations are generated randomly
    from S2 to S9.
    For each pair of Pickup and drop stations:
        While they are the same:
            Replace the drop station by another one
    Reorder if required

While j< Max Iteration:
    Initialise parameters
    While missions <= total operation time OR Total number missions required to
    complete:
        Generate a mission for each AGV without a mission
        AGV with lowest running time (random one if they are the same) is chosen
        Knowing the current position of AGV and its next target, optimise the route

        If current position≠ next target:
            Define the path going to use
            If the path is not in using paths:
                Replace the path of the AGV in using paths
                current position = next station
                time of the AGV += the time travel on the path
            Else: # it means there are more than one AGV on the same path
                If the travelling directions are the same:
                    Move as usual
                Else:
                    time of the AGV= max (time of the AGVs travelling opposite)-δt
                    # hence the AGV will move first after the path is clear
            If the path is in blocked paths:
                Ignore the movement above, Optimise the recycle route,
                Move to the next station
        If current position= next target:
            current position = current position
            time of the AGV += the time for pickup or drop item
        If the running time of the AGV >= time to failure of the AGV:
            Record the failure, ignore the operation above, define the failure location
                Optimise the route from the maintenance site/base to the location
            If there is backup AGV:
                Mission the AGV= base to failure location to base
                Backup AGV reduce by 1 (add back after maintenance)
            Else:
                Mission the AGV= base to failure location to base + stay in base until
                repaired
    j=j+1
end while

Postprocess results and visualisation
```

Figure 7.11 Pseudo code for AGV system with failure and maintenance considered

Step 1: Initialise the model through:

a) defining the values of the timed transitions. These times are based on the phase lengths assumed in Table 6.1 and the times required to complete the travelling on each single path. In parallel, the time to failure of each AGV is generated by using the random sampling and the Weibull distribution method;
b) placing coloured tokens that represent different AGVs into 'Phase 1' place in the MPN.

Step 2: Identify and fire the transition with the minimum switching time in the whole model; it should be noted that the transitions for pickup and unloading always have priority over the movement to the next stations.

Step 3: Search through the immediate transitions such as conflict check, mission allocation, etc. If any is found enabled, fire it.

Step 4: Repeat Step 3 until no more immediate transition is enabled;

Step 5: Test for any of the following conditions and log them:

c) if all AGVs in the system have failed, start next simulation;
d) if the operation time exceeds the given period, start next simulation. If not, go back to Step 2.

Step 6: Iterate the above simulation until the predefined iteration time is reached to obtain converged results.

7.11 Simulation Results

Embedding the CPN models into a simulation, the performance of different AGV systems is evaluated. According to the convergence study conducted in Section 6.5, 3,000 simulations have been performed for each system configuration to ensure a reliable computing result. The time taken for the simulation is highly dependent on the number of AGVs, load-carrying capacity of the AGVs, time interval and adaptation of corrective maintenance. The longest simulation time is about 2 hours for 3,000 simulations when the number of AGVs is 5, the load-carrying capacity is 4, the time interval is one year, and onsite corrective maintenance strategy is taken for repair.

7.11.1 Analysis of Impact of AGV's Failure

In this Section, the operating time of the AGV systems is set to be 10 hours per day due to the same assumption made in Chapter 5. The total operation time is set to be 4 months. The number of AGVs varies from 1 to 5 and their load-carrying capacity is 3. These settings are employed to demonstrate the influence of the AGV's failure on the performance of the system. All AGVs in the systems could either fail according to the failure time of each AGV that is a random variable obtained based on the Weibull distribution, or are assumed to never fail during the operations which are assumed in a lot of previous researches [10]. This study has been undertaken in order to investigate the effect of vehicle failures on system performance. Figure 7.12 shows the variation tendencies of the performance of the AGV systems against the number of AGVs before and after the AGVs' reliability is considered.

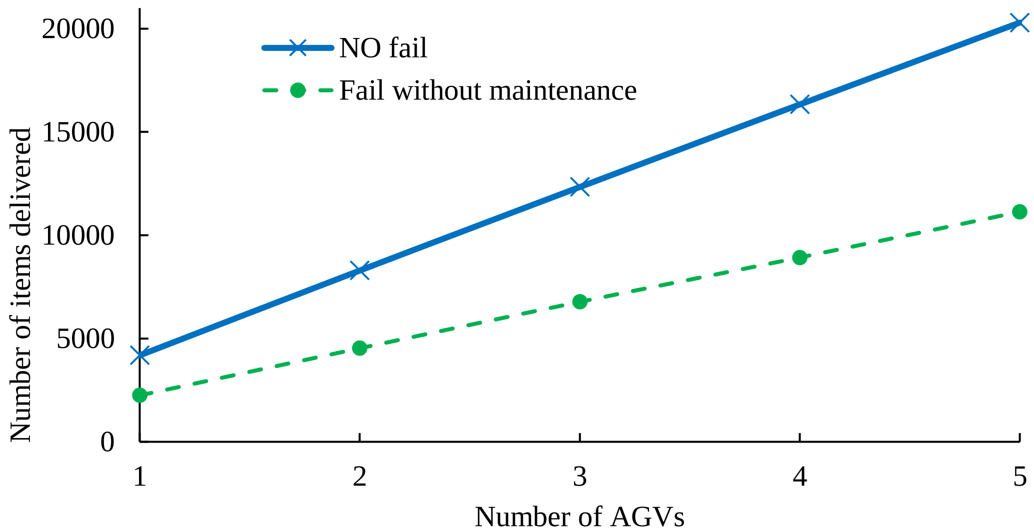


Figure 7.12 Performance with and without AGVs' failure considered

From Figure 7.12, it is found that the number of items delivered by the AGVs without failure is always larger than the results obtained after considering the failure of AGVs. The difference between the results is the smallest when the number of AGVs equals one. As the number of AGVs increases, the gap between the results increases. This suggests that the reliability of the AGVs will have a significant influence on the system performance when the system consists of multiple AGVs. Therefore, the reliability of the AGVs should not be neglected in the research.

7.11.2 Corrective Maintenance

To demonstrate that corrective maintenance is effective to maintain the performance of the AGV systems, the performances of the three-load AGV systems when adopting two different corrective maintenance strategies (i.e. onsite maintenance and offsite maintenance as described in Section 7.8) and without adopting any maintenance are simulated. The simulation results are shown in Figure 7.13, where the red line, blue line and green line represent the results of onsite maintenance, offsite maintenance and without any maintenance, respectively.

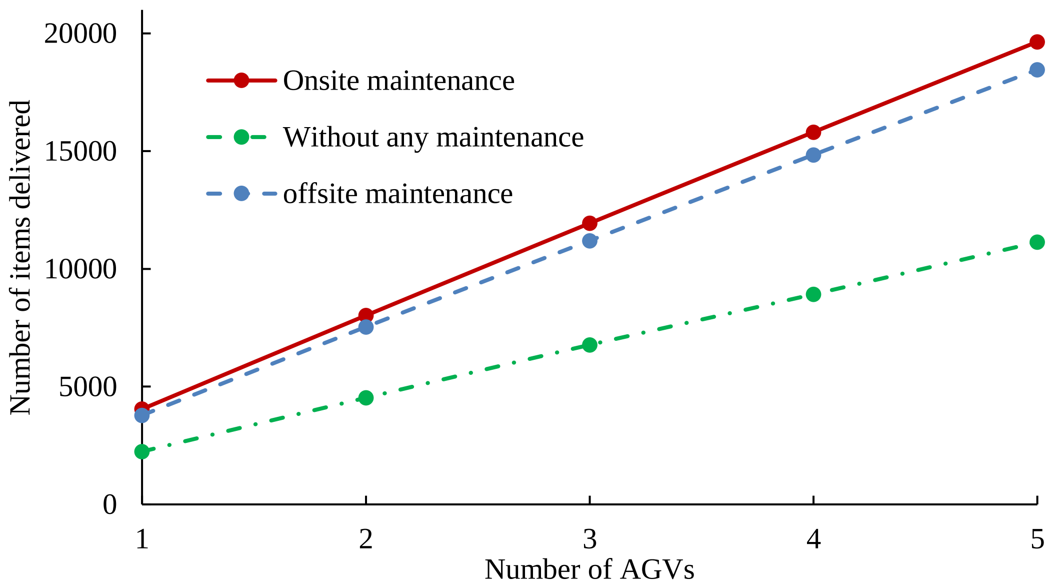


Figure 7.13 Performance with and without corrective maintenance

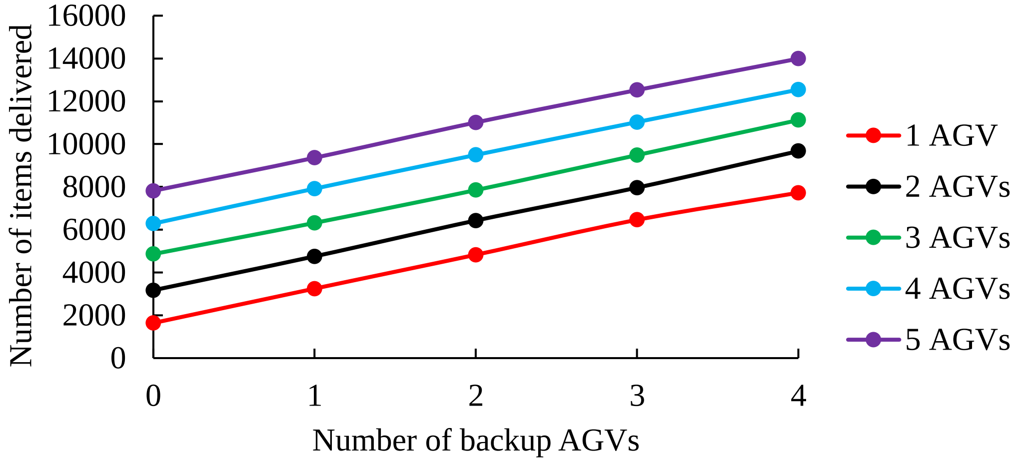
From Figure 7.13, it is seen that the lines representing the system with corrective maintenance are always significantly higher than the line representing the system without maintenance. This suggests that the system without adopting any corrective maintenance shows a fairly poor performance. In addition, the difference between the lines increases with the increase of the number of the AGVs in the system. This indicates that corrective maintenance will play a more vital role when the system consists of more AGVs. In addition, it is seen that due to requiring shorter repair time, the system that adopts onsite maintenance strategy shows a better performance than the system that adopts offsite maintenance strategy does. In other words, the former can deliver about 6% more items than the later does. However, the extra cost might be required to enable the onsite maintenance, which will be further studied in Chapter 8.

7.11.3 Periodic Maintenance

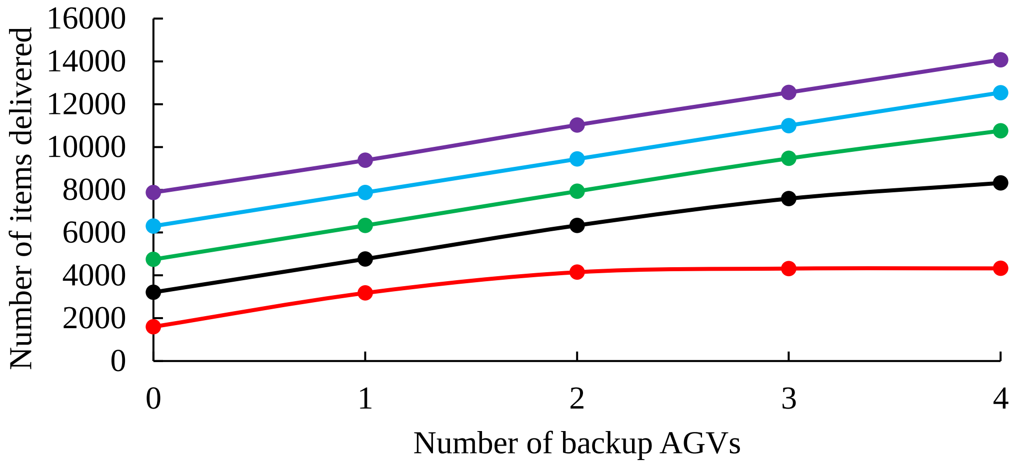
With the increase in the operating time of the AGVs, they are more prone to failure due to the more serious ageing issue. As opposed to corrective maintenance, regular inspection, also known as periodic maintenance, could be a more effective way to avoid the kind of failure of the AGVs in the same duration. The influence of the periodic maintenance with eight different time intervals (i.e. one year, half years, four months, three months, two months, one month, two weeks, and one week) on the system performance will be investigated in this Section. In addition, the effectiveness of using backup AGVs, instead of applying corrective maintenance, to meet the required performance of the system, are studied.

The variation tendencies of the number of completed tasks against the number of available backup AGVs within different periodic maintenance intervals are calculated and the results are shown in Figure 7.14. Herein, the load-carrying capacity of the AGVs in the systems is assumed to be 1 for concentrating the investigation on the effect of using backup AGVs. To investigate the effectiveness of this new strategy, the number of tasks completed by the system that respectively adopts eight different time intervals of periodic maintenance [63] are calculated, and the results are plotted in the subplots of Figure 7.14. The results obtained when using different numbers of AGVs in the system are indicated by different colours. It should be noted that it is not feasible to use more backup AGVs than the operating AGVs in a real AGV system because this will be regarded as a waste of resources. Herein, this scenario is also simulated only for understating the effect of such a new strategy in extreme events. These unrealistic settings will be eliminated from the optimal system strategy after considering the overall cost as described in Chapter 8.

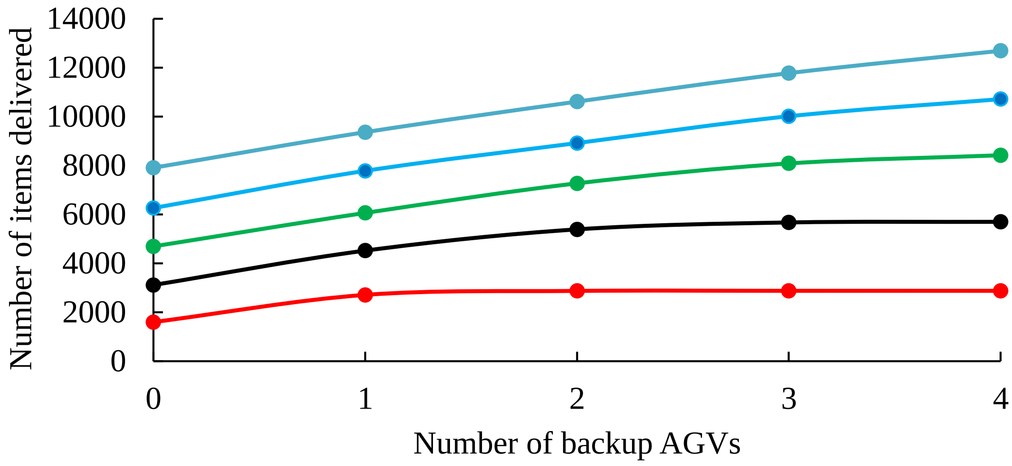
From Figure 7.14(a), it is seen that the number of completed tasks is positively proportional to the number of the backup AGVs being used in a year. Moreover, the lines obtained when the system uses different numbers of AGVs show a very similar tendency. However, there is a noticeable drop in line gradient when the number of the backup AGVs increases from 3 to 4 especially when only one AGV is allowed to run in the system. This suggests that the contribution of backup AGVs to system performance may decrease when there are too many of them in the system. The lines in Figure 7.14(b) for a 6-month interval show a similar trend, but the lines, particularly the line indicating the use of one AGV, start to deviate from the original increasing tendency since the number of backup AGVs is greater than 2. This suggests that when using more than two backup AGVs in the system, they will no longer bring significant improvement to the system performance in this scenario. Therefore, it can be inferred that when using a shorter periodic maintenance interval (i.e. more frequent periodic maintenance), the influence of backup AGVs on system performance will decrease and eventually become negligible when more frequent periodic maintenance is applied to the system. Such a conclusion is further proved by the calculation results shown in Figure 7.14(c) to Figure 7.14(h). From them, it is found the backup AGVs are not any more able to improve the performance of the system when the time interval of the periodic maintenance is less than 2 months, which can be explained using the assumed value of Weibull parameter. As mentioned at the beginning of this Chapter, the characteristic life of the AGVs is set to be 730 hours. While when the time interval of the periodic maintenance is 2 months, the AGVs' operation time is about only 600 hours. In such a scenario, the AGVs operating in the system are not very possible to fail and the backup AGVs will, therefore, have low chance to contribute to the performance of the AGV system.



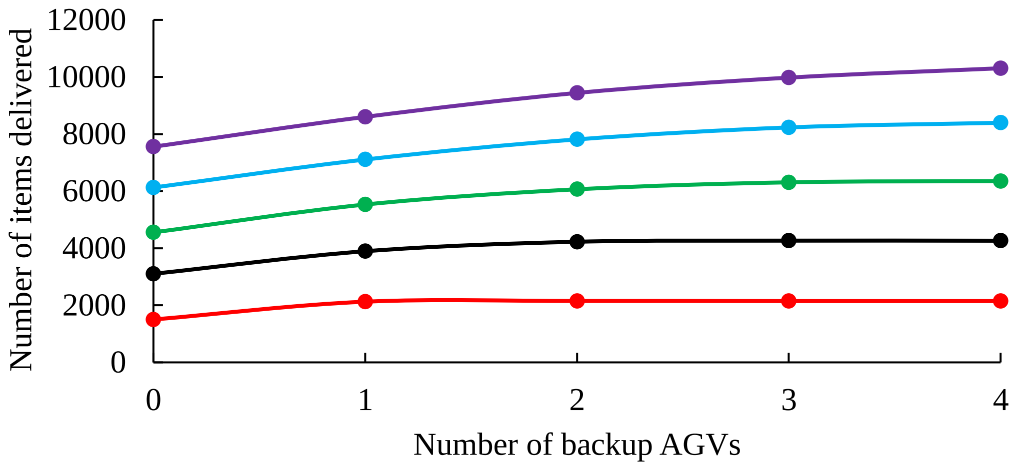
(a) One Year



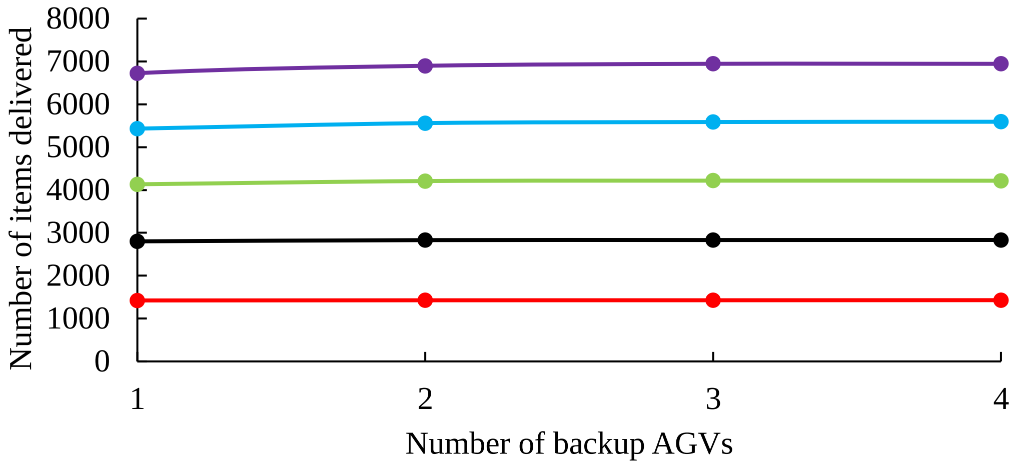
(b) Six Months



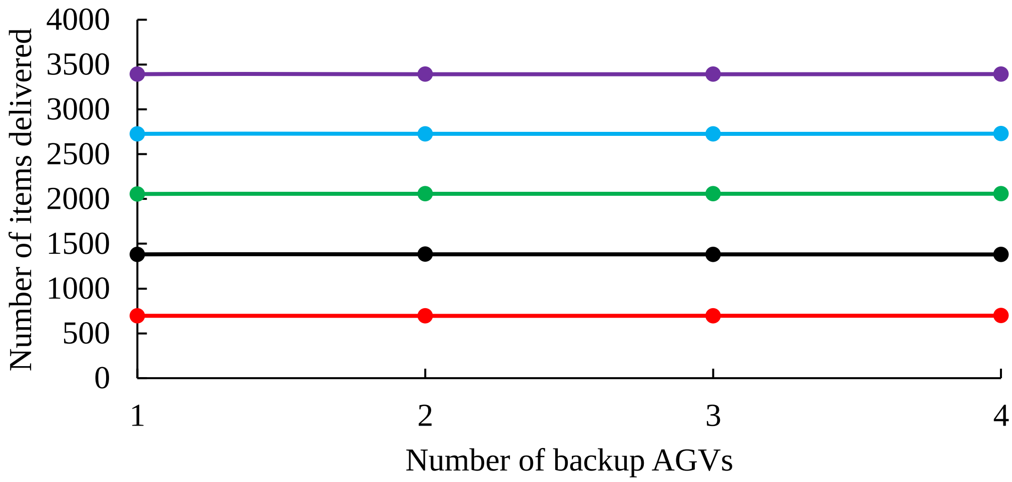
(c) Four Months



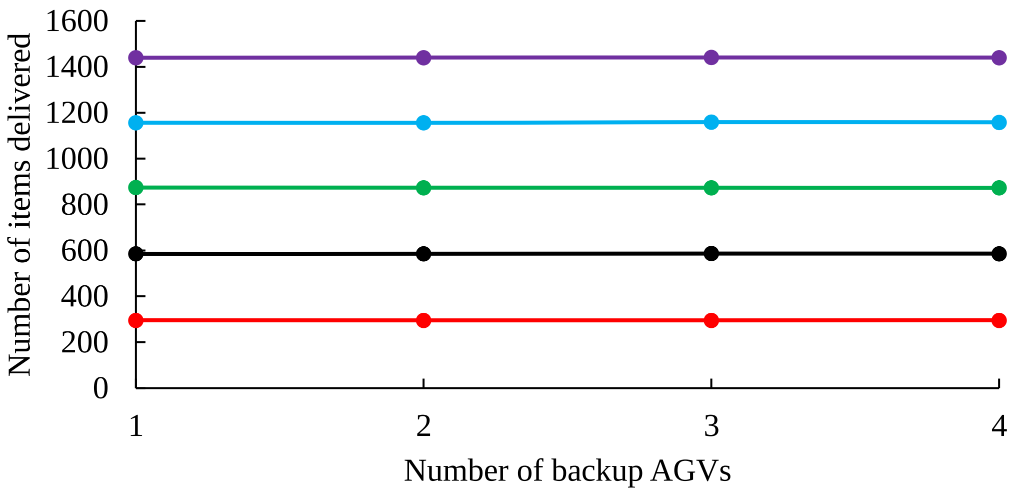
(d) Three Months



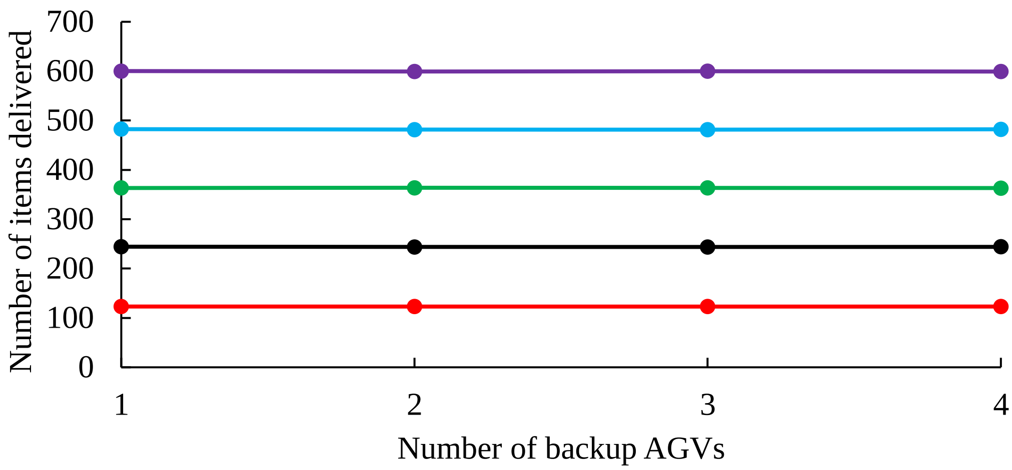
(e) Two Months



(f) One Month



(g) Two weeks



(h) One week

Figure 7.14 Performance with different number of backup AGVs

Inspired by the advantage of the combined use of periodic maintenance and corrective maintenance that has been proved in Chapter 5, the possibility of using these two types of maintenance strategies to replace the use of backup AGVs is further investigated in the following. A system consisting of 3 three-load AGVs is simulated in the research. The calculation results of the items delivered by the system in a year against the interval of periodic maintenance are shown in Figure 7.15. 8 periodic maintenances with different time intervals, i.e. one year, half years, four months, three months, two months, one month, two weeks, and one week, which are aided by two types of corrective maintenance, are considered in the simulations. The average repair time of the onsite maintenance and offsite maintenance is 20 hours and 100 hours, respectively. The calculation results will be compared with those obtained in 5 scenarios of combinedly using backup AGVs and periodic maintenance. In these 5 scenarios, the number of backup AGVs is 0, 1, 2, 3, and 4, respectively.

From Figure 7.15, it is found that the dotted green line, which represents the performance of the system obtained when combinedly using periodic maintenance and onsite corrective maintenance, is always the best among all scenarios being considered in the research. But it is noticed that the dotted green line shows a slight decrease in trend as the interval of the periodic maintenance decreases. This suggests that for a system consisting of 3 three-load AGVs, the application of only onsite corrective maintenance has been enough to maintain the best performance of it in one year. The dotted red line, which represents the performance of the system obtained when using periodic maintenance and offsite corrective maintenance in combination, is below the dotted green line and reaches its best performance when the interval of the periodic maintenance is one month. Although its performance is lower than in the case of using periodic and onsite maintenance, the costs for enabling onsite maintenance can be avoided. From the figures, it is also found that with the increase of the interval of periodic maintenance, the system performances obtained in the scenarios of combinedly using backup AGVs and periodic maintenance increase first and then drop after they reach their top values. But despite their variation tendencies against the interval of periodic maintenance, all curves obtained in these scenarios are below the dotted green line. This means that the system that in combination uses backup AGVs and periodic maintenance can reach a similarly good performance when an appropriate periodic maintenance interval is applied.

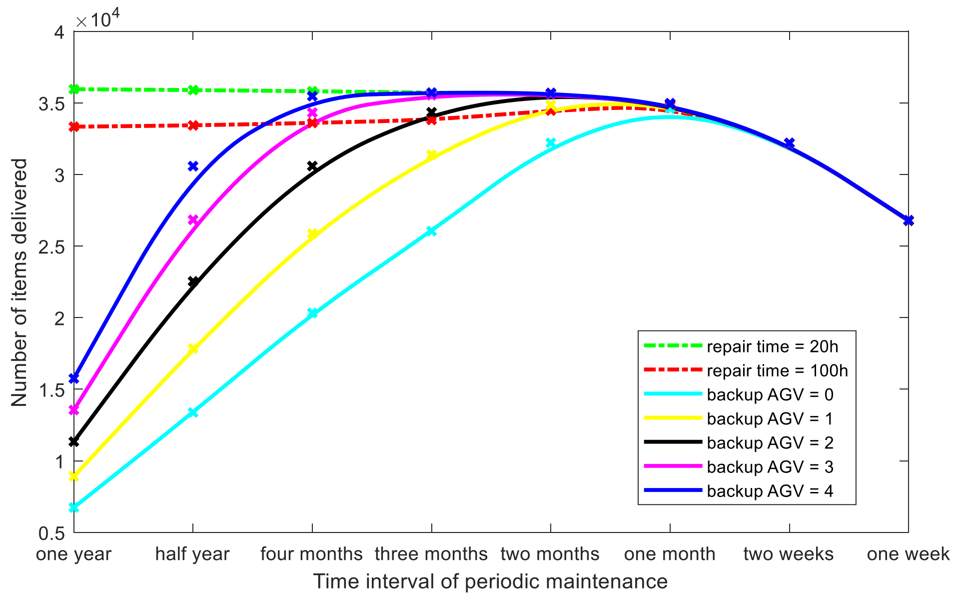


Figure 7.15 Performances when using combined maintenance and backup AGVs

7.11.4 Number and Load-Carrying Capacity of AGVs

To further investigate the combined effect of the number and load-carrying capacity of AGVs on system performance, simulations are conducted in this Section by using different numbers and load-carrying capacity settings of the AGVs in the system. The number of AGVs varies from 1 to 5 and their load-carrying capacity changes from 1 to 4 in total operation time of four months. In previous research about multi-load AGVs, the load-carrying capacity of the AGV is usually set up to 4. This is because it is not practical that the load-carrying capacity of the AGV can be over 4 [11, 47, 49]. It should be noted once again that in the simulations, only those AGVs with the same load-carrying capacity are allowed to operate in the system at the same time. This is essential for AGV systems to ease control and allocation process.

Table 7.2 Performance of the AGV systems with corrective maintenance

Number of AGVs	**Load-carrying capacity of AGVs**	**Average number of items delivered by the system**	**Average number of items delivered by each AGV**	**Average number of conflicts**	**Average number of failures**	**Average number of reroutes conducted**
1	1	2878	2878	0	1	0
2	1	5707	2854	652	3	0
3	1	8499	2833	1884	4	1
4	1	11269	2817	3624	5	3
5	1	14017	2803	5814	7	8
1	2	3509	3509	0	1	0
2	2	6957	3479	634	3	0
3	2	10358	3453	1834	4	1
4	2	13724	3431	3535	5	3
5	2	17063	3413	5674	7	5
1	3	4048	4048	0	1	0
2	3	8021	4011	608	3	0
3	3	11939	3980	1765	4	1
4	3	15810	3953	3403	5	5
5	3	19644	3629	5471	7	10
1	4	4539	4539	0	1	0
2	4	8995	4498	587	3	0
3	4	13383	4461	1705	4	1
4	4	17708	4427	3292	5	3
5	4	21993	4399	5294	7	4

In addition, only onsite corrective maintenance is adopted to focus the study on investigating the influence of the number of AGVs and their load-carrying capacities on the system performance. But the influence of other maintenance strategies will be considered in the system optimisation in Chapter 8. The calculation results of the average number of items delivered by the system (i.e. the number of completed tasks), the average number of items delivered by each AGV, the average number of conflicts and failures occurred, and the number of rerouting process conducted, with respect to different load-carrying capacities of the AGVs are listed in Table 7.2. In the meantime, the average number of items delivered versus the number of AGVs obtained in different scenarios of load-carrying capacity are also graphically shown in Figure 7.16 for easing the observation of the trends.

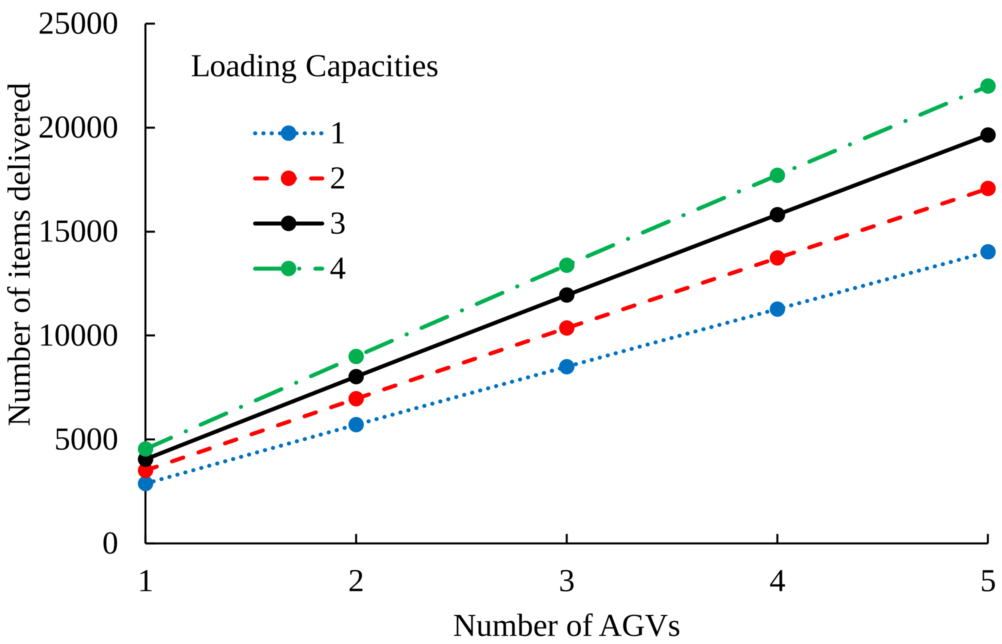


Figure 7.16 Number of items delivered versus the number of AGVs

From both Table 7.2 and Figure 7.16, it is found that the more AGVs are employed, the more tasks can be completed by the system. From the further observation of Figure 7.16, it is found that the number of delivered items shows a linear increasing tendency against the number of AGVs. Moreover, the larger the load-carrying capacity of the AGVs, the larger the gradients of the lines will be. So, it can be said that to increase the load-carrying capacity is helpful to increase the performance of the AGV system. However, the data listed in the fifth column of Table 7.2 have shown that the number of conflicts will increase as well with the increase in the number of AGVs. In principle, the increased number of conflicts will lead to more loss of system efficiency, however this phenomenon cannot be observed from Figure 7.16.

In order to demonstrate the impact of the conflicts of the AGVs on the system performance, the variation tendencies of the average number of items delivered by each AGV against the number of AGVs are plotted in Figure 7.17.

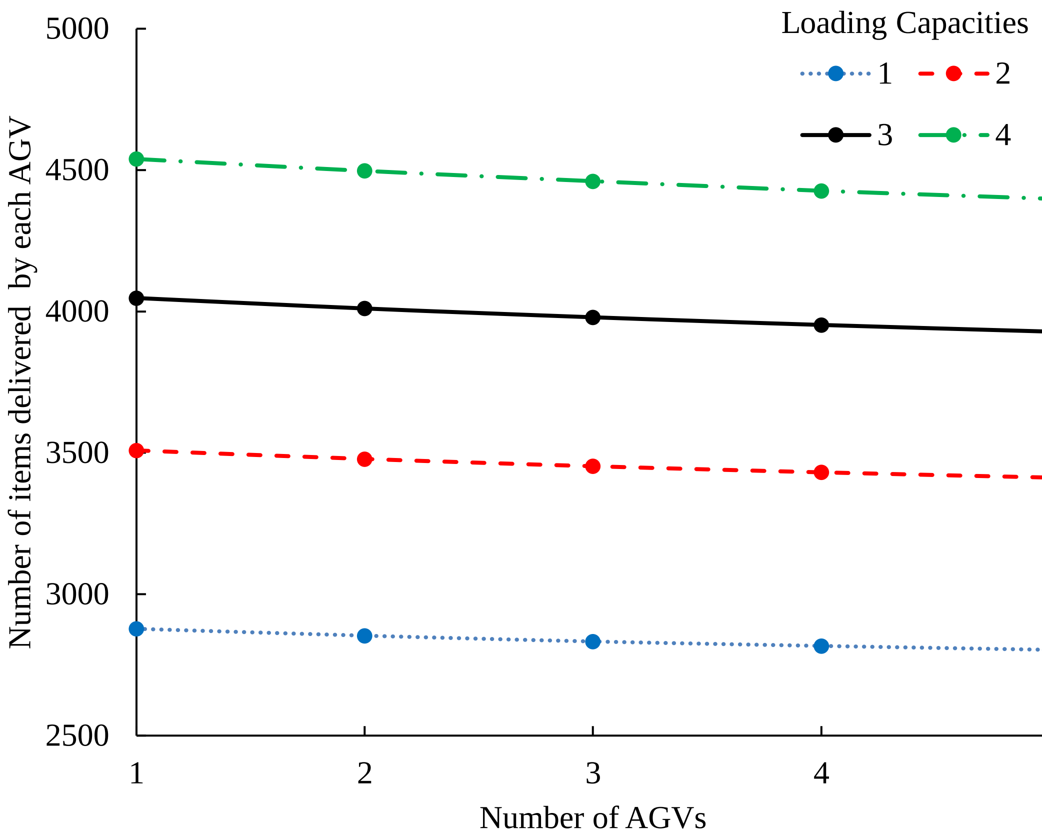


Figure 7.17 Delivery tasks completed by each AGV versus the number of AGVs

From Figure 7.17, it is seen that despite the load-carrying capacity of the AGVs, the average number of items delivered by each AGV does decrease slowly with the increase of the number of AGVs in the systems. In addition, from Table 7.2 it is seen that the number of conflicts decreases gradually with the increase of the load-carrying capacity of the AGVs when the same number of AGVs are employed in the system. This is attributed to the reduced number of job allocations to all AGVs when using larger load-carrying capacity AGVs. This partially explains why multi-load AGVs can improve system performance.

7.11.5 Conflicts Between AGVs and Obstructions due to Failed AGVs

To investigate the impact of the conflicts between AGVs and obstructions due to the failed AGV on the performance of the AGV system, two different path widths are simulated. In the AGV system with narrow paths, the width equals 1 unit, which only allows those AGVs moving in the same directions to travel on it. In the system with the wide path, the width equals 2 units, which allows the AGVs moving in both the same and opposite directions to travel on it at the same time and the failed AGV will no longer block the path. For this reason, the DAPN and RTPN will be abandoned for such a system because in real life, the probability of that two AGVs moving on the same path but in opposite directions fail at the same time is extremely low. In the simulation, the number of AGVs varies from 1 to 7, and the total operation time is set to be one year. For simplifying the simulation, the load-carrying capacity of the AGVs is set to be 1, and only onsite corrective maintenance strategy is adopted in the system. The simulation results are illustrated in Figure 7.18.

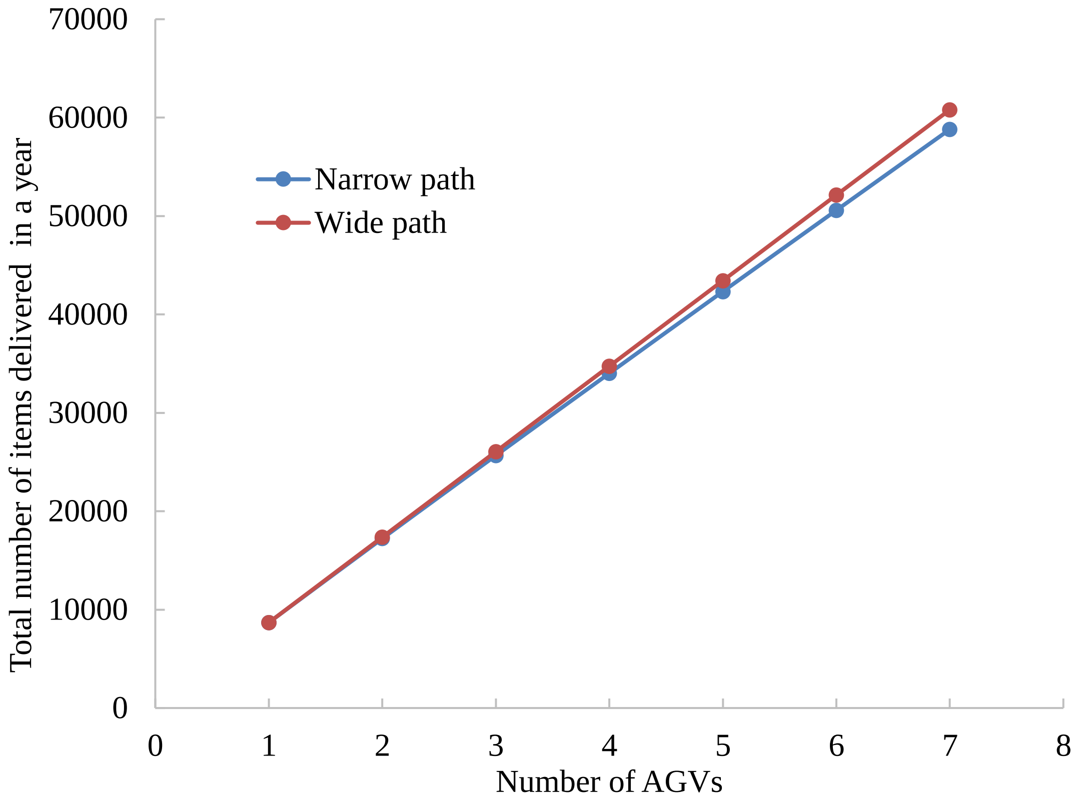


Figure 7.18 Delivery tasks completed in the AGV systems with different path width

From Figure 7.18, it is found that the performances of the two systems are the same when there is only one AGV running in them. However, when they consist of more AGVs, their performances will become different. The performance of the system that uses wide paths is obviously better than the performance of the system that uses narrow paths. Moreover, with the increase in the number of AGVs, the superiority of the former becomes more obvious over the latter. This suggests that the use of wide paths is beneficial to improve the performance of the AGV systems, especially those consisting of multiple AGVs.

7.12 Conclusions

The influences of the load-carrying capacity and maintenance strategies of the AGVs on the performance of the AGV systems are investigated in this Chapter by simulating a variety of AGV systems that are designed and maintained in different manners. From the investigation results, the following conclusions can be reached:

1) Increasing the number of AGVs in the system will increase the number of completed tasks. However, with the increase in the number of AGVs in the system, the efficiency of each AGV in the system will decrease due to the increased number of conflicts between the AGVs.
2) With the increase in the number of AGVs, the impact of AGV failures on the loss of system performance will become more significant. The combined use of periodic and corrective maintenance strategies can keep the system to operate at high efficiency for a long-term.
3) In contrast to offsite maintenance strategy, the onsite corrective maintenance is more effective to help a system that already adopts periodic maintenance strategy to achieve a higher system performance. However, extra costs will be essential to enable the activities of onsite corrective maintenance.
4) The performance of the system can be improved also by the combined use of periodic maintenance and backup AGVs if an optimal interval of periodic maintenance can be obtained. But from the point of view of the system performance only, it is still inferior to the strategy that uses onsite corrective and periodic maintenance in combination.
5) In comparison of the use of narrow path, the use of wide paths is beneficial to

improve the performance of the AGV systems, especially when the AGV systems consist of multiple AGVs.

The CPN models developed in this Chapter pave the way to further study more realistic AGV systems that involve multiple factors, such as reliability, maintenance, routing, and conflict and deadlock avoidance. In the research conducted above, the importance of the reliability and availability of the AGVs on the performance of the whole AGV system has been demonstrated. But for a practical AGV system, besides this, the associated costs for keeping the high reliability and availability of the AGVs should be considered. However, the relevant costs have not been considered in the above research. Therefore, a multi-objective optimisation technique will be developed in the next Chapter to solve this problem.

8 Optimisation of AGV system

8.1 Overview

The CPN models developed in Chapter 7 are able to simulate the AGV system with different numbers of AGVs of various load-carrying capacities and adopt different maintenance strategies. The correct selection of the number and load-carrying capacity of the AGVs and their maintenance strategy will not only affect the efficiency and performance of the AGV system, but will also affect the design, construction, operation and maintenance costs of the whole project. So, both the performance and cost of the system should be optimised together when designing or assessing an AGV system. The research that will be conducted in this Chapter is for exploring a solution for such a multi-objective optimisation problem. In the research, Genetic Algorithm (GA), a popular meta-heuristic algorithm, will be adopted to develop the optimisation technique as it is particularly well-suited for handling the kind of multi-objective optimisation problem. A brief introduction of the GA has been given in Section 2.7.6. In the optimisation algorithm, all the aforementioned factors that may influence the performance and cost of the AGV systems, such as the number of AGVs, the load-carrying capacity of the AGVs, their maintenance strategies, and the number of backup AGVs, will be considered.

8.2 GA Optimisation

Herein, all research findings obtained from the above CPN simulations will be considered in the development of the GA optimisation technique. For example, from the simulation results in Chapter 7, it is found that the overall throughput of the AGV system will increase as the number and load-carrying capacity of the AGVs increase. But in the meantime, the application of more and larger AGVs will inevitably increase the initial capital investment and operation and maintenance costs of the AGV system. Moreover, the research has disclosed that the application of more AGVs in one system may decrease the average efficiency of each AGV due to the potentially increased number of conflicts between the AGVs. This necessitates the optimisations of the number and load-carrying capacity of the AGVs in the system. In addition, an optimal maintenance strategy is always critical for achieving an efficient and cost-effective multi-AGV system. So, an optimal AGV system must have considered all of these factors and is able to achieve excellent performance at a relatively low or acceptable cost. This is a typical multi-objective optimisation problem. However, to date, there has not been a well-established technique dedicated to optimising the configuration of AGV system. At the moment, the AGV system is developed still based on the limited knowledge and experience of the AGV users. Consequently, current AGV systems often show problems in various aspects, especially their performance needs to be maintained at high cost. This kind of problem will be solved in this Chapter with the aid of the GA.

As mentioned earlier, to implement the GA an initial population of individuals (also known as chromosomes consisting of genes) should be generated first. Then, the fitness of every chromosome in the population will be evaluated using the predefined objective functions. Those individuals having higher fitness values will have more chance to be selected as parents to produce their offspring chromosomes, while those individuals having the smallest fitness values will be abandoned and replaced by newly produced chromosomes if these new chromosomes have higher fitness values. In the evolution of every time, the offspring chromosomes will be produced by the selected pairs of parents mainly by the means of crossover and mutation, which have been explained in Section 2.7.6. Through repeating the evolution, the average fitness level of the chromosomes in the population will improve gradually and finally reach a saturated value. The chromosome that has the highest fitness value in this population will indicate the best design of the AGV system being assessed.

8.3 Fitness Functions

Following the aforementioned idea, a GA optimisation program is developed dedicatedly for optimising the multi-AGV system. The flowchart of the optimisation program is shown in Figure 8.1. Considering the optimisation results derived from the GA are often sensitive to the settings of the GA parameters (e.g. population size, the number of generations, crossover rate, and mutation rate), the settings of these parameters are carefully selected in the research to ensure an efficient and reliable optimisation of the multi-AGV system. After performing a series of tests, the settings of the GA parameters are finally determined, which can ensure that the optimisation results can converge to a globally optimal solution in reasonable time. In the settings, the population size is 2000, the crossover rate is 0.7, the mutation rate is 0.02, and the maximum iteration time is 1000. The optimisation is implemented in Python. In the process, the initial population is generated, then the fitness of each individual in the population is evaluated using the predefined fitness function. To allow the individuals that have higher fitness values to have more chance to pass their genes to the next generation of the population, a 'breed pool' mechanism is adopted. According to the 'breed pool' mechanism, the individuals in the current population will be copied and their copies will be placed in the 'breed pool'. But the number of the copies of each individual in the 'breed pool' is strictly controlled based on its fitness value. In other words, the individuals that have higher fitness values will have more copies in the pool, while those having lower fitness values will have less copies and even without copy at all if their fitness values are too small. Consequently, in the 'breed pool' there will be more copies of those individuals having higher fitness values and less copies of the individuals having lower fitness values. Then, the pairs of parents of offspring chromosomes will be randomly selected from the copies in the 'breed pool'. In such a way, it can be very well guaranteed that the individuals that have higher fitness values in the current population will have more chance to pass their genes to the next generation of population because they have more copies in the pool.

Two evolution operators, namely crossover and mutation, are chosen for producing offspring chromosomes as described in Section 2.7.6. The fitness of the newly produced chromosome will be assessed using the fitness function. If its fitness value is higher than the fitness value of the poorest individual in the current generation of population, it will be used to replace the poorest individual. Otherwise, it will be abandoned. In this way, the average fitness level of the population can be improved gradually generation by generation. At every time when completing a run of crossover and mutation operation, the average fitness level of the population will be calculated. If the average fitness of the new population is close to the average fitness values of the previous generations or the predefined maximum iteration times is reached, the evolution will be terminated. Otherwise, the evolution will continue by repeating the above process until either one of the termination conditions is satisfied. Once the evolution is stopped, the optimal design of the AGV system can be derived from the individual that has the highest fitness value. Herein, it is worth noting that if the fitness was not converged at the maximum iteration time, the GA parameter settings should be adjusted again until obtaining a satisfactory convergence curve of the population average fitness level.

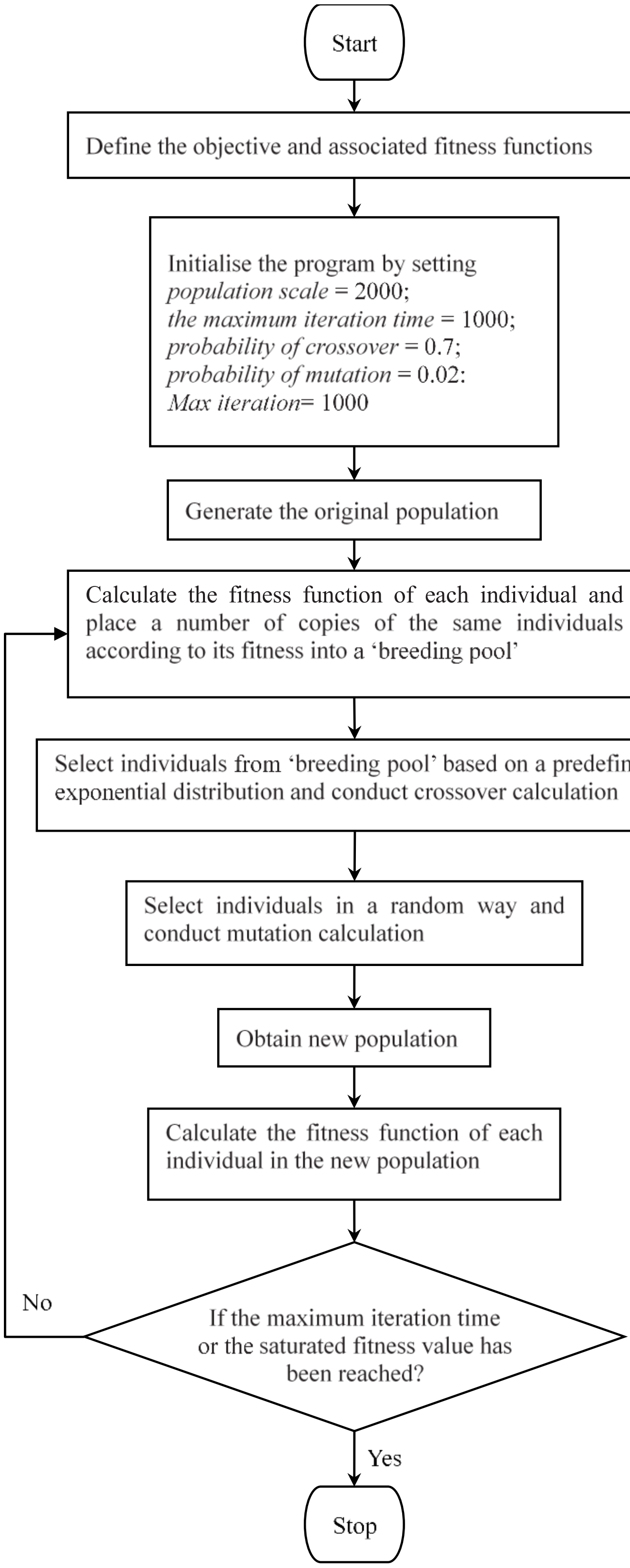


Figure 8.1 Flowchart of the GA based optimisation program

There are two approaches to realise the multiple-objective optimisation. One is to combine the individual objective functions into a single one, another is to determine a completely new Pareto optimal solution [118]. A Pareto optimal set is a set of solutions that are nondominated with respect to each other. To gain the balance of them, there is always a certain amount of sacrifice in some objectives. Pareto optimal solution set is often preferred to a single solution. Considering there are only two objectives (i.e. system performance and cost) need to be optimised in the research of this Section, the first method is adopted here. The division of them can be seen as the unit cost of the task. Therefore, a single best solution can be achieved directly without making trade-off by decision makers as did in pareto optimal solution method. The system described in Chapter 7 and all the obtained corresponding simulation results are used for performing the optimisation. These can be easily adapted for other AGV systems if their system performance data can be obtained in the future. The performance of the system and the corresponding cost in one year are used as two objective functions for optimising the system design. The objective functions are formulated as following and the values of all of their parameters are listed in Table 8.1.

Objective function 1: The maximum number of tasks completed within a given time.

$$Tasks = Max(N_t \times N_p) \tag{8.1}$$

Objective function 2: The minimum cost for completing the tasks.

$$\begin{aligned} Cost = Min\Big((N_A + N_{BA}) \times \big(C_A + N_p \times C_p\big) + N_F \times C_{CM} + R_w \times C_R \\ + N_E \times C_E + C_{MS}\Big) \end{aligned} \tag{8.2}$$

Based on the above two objective functions, a fitness function is designed as below

$$fitness = -\frac{Cost}{Tasks} \tag{8.3}$$

The maintenance strategy is optimised subject to:

$$N_A \leq 7 \quad (8.4)$$

$$N_{BA} \leq 4 \quad (8.5)$$

$$N_{BA} = 0 \; if \; there \; is \; corrective \; maintenace \quad (8.6)$$

where, Equation (8.1) is the total items delivered or the performance of the system in a year, it is the product of the average number of items delivered within a periodic maintenance interval and the total times of periodic maintenances conducted in a year. Equation (8.2) is the total costs which include the site lease cost, maintenance cost, and labour cost per year. Equation (8.3) is the fitness function defined, its physical meaning is the average cost for delivering one item. The negative sign in the formula allows the lower average cost to have higher fitness with respect to the problem of interest. Equation (8.4) means that the number of AGVs operating in the system is not more than 7. Equation (8.5) means that the number of backup AGVs is not more than 4. Finally, Equation (8.6) means that the backup AGVs will not be employed if corrective maintenance is adopted. These settings are made to eliminate unnecessary cost. It is worth noting that although the AGV system being investigated is relatively small in scale, but there are still 1,736 different combinations of the configurations of the AGV system. It means that the simulations must be conducted for assessing the performances of all these configurations. On average, about 2,000 simulations are conducted for each configuration of the AGV system to ensure the convergence of the results. This calculation will take about 3 minutes for a single-AGV system and 15 minutes for a 7-AGV system if the calculations are conducted in a computer with Intel(R) Core(TM) i7-7500U CPU @ 2.70GHz, 16GB RAM. Therefore, it will take about total 300 hours to compute all the simulation results for the optimisation.

Table 8.1 Parameters used in GA program

Parameter	**Symbol**	**Value**
Number of AGVs	N_A	[1, 2, 3, 4, 5, 6, 7]
Loading capacity of AGVs	L_A	[1, 2, 3, 4]
Capital cost of an AGV per year (£)	C_A	$3000\left(1 + \frac{L_A}{4}\right)$

Business costs of a maintenance site per year (£)	C_{MS}	20000 - with onsite corrective maintenance 4000 - without onsite corrective maintenance
Number of tasks competed within a periodic maintenance interval	N_t	Obtained using simulation described in Chapter 7 (given in Appendix B)
Time interval of periodic maintenance	T_p	1 year, 6 months, 4 months, 3 months, 2 months, 1 month, 2 weeks, 1 week
Number of periodic maintenances per year	N_p	[1, 2, 3, 4, 6, 12, 26, 52]
Periodic maintenance cost per AGV (£)	C_p	500
Number of maintenance engineers on site	N_E	1
Cost of one onsite engineer in a year (£)	C_E	20000
Number of backup AGVs	N_{BA}	[0, 1, 2, 3, 4]
Total number of failures occurring in the system per year	N_F	Obtained using simulation described in Chapter 7 (given in Appendix B)
Average cost of each AGV corrective maintenance (£)	C_{CM}	[Onsite – 1500, Offsite – 2000]
Unit route width	R_w	[1, 2]
Route cost per year (£)	C_R	10000

In Table 8.1, the number of AGVs, N_A, varies from 1 to 7. The loading of capacity of AGVs, L_A, varies from 1 to 4. It should be noted that the load-carrying capacity of the AGVs in the system is assumed to be the same. The capital cost of a single-load AGV per year, C_A, is assumed to be £3,000 and this cost will increase by £750 as the AGV capacity increases by one. The business cost of a maintenance site per year, C_{MS}, is assumed to be £20,000 when possessing onsite repair function and £4,000 when without onsite repair function. The number of completed tasks or items delivered within a periodic maintenance interval are obtained via simulation. The number of periodic maintenances per year, N_p, is derived from the time interval of the periodic maintenance, T_p. The cost of the periodic maintenance per AGV, C_p, is assumed to be £500. It is assumed that there is zero or one engineer at onsite maintenance site, whose cost is £20,000 per year. The number of backup AGVs, N_{BA}, varies from 0 to 4. The number of AGV failures, N_F, is also obtained via simulation. The costs for onsite and offsite maintenances are £1,500 and £2,000, respectively. The width of the paths could be doubled so that two AGVs can travel parallelly on the same path and the failed AGV will not cause a blockage of the path. However, this will double the capital route cost per year. It is worth noting that all the costs are assumed here just for demonstration purposes, not representing the actual costs arising in real-life AGV applications.

In the optimisation program, an exponential function is specifically defined for simulating the 'survival of the fittest' principle in the natural evolutionary process because exponential based scaling functions can lead to better results than linear scaling function and convergence is always faster [119]. For the i-th individual, its probability P_i being selected for participating in the GA's crossover operation can be expressed as:

$$P_i = \frac{e^{w(f_i - f_{min})}}{\sum_{j=1}^{N} e^{w(f_i - f_{min})}} \times 100\% \tag{8.7}$$

where N denotes the size of the population, which is 2,000 in this problem; f_i is the fitness of i-th individual; f_{min} is the fitness of the poorest individual; and w is a constant for controlling the efficiency, or in other words the speed of convergence, of population evolution. It is worth noting that the larger the value of w, the more efficient the evolution tends to be because it increases the significance of the fitness exponentially. However, it should be noted that a too large value of w would increase the risk of failure to obtain a global optimisation result. This is because those chromosomes with higher fitness levels will have greater chance to be copied in the construction process of the 'breeding pool', while those chromosomes will have a lower probability to be copied in the same process. Hence, the diversity of the individuals in the 'breeding pool' will become worse when its size is large. Consequently, it will become difficult to obtain a global optimisation result when w is assigned a too large value. After a series of tests, w is taken to be 5 in this research since it is an efficient value for achieving a global optimal result.

8.4 Coding

In order to optimise the multi-AGV system, 7 major factors that may influence its system performance are considered in the GA optimisation program. They are the interval of periodic maintenance, the number of AGVs, the load-carrying capacity of AGVs, the path width, the adoption of corrective maintenance, the type of corrective maintenance, and the number of backup AGVs. The performance data of the AGV system corresponding to the specific values of these factors are obtained from the simulations described in Chapter 7. These seven parameters are coded into binary numbers and then combined together to create a single chromosome as shown in Figure 8.2.

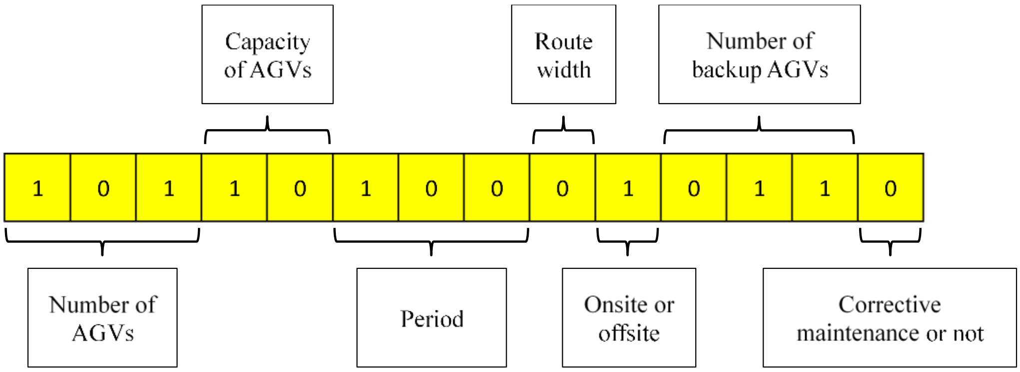


Figure 8.2 A typical chromosome

If the binary code indicating the seven factors in the chromosome in Figure 8.2 is decoded into decimal numbers, then seven decimal numbers can be obtained. They are 5, 2, 4, 0, 1, 3, and 0, respectively. It should be noted that these decimal numbers are not the actual values of the parameters, but they indicate the positions of the actual values of the parameters given in Table 8.1. For example, the first number '5' indicates that the parameter value should be the (5+1)th number in the list of $N_A = [1, 2, 3, 4, 5, 6, 7]$, which is 6. This means there are 6 AGVs in the system. It should be noted that the chromosome will be abandoned if the decoded position is out of the range of the lists. The second number '2' indicates that the parameter value should be the (2+1)rd number in the list of $L_A = [1, 2, 3, 4]$, which is 3. This means that the load-carrying capacity of the AGVs in the system is 3. '4' indicates the (4+1)th number in the list of $N_p = [1, 2, 3, 4, 6, 12, 26, 52]$ is the actual value of the parameter, it is 6.

The fourth number '0' indicates the (0+1)st number in the list of $LW = [1, 2]$ is the actual value of the corresponding parameter, it is 1. This means the route width is single, which does not allow two AGVs travelling in opposite directions to travel on the same path at the same time. The fifth number '1' means the offsite corrective maintenance is adopted. The sixth number '3' indicates the (3+1)th number in the list of $N_{BA} = [0, 1, 2, 3, 4]$ is the actual value of the parameter, which is 3. This means there are 3 backup AGVs available in the system. The final number '0' means that corrective maintenance will not be adopted by the system.

8.5 GA Results and Discussion

The GA optimisation is programmed in Python and its code is given in Appendix A. By using the developed GA optimisation program, the interval of periodic maintenance, the number of AGVs, the load-carrying capacity of AGVs, the width of paths, the adoption of corrective maintenance, the type of corrective maintenance, and the number of backup AGVs are optimised based on the fitness function that are constructed using the two objective functions. By applying the parameters and relative costs defined in Table 8.1 to the program, the population starts to evolve gradually. The resultant variation tendency of the average fitness level of the population against the number of evolution times is shown in Figure 8.3.

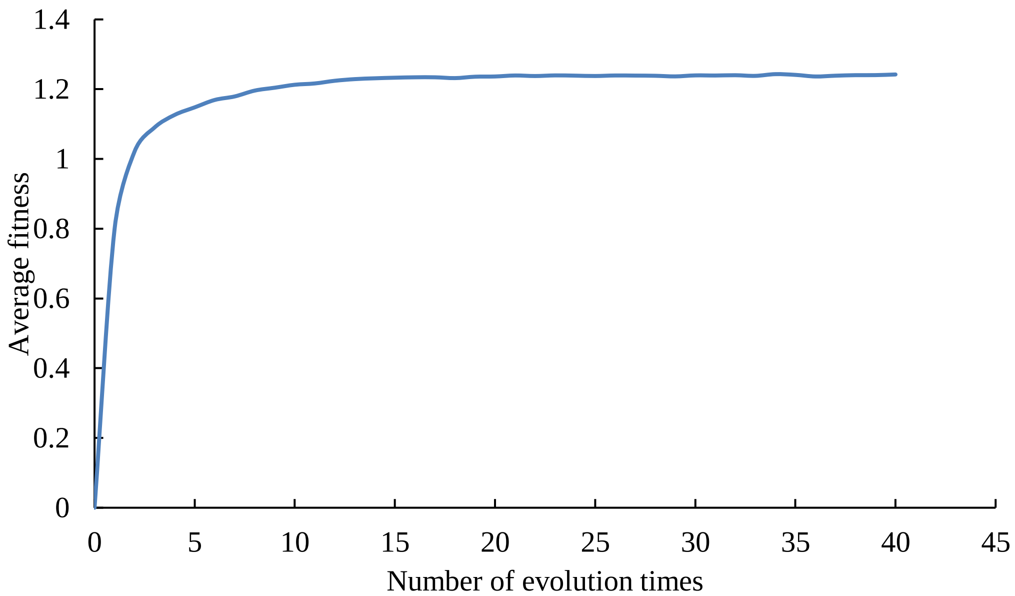


Figure 8.3 Evolution of GA population

From the figure, it is found that after the population evolved for about 25 times, the average fitness of the population has converged to a saturated value. That means the optimal design of the multi-AGV system can be achieved through performing 85 times of evolution calculations. The optimal results that are indicated by the best fitted individual in the population are listed in Table 8.2.

Table 8.2 Optimal results obtained from GA

Number of AGVs	7
Loading capacity of AGVs	4
Number of occurrences of periodic maintenance per year	4
Road width	1
With corrective maintenance?	No
Which type of corrective maintenance?	
Number of backup AGVs	4
Total cost (£)	70,000
Tasks completed per year	87,352

From optimisation results listed in Table 8.2, it can be inferred that

- The employment of backup AGVs is an effective strategy for maintaining the long-term high efficiency of a multi-AGV system when the periodic maintenance is arranged for 4 times a year;
- Arranging the maintenance site to share the same site with the AGV base will save the cost on land, therefore resulting in the minimum average cost of completing one mission;

Table 8.2 shows the optimal results for the optimisation problem specified. Furthermore, the GA optimisation can be conducted to obtain the optimal solution for different throughput criteria. As an example, the scenarios below have been considered:

$$Tasks \geq 92000 \tag{8.8}$$

$$Cost \leq 120000 \tag{8.9}$$

where, Equation (8.8) means that the number of delivery tasks required to complete by the system within one year is not less than 92,000; Equation (8.9) means that the total cost of the AGV system per year should not exceed £120,000. By running the program, the optimal results are listed in Table 8.3.

Table 8.3 Optimal results for given criteria obtained from GA

Number of AGVs	7
Load-carrying capacity of AGVs	4
Number of periodic maintenances per year	12
Road width	2
With corrective maintenance?	Yes
Which type of corrective maintenance?	Offsite
Number of backup AGVs	0
Total cost (£)	117,552
Tasks completed per year	92,988

The comparison of Table 8.2 and Table 8.3 suggests that in order to increase the throughput of the system whilst reducing the overall downtime in a year, the corrective maintenance and more frequent periodic maintenance should be adopted. However, this will lead to a significant increase in the total cost.

8.6 Conclusions

In order to develop a feasible and efficient approach to optimising the design, operation, and maintenance of a multi-AGV system, the CPN simulation models and the GA optimisation approach are developed in this Chapter. From the research results described above, the following insights can be drawn:

1. The combined use of the CPN and GA has been demonstrated as an effective approach to assessing the performance of multi-AGV systems.
2. This hybrid approach enables the prediction to the optimal time interval of periodic maintenance and the assessment of the influence of corrective maintenance on system efficiency.
3. From the optimisation results, the optimal number of AGVs and the load-carrying capacity of AGVs required can be readily inferred.
4. The optimisation of multiple objectives can be realised by combining the individual objective functions to a composited single objective optimisation function, which is the fitness function indicating the unit mission cost.
5. Corrective maintenance can aid periodic maintenance to maintain the long-term high efficiency of the system, although it may lead to extra maintenance costs.

However, the AGV systems investigated in this Chapter are relatively small in scale. Hence, in the next Chapter, the model will be extended to more complex AGV systems, so that the design and operation of real multi-AGV systems can be better understood.

9 Study on the Modelling of More Complex AGV Systems

9.1 Overview

In order to meet the different manufacturing demands and restrictions, larger and more complex advanced AGV systems should be considered. Several real-life scenarios increasing the complexity of AGV systems are listed in the following:

- The AGV's waiting time in the station that has been neglected in previous Chapters cannot be ignored in some practical applications.
- The throughput is large so that the number of AGVs and the space required for AGV systems has to increase.
- AGV systems are sometimes restricted by the environment in terms of the space so that the regular square shape of the AGV systems considered in previous Chapters are no longer possible.
- The buildings or structures existing in the system could block connections between stations.
- Sometimes, the pickup or unloading stations are specified.

The CPN models described in Chapter 6 and 6 will be further developed to simulate and study these complex systems briefly. The aforementioned scenarios will be investigated one by one to evaluate their impact on system performance. In addition, it is necessary to note that all parameters used in the simulation models in this chapter are the same as the settings given in Section 7.11 unless they are specified.

9.2 The Impact of Task Waiting Time

As mentioned in Section 7.2, all the simulation results obtained in previous Chapters are based on several assumptions. Two of them are:

1. The operation of an AGV will not interrupt or even stop the operation of other AGVs in the same station.
2. An AGV failed at a station will not cause a blockage at the station.

This is usually the case in food and drink production centre's where the operation of AGVs will not interrupt other AGVs in the same station. One example of this scenario is shown in Figure 9.1. The AGVs are able to pick up trolleys without blocking others. Therefore, in the simulation models described in previous Chapters, the size of the stations is assumed to be big enough, thereby avoiding the interruption between different AGVs. But in reality, this is sometimes restricted by the available number of machines and spaces in the station. So, the influence of these two factors on the system performance should be investigated in future research.

Figure 9.1 No interruption caused by other AGVs [120]

In most of the flexible manufacturing systems and distribution centres, the AGVs transfer items or materials between different machines or stations, each with a specific operation or functions, such as milling, washing, or assembly [121]. In such systems, the AGVs will have to wait if there are other AGVs arriving at the stations or machines earlier and have not completed the tasks undertaken by them. When the machines in a manufacturing system or the stations in distribution centres have only a little space for load buffering, the system may be blocked by buffers overflowing. One example is given in Figure 9.2. Where, the AGVs must queue to pick up the purple basket and then move away from the collection point.

Figure 9.2 Interruption caused by other AGVs [122]

In order to simulate this, the Master Petri Net (MPN) model described in Section 7.4 is modified by adding a model of station resource-oriented Petri Nets, which is shown in Figure 9.3. This kind of PN was introduced by Wu et al. in 2001 when they simulated the automated manufacturing systems for deadlock avoidance [100].

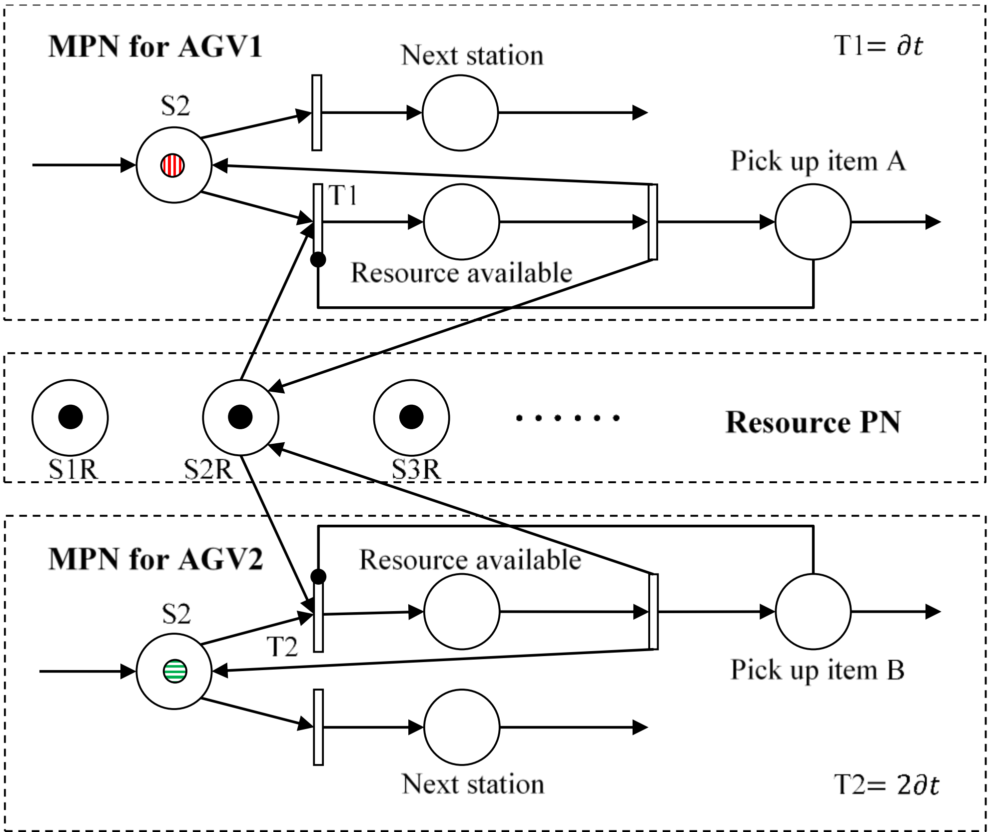


Figure 9.3 Station resource-oriented Petri Net

In Figure 9.3, there are two AGVs running in the system. The AGV-1, indicated by the 'red' token, is going to pick up item A from S2 and then travel to S5. The AGV-2, indicated by the 'green' token, is going to pick up item B also from S2 but then travel to S3. A new concept, called the resource availability of station, is introduced here.

In the figure, there is a group of PNs, namely the resource PNs, which represent the resource availability of each station and connect to the MPN of each AGV. There is one token in each place in the resource PN since only one AGV is allowed operate in a station at any time. It should be noted that the tokens in the resource PN are always common tokens, which means they are not given any colour so that they are able to enable any type of transitions. The AGV which arrives the targeted station earlier will perform its action first. However, in the example given in Figure 9.3, the two AGVs represented by the 'red' token and 'green' token may arrive at S2 at the same time, although this rarely happens in practice. To prevent the activation of both transitions, T1 and T2, connecting to 'Resource available' place in each MPN at the same time, the transitions are given two different transition time '∂t' and '$2\partial t$', respectively. '∂t' can be seen as a fraction of time but enough to give the order of activation of the transitions. Since $\partial t < 2\partial t$, the transition T1 will be activated first. It should be noted that the AGVs are not ranked by priorities so that the activation orders of the transition for each AGV are given randomly. After the transition connected to 'Resource available' place in the MPN of AGV-1 is activated, both tokens in S2 place in AGV-1 MPN and S2R place in the resource PN will be removed and a 'red' token will be produced in 'Resource available' place. After item A is picked up, a 'red' token will be produced in S2 again, a common token will be produced in S2R place, and a 'red' token will be produced in 'Pick up item A'. The token in 'Pick up item A' will disable T1, so that the AGV-1 will not use the resource in S2 and start to move to the next station. Finally, the AGV-2 can start its pickup task. This newly constructed PN model is able to simulate the job waiting scenario happening in a practical AGV system.

In addition, once an AGV fails during its operation in a station, it will prevent other AGVs performing actions in the same station. The station will become available again only after the failed AGV is towed away. Hence, the Recycle of Failed AGV Petri Nets (RFAPNs) are modified to ensure the availability of the stations can be restored after the failed AGV is taken away as shown by the additional red parts in Figure 9.4. Once a fault is detected in an AGV during its operation in a station, the resource in that station will become unavailable and the token in ‘Failed station resource’ place will be removed so that no further tasks can be performed by the other AGVs in the same station although they can still travel through it. Once the recycle AGV reaches the failed AGV and towed it away, the token in ‘Failed station resource’ place will be produced again to enable the resource.

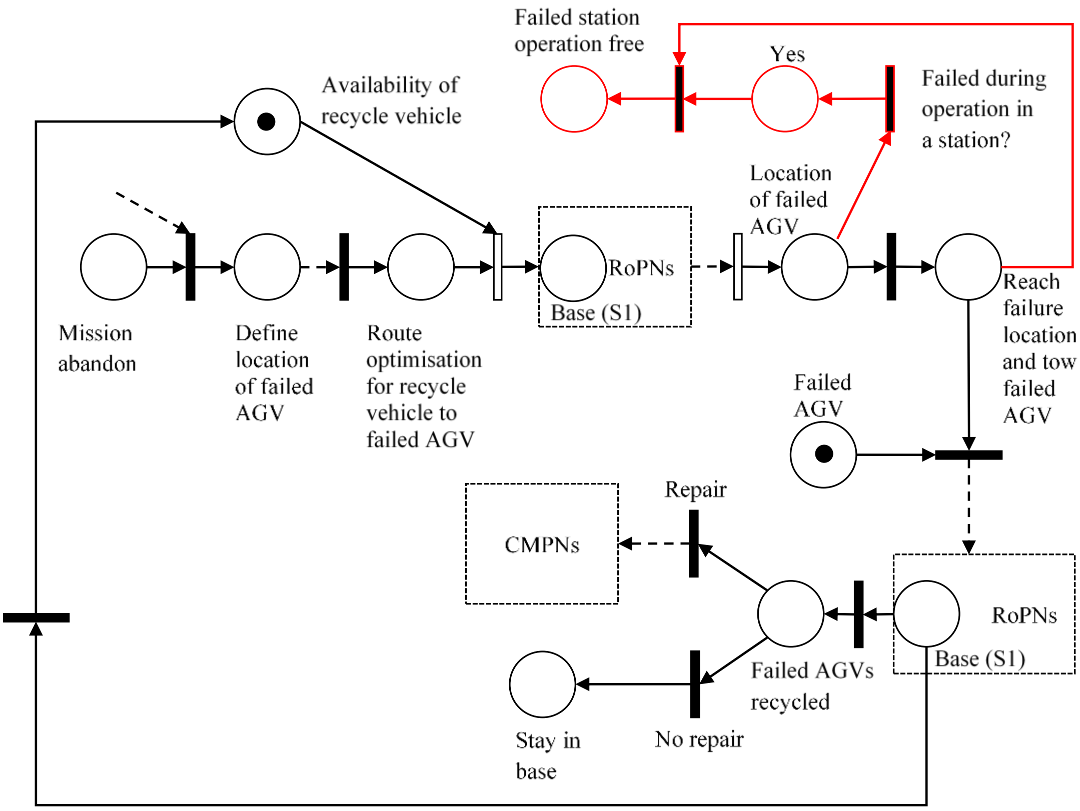


Figure 9.4 Modified Recycle of Failed AGV Petri Net (RFAPN)

The simulations have been conducted to investigate the impact of waiting time on the system performance. In the simulations, the AGV systems consisting of different numbers of single-load AGVs were assessed in the same layout configuration described in Section 6.2. The total operation time was assumed to be 4 months. 1,000 simulations are conducted for each group of the parameters. It will take about 3 minutes for a single-AGV system and up to 25 minutes for a 20-AGV system. The system performances obtained before and after considering waiting time were calculated for comparison. The results are shown in Figure 9.5, where the red and blue curves respectively indicate the simulation results obtained with waiting and without waiting time is considered.

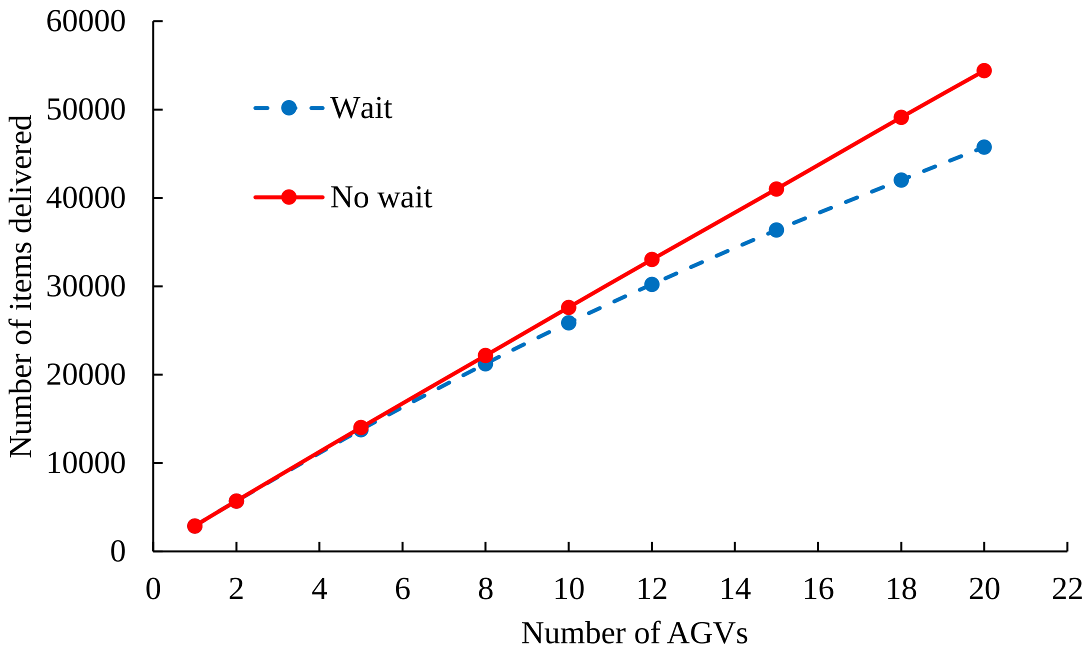


Figure 9.5 The influence of the waiting time on the number of items delivered

From Figure 9.5, it is interestingly found that the two curves are close to each other when the number of AGVs is small. Then, they start to deviate from each other with the increase in the number of AGVs. Moreover, the more AGVs are used, the more significant the difference between the two curves tends to be. This phenomenon suggests that the influence of waiting time on the system performance will become more significant when more AGVs are employed in the system. Moreover, the more AGVs are used, more influence will be resulted by the waiting time. As a consequence, it can be also observed from Figure 9.5 that the approach to increasing system performance by using more AGVs will become less effective due to the increased influence of waiting time. This can be inferred from the decreased gradient of the blue curve with respect to the increase in the number of AGVs.

The impact of the average time spent on item pickup and unloading on the waiting time is also investigated. Figure 9.6 shows the variation tendencies of the total waiting time and the percentage loss of the throughput of the system against the average time spent on item pickup and unloading. The percentage loss of the throughput ($Loss$) is calculated by using the following Equation (9.1):

$$Loss = \frac{X_{nw} - X_w}{X_{nw}} \times 100\% \tag{9.1}$$

where X_w is the number of items delivered when considering the waiting time, and X_{nw} number of items delivered without considering the waiting time.

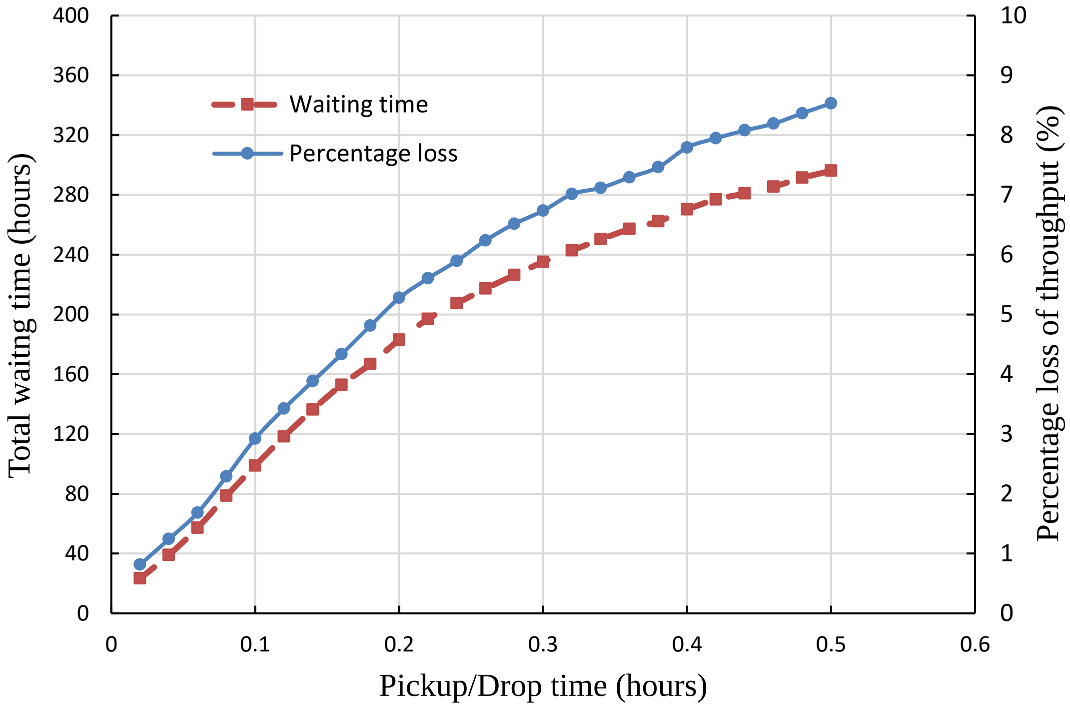


Figure 9.6 Analysis of the impact of pickup/drop time

From Figure 9.6, it is found that both the total waiting time and the percentage loss of the throughput of the system increase as the average time taken for item pickup and unloading increases. Both curves show similar varying trends. This suggests that the longer the average action time, the longer the waiting time will be.

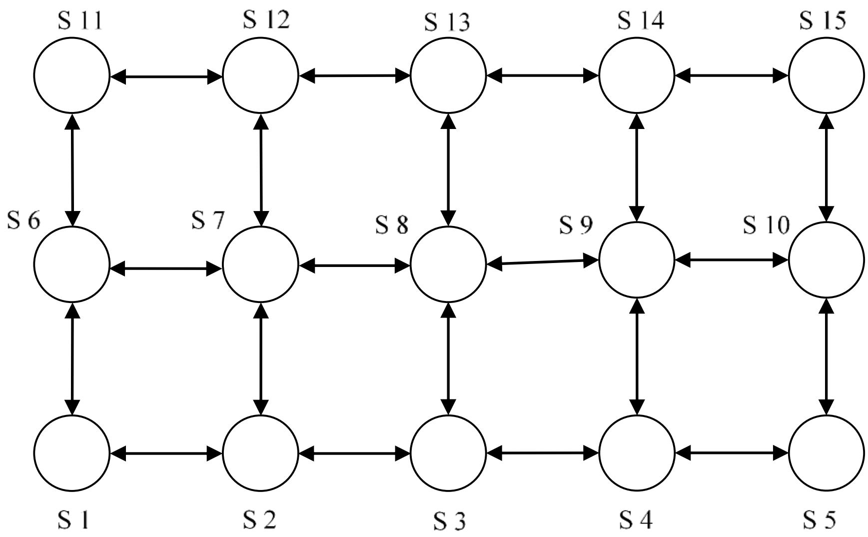
9.3 Regular AGV System Layouts

The AGV system considered in Chapter 5 can be regarded as a typical example of simple single-loop system layout configuration with 3 stations. The AGV system described in Section 6.2 can be regarded as a typical example of a conventional system layout configuration with 9 stations. So far, there is still a type of system layout configuration, namely tandem system configuration [123, 124, 125], has not been studied in this thesis. For example, Bozer and Srinivasan compared the performance of tandem and conventional AGV systems [26]. The system that they considered consisted of 8 AGVs and 20 workstations. Their research suggested that the conventional AGV system can perform better only when it uses three or four vehicles in operation. In order to further validate their research finding, a new system layout is constructed in this Section. The system has 15 stations that are evenly distributed by 3 rows and 5 columns as shown in Figure 9.7. The even distribution is one of the popular layout designs in distribution centres as discussed in Section 6.2.

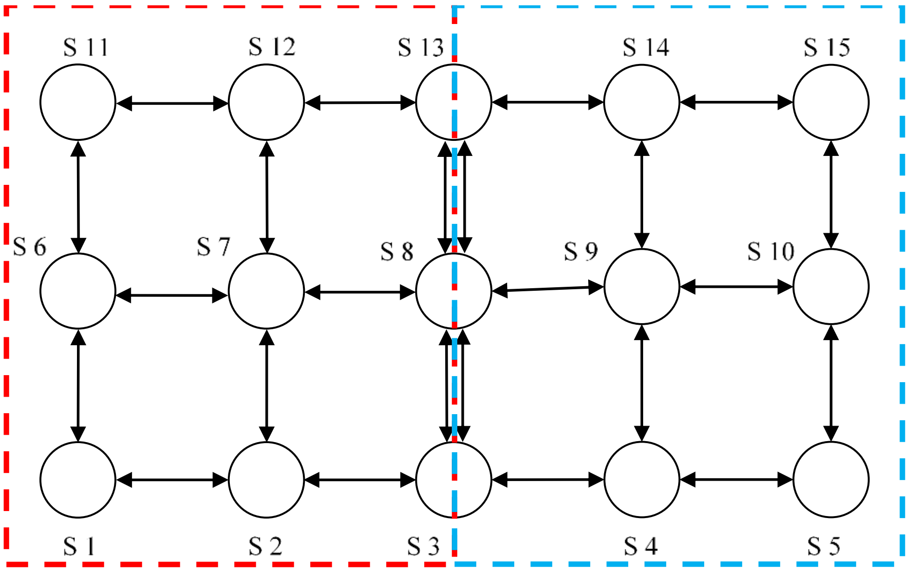
The system can be considered as a completely conventional topology or a tandem configuration assembled by two symmetric zones and each zone has 9 stations. In the conventional system layout shown in Figure 9.7(a), the AGVs can move freely to all the stations in the system. By contrast, the AGVs are only allowed to move within its own zone in the tandem configuration shown in Figure 9.7(b). Two zones share the resources via three shared stations, which are S3, S8, and S13. If an item is required to move from one zone to another and the pickup or unloading station is not one of the shared stations, the task has to be broken down into two parts. In the first part, an AGV in one zone will travel to the pickup station to pick up the item and then carry the item to one of the shared stations. In the second part, an AGV in another zone will come to pick up the item from the shared station and then carry the item to the unloading station. Therefore, in essence, this can be regarded as two independent tasks in the two zones. Since the two zones are symmetric, the total number of completed tasks is the double of the tasks completed in either zone. Following this logic, the overall performance of the AGV system with the tandem layout in Figure 9.7(b) can be calculated via Equation (9.2).

$$Performance = 2 \times \left(\frac{7}{12} + \frac{5}{12} \times 50\%\right) X_z \tag{9.2}$$

where X_z is the number of items delivered in one zone. There are 12 possible unloading stations, of which 7 are in the current zone and 5 in another zone, for each AGV, because S1 and S5 for AGV storage and the current pickup station cannot be used as the next unloading station. The mission to another zone will be regarded as 50% completed as long as the items are moved to the boundary stations S3, S8, and S13. Since the paths between the three boundary stations are frequently used and likely to cause conflicts, it is adviced to set up two more extra paths between S3, S8, and S13 to eliminate the potential conflicts.



(a) Conventional layout



(b) Tandem layout

Figure 9.7 Systems with 15 stations

To investigate the system performance after adopting the above two types of layout configurations, a series of simulations were conducted, which assume there are different numbers of single-load AGVs running in the system for 4 months. Again, The simulation for each group of the parameters is conducted for 1,000 times to achieve a convergent value of the simulation results. It takes about 7 minutes for a single-AGV system and up to 90 minutes for a 14-AGV system. The simulation results are shown in Figure 9.8.

From Figure 9.8, it is seen that the line indicating the tandem configuration is always above the line indicating the conventional configuration. This suggests the performance of the tandem configuration is always better in such a 15-station system. This is because that the AGVs in the conventional layout have a larger space and more options to manoeuvre and the allocated missions will have longer delivery distances if the AGV is requested to travel from one side of the system to another side. In addition, it is found that the blue line shows a gradient that is apparently steeper than that of the red line. This suggests that the superiority of the tandem configuration over the conventional configuration will become more significant with the increase of the number of AGVs in the system.

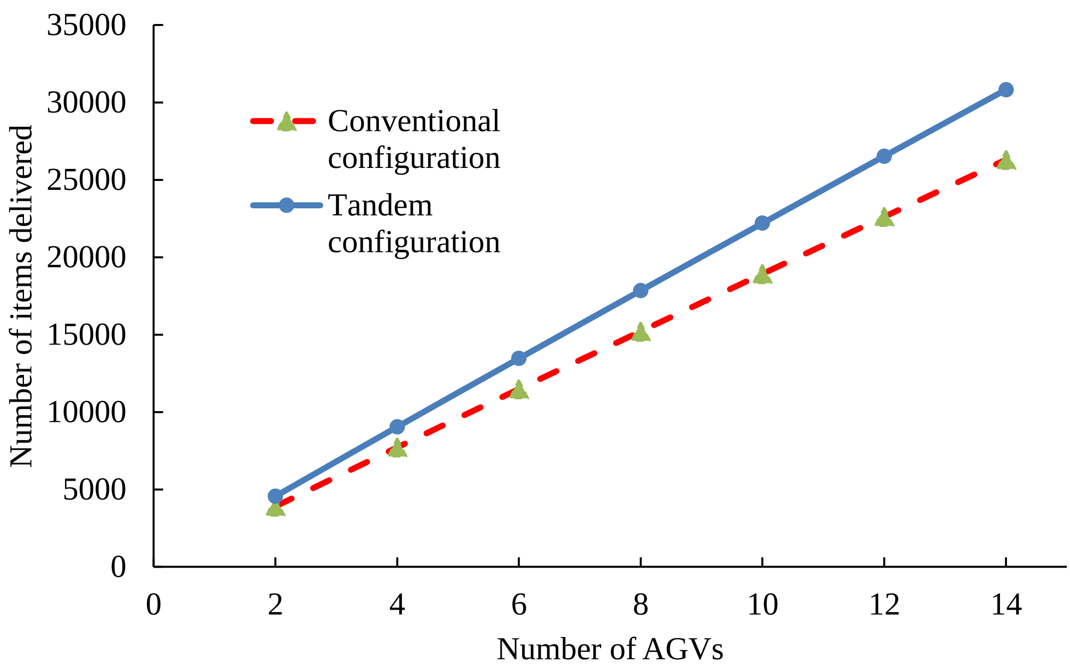


Figure 9.8 Tandem system figuration vs. conventional system figuration.

9.4 Irregular AGV System Layout

In the simulation models considered in Chapter 6 and 7, the layout has a regular shape and even the paths that connect neighbouring stations are defined to have the same length for simplifying the simulation. However, the layout of a practical system may be irregular sometimes due to the limitations of land space, obstacles, buildings, cost, etc. The irregular layout will increase the difficulty of system simulation as the route optimisation has to be conducted based on different rules.

An example of an irregular layout of AGV system is shown in Figure 9.9, which can be easily modified for simulating the layouts in other AGV applications. The time taken to travel from one station to another is defined in Table 9.1.

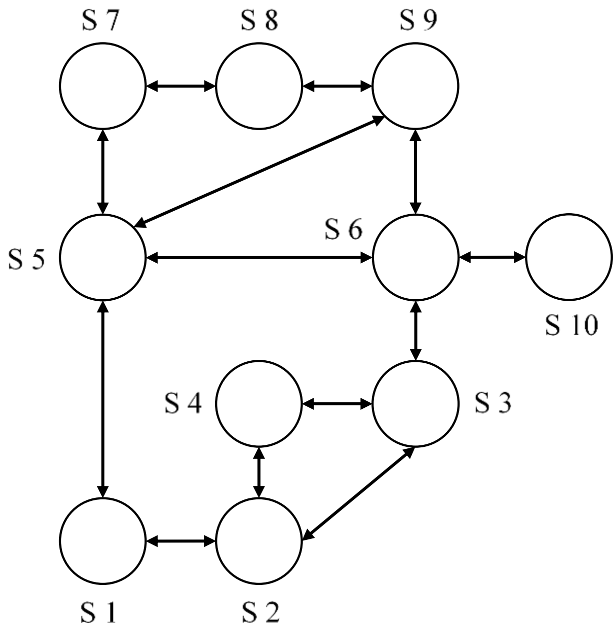


Figure 9.9 An irregular AGV system

It should be noted that the rules for regulating the movements of the AGVs defined in Section 6.3.1 are no longer valid for this application as these rules are only valid for rigorous horizontal and vertical paths of the same length. Therefore, Dijkstra algorithm is adopted to optimise the route in such irregular AGV system layouts. However, this extra optimisation will significantly increase the burden of computation. On the other hand, the reroute process that was proposed in Section 7.7 in order to avoid the paths blocked by the failed AGVs has to be abandoned due to the irregular layout. Consequently, the blocked AGVs are assumed to have to stay in their nearest station until the failed AGV is towed away from the path.

The single-load AGV system with the irregular layout in Figure 9.9 is simulated, its performance for running for 4 months is shown in Figure 9.10. From the figure, it is found that as the number of AGVs increases in the system, the performance of the system also increases. However, it is noticed that the gradient of the curve decreases gradually with the increase of the number of the AGVs in the system. This suggests that the effectiveness of the approach to increasing the system performance by increasing the number of AGVs will decrease when more AGVs are employed in the system. This should be related to the increased number of conflicts between the AGVs on some paths such as the path connecting S6 to S10.

Table 9.1 Assumed travelling time from one station to another

Paths	**Time taken to travel from one station to another** (hour)
S1-S2	0.1
S1-S5	0.2
S2-S3	$\sqrt{2} \times 0.1$
S2-S4	0.1
S3-S4	0.1
S3-S6	0.2
S5-S6	0.2
S5-S7	0.1
S5-S9	$\sqrt{5} \times 0.1$
S6-S9	0.1
S6-S10	0.1
S7-S8	0.1
S8-S9	0.1

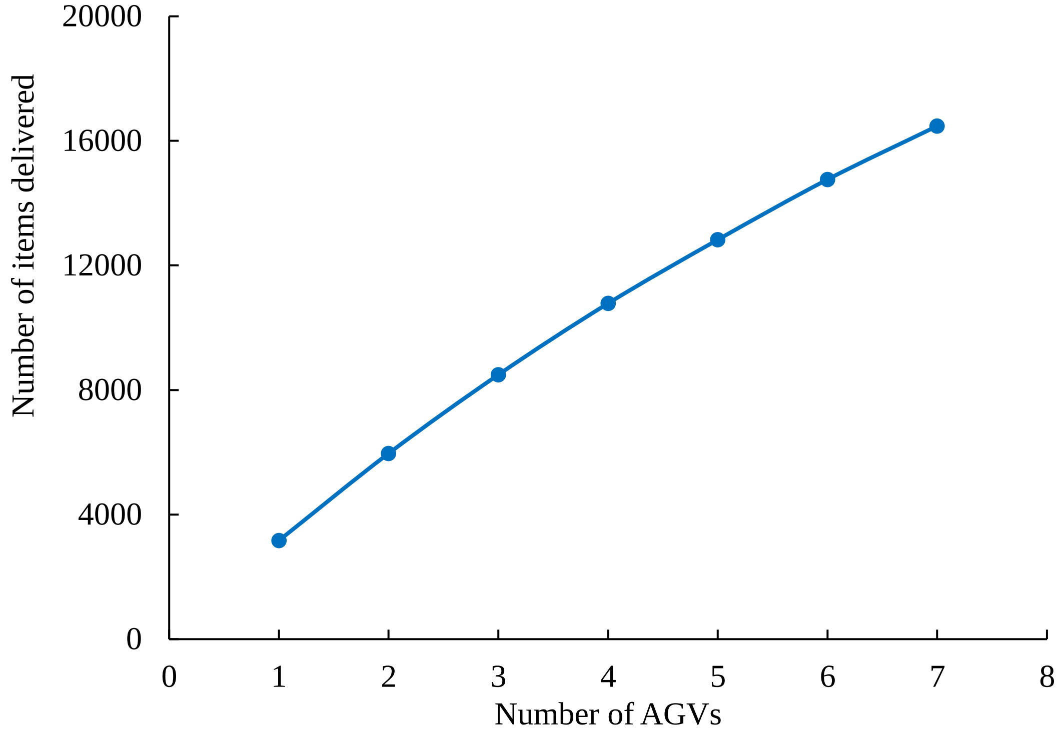


Figure 9.10 Performance of the irregular AGV system

9.5 Case Study

A case study is conducted in this section to demonstrate the adaptability and capability of the developed CPN models in dealing with real-life AGV systems. It considers an AGV system operating in the warehouse of a $400 \times 500\ m$ distribution centre [42], in which the AGVs operate 10 hours a day. The function of the distribution centre is to receive and store items from other places and dispatch the stored items to somewhere else. The layout of the AGV system in its warehouse is illustrated in Figure 9.11.

As shown in Figure 9.11, there are total 11 stations in the AGV system. They are defined with different functions and marked with different colours. The green square is the base of AGVs, where the AGVs are parked when they are idle. To save space, the base is also used as the maintenance area to repair the AGVs after they failed. The pickup stations, P1 and P2, are represented by blue squares, where the items received from outside will be picked up and moved to storage stations. In the system, there are total 4 storage stations. They are DP1, DP2, DP3, and DP4 represented by orange squares. Once an item in a storage station is requested to be delivered to somewhere else, an AGV will come to pick up it and then move it to the prescribed drop station. In the system, total 4 drop stations are defined, i.e. D1, D2, D3, and D4 indicated by yellow squares. Once the item arrives at the prescribed drop station, it will be unloaded and then dispatched from the warehouse. It should be noted that the rectangles with red edges represent the buildings, structures or other types of obstacles that prevent the construction of AGV paths. Due to the limited space, the paths in the system only allow the AGVs moving in the same direction to travel on them. The average speed the AGVs operating in the system is 1 m/s [7]. The AGVs are maintained by taking a hybride onsite corrective maintenance and periodic maintenance strategy.

Figure 9.11 The layout of the AGV system for the case study

To enable the modelling of the AGV system using the developed CPN models, the layout of the system is projected to a coordination system first, which is shown in Figure 9.12. The actual paths connecting the stations are represented by the solid arrows. Those paths that are not allowed to be built due to the buildings, structures and other types of obstacles are represented by the dotted lines. The length of each path between two adjacent coordinate points is 100 m. This means that the AGVs will take 100 seconds to complete their travel on each path.

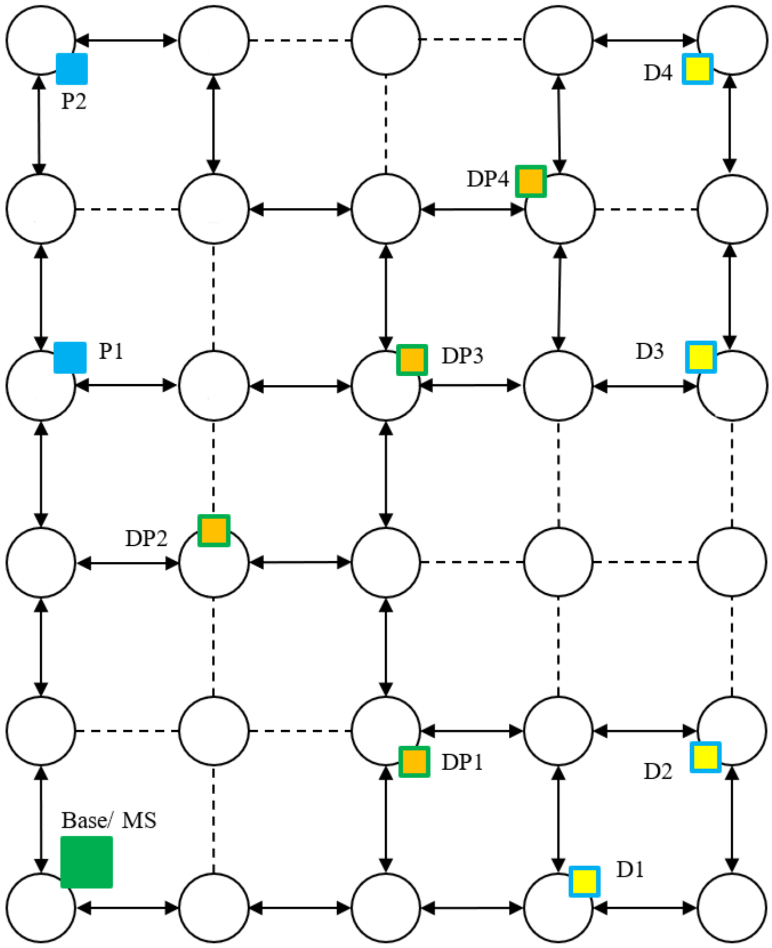


Figure 9.12 The layout projected in the coordinated system

The developed CPN models are employed to simulate this AGV system and the full CPN model constructed for the system is shown in Figure 9.13. The model consists of 7 different CPNs. They are MPN, RoPN, DAPN, AHSPN, RFAPN, CMPN, and PMPN, respectively. The functions of these purpose-designed CPN models have been defined in Chapter 7. Herein, it is necessary to note that the reroute process for avoiding the paths blocked by failed AGVs is not considered since the rules set in Chapter 7 are no longer valid in this system due to the disconnections caused by the buildings and structures between adjacent stations. Therefore, the RTPN model is not considered in this case study.

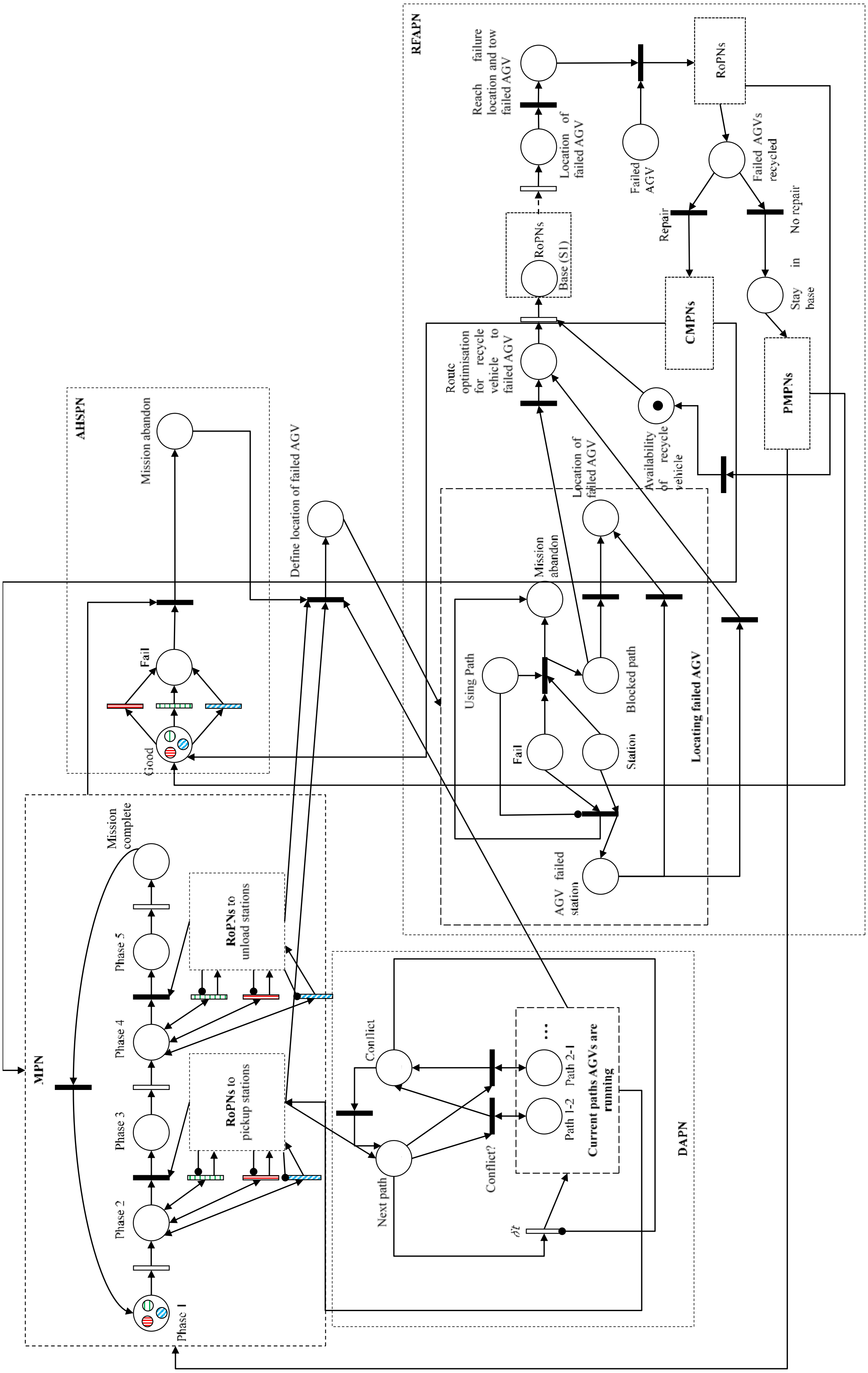


Figure 9.13 Full PN for the case study

Since the functions of all stations in the system have been defined in advance, the generation of the AGV missions described in Section 6.3.1 needs to be modified correspondingly. The modified mission generation algorithm is shown in Figure 9.14. Where, the items picked up from a pickup station can be delivered only to the prescribed storage station. Likewise, the items picked up from a storage station can be delivered only to the prescribed drop station. After the missions of the AGVs are generated, their routes will be optimised immediately by performing Dijkstra algorithm [115].

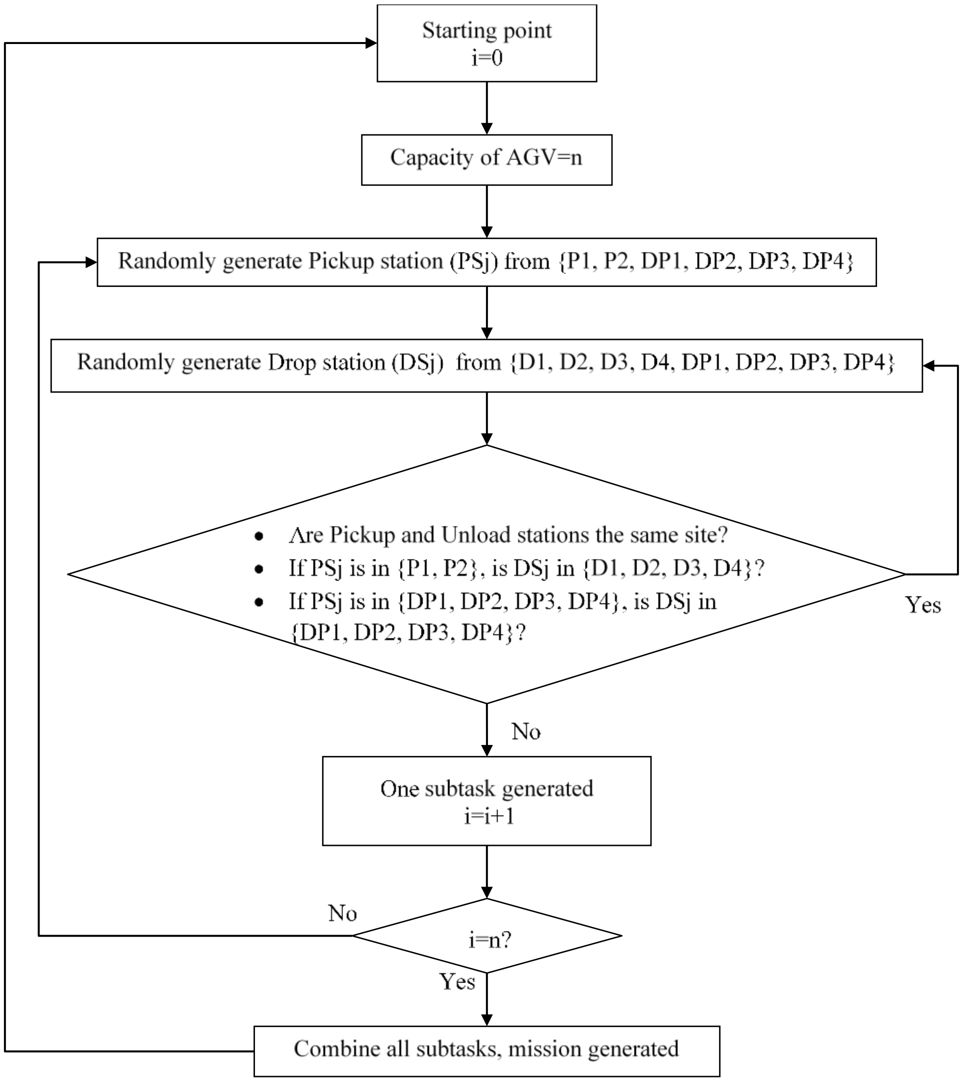


Figure 9.14 The modified mission generation algorithm

In the simulation, the time interval of the periodic maintenance is set to be 4 months. Single-load AGVs with the failure distribution described in Section 7.5 are employed in the system, and the number of AGVs varies from 1 to 20. The number of missions completed by a single AGV within 4 months against the number of simulations are plotted in Figure 9.15.

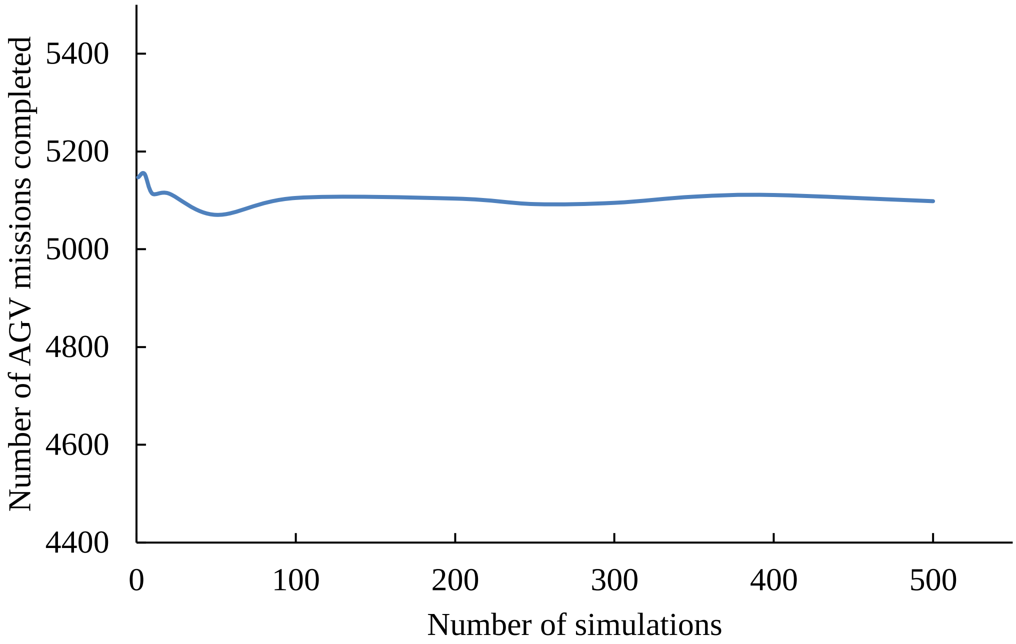


Figure 9.15 Convergence study of the CPN model for the case study

From Figure 9.15, it is found that the simulation result reaches a saturated value after performing about 200 simulations. It takes about 10 minutes to run 200 simulations for the system with one AGV, while takes up to 5 hours to complete all the simulations for the system with 20 AGVs. This significant time difference is due to the increase in the number of the activations of DAPN and the dramatic increase in the number of conflicts in the system. The performance and the associated costs of the systems per year are calculated using Equations (8.1) and (8.2) and the calculation results are listed in Table 9.2.

Table 9.2 Performance and the associated costs of the AGV systems

Number of AGVs	**Number of missions completed per year**	**Number of failures per year**	**Cost per year (£)**
1	15282	4	59990
2	30390	8	71420
3	45203	12	82220
4	58432	16	92660
5	72505	20	102740

6	86944	25	114980
7	100607	28	123710
8	112537	33	135230
9	124806	38	146750
10	138000	40	155300
11	147416	45	167000
12	160179	48	176630
13	168772	53	187790
14	181650	58	199490
15	187656	61	209480
16	195454	64	218300
17	210558	68	227900
18	217293	73	240800
19	220968	78	251900
20	235067	80	260150

To investigate the effectiveness of increasing the number of AGV in improvement of system performance, the system performance is plotted against the number of AGVs in the system in Figure 9.16.

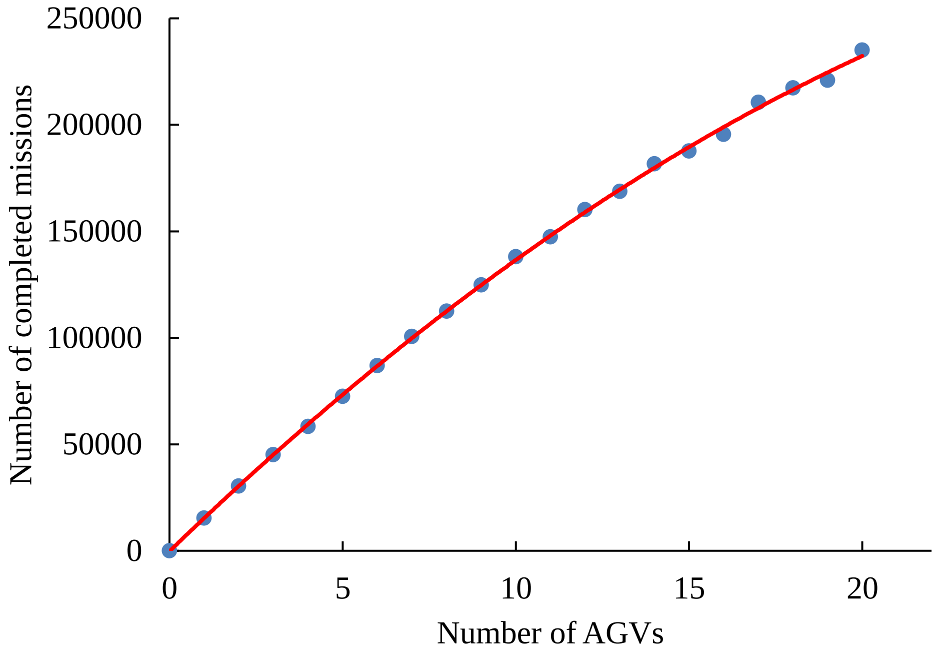


Figure 9.16 The performance of the AGV system in the case study

From Figure 9.16, it is found that the performance of the system increases with the increasing number of AGVs in the system. However, the decreasing value of the curve gradient implies that the effectiveness of the approach to increasing the system performance by increasing the number of AGVs will decrease gradually when more AGVs are used. As mentioned earlier, this should be related to the increased number of conflicts between the AGVs when more AGVs are used and consequently the paths become crowded.

9.6 Conclusions

In order to investigate the adaptability and capability of the developed CPN models in assessing more complex and larger AGV systems, the extended models for more complex system layout configurations have been developed in this Chapter. From the research results described above, the following conclusions can be drawn:

1. The CPN model can be extended for different AGV system settings and layouts;
2. The performance of the same AGV system with different configurations, namely tandem and conventional, can be evaluated and compared;
3. It is more difficult to model the irregular AGV systems since the existing AGV movement rules that are already established for regular AGV systems cannot be employed. However, this method shows the ability for dealing with the irregular system layout which has rarely been studied in previous literature.

It should be noted that the reroute processes for the irregular system layout and the layout with blocking structures have not been studied here. This could be investigated in future work.

10 Conclusions and Future Work

10.1 Overview

All six research objectives of this thesis listed in Section 1.5 have been successfully achieved. They are concluded below.

The first objective was to gain an understanding of the failures of key AGV subsystems. The root causes of AGV failures and their effects on both AGVs and AGV systems have been successfully studied using the FMECA approach (in Section 4.4). Moreover, with the aid of the Risk Priority Number (RPN) the key subsystems in these AGVs have been identified. The research identified that despite these new insights offered by FMECA it was unable to accurately describe the interdependence between the different subsystems of AGVs, hence an alternative method was required to perform the AGV reliability analysis.

The second objective was to investigate the relationships between subsystem failures and mission failures, which was achieved through performing Fault Tree Analysis (FTA) of the AGV systems (in Chapter 4). With the aid of the FTA, the relationships between subsystem failures and mission failures were established and based on which, the crucial mission phases in the operation of a single-AGV system were successfully identified. However, for large system analysis the limitations of the FTA quantification process restricted the quantification potential. Moreover, it was also found difficult to apply FTA to describe some problems in AGV systems such as routing and deadlock. This motivated the further study of the Petri Net (PN)-based technology, also described in Chapter 4. It was found that the PN method does show a number of superiorities over FTA in dealing with the reliability issues in single-AGV systems. The modelling at this stage, however, did not describe the deadlock, maintenance, and interaction issues that may be encountered in multi-AGV systems.

The third objective was to study the reliability issues in multi-AGV systems. This was achieved by developing Coloured Petri Net (CPN) models for a three-station multi-AGV system (in Chapter 5). Then with the aid of the developed CPN models, the performance of the multi-AGV system and the influence of individual AGVs' reliability on it were successfully studied. It was found that the CPN method is more powerful than the traditional PN technology in modelling complex AGV systems, in particular in dealing with the complex problems of maintenance and interactions of AGVs. Moreover, the simulation results have shown that the reliability of an individual AGV does have significant influence on the performance of the entire multi-AGV system. In addition, the performance and availability of the multi-AGV system are also highly dependent upon the defective AGV recycling and maintenance strategies adopted.

The fourth objective was to investigate the influence of the loading capacity of individual AGV on the performance of whole AGV systems. This objective was achieved in Chapter 6 by modelling a multi-load AGV initially and then calculating and comparing its performance with a system comprising of multiple single-load AGVs that ran along the paths defined by the same layout with nine stations. From the research, it was interestingly found that with the increase of the number of single-load AGVs used in the system, the efficiency of individual single-load AGV is reduced due to the increased confliction issues. The application of multi-load AGV's has potential to reduce the total operation time of the system. There is no doubt that this advantage of the multi-load AGV is beneficial to reduce the total cost of the system. However, as opposed to the application of single-load AGVs, the application of multi-load AGVs may increase the risk to the system due to their reduced numbers. It can easily be imagined that the performance of multi-load AGV system's will be affected more significantly once any multi-load AGV in the system breaks down in service. Accordingly, this issue is further investigated in Chapter 7 by considering a nine station multi-load AGV system. It is found that the impact of the failure of a multi-load AGV on system performance can be successfully addressed by the approach of re-routing and maintenance optimisation.

The fifth objective was to optimise the design, operation and maintenance of a multi-AGV system take into account both performance and cost factors. This objective was achieved in Chapter 8 by taking advantage of the Genetic Algorithm (GA) technique in the process of realising multi-objective optimisation. In the research, the simulation results obtained from CPN models in Chapter 7 are employed for implementing the GA optimisation. Through conducting this research, it can be concluded that the combined use of CPN's and GA's provides an effective and efficient approach to assessing and optimising the design, operation and maintenance of multi-AGV systems. In addition, the research discloses that after considering the cost of the system, the most desired AGV system is not necessary the system that has shown the best performance. This explains in the situation experienced in real life, the best system option is usually a compromise of performance and cost.

Finally, the last objective achieved in Chapter 9 is to investigate the adaptability and capability of PN-based simulation technology in dealing with more complex AGV systems. To achieve this objective, the resources in the system and the availability of individual stations were taken into account in order to achieve a more advanced PN-based modelling technology that considers the waiting time occurring in the actual operation of some AGV systems. Secondly, the PN-based modelling technologies for describing three more complex AGV systems were studied extensively. The three scenarios being studied are respectively (1) tandem layout configuration, (2) irregular layout configuration, and (3) regular layout configuration that includes up to 20 AGVs and occupied areas that AGVs cannot go through. Through conducting the above research, not only the effectiveness, adaptability and capability of PN-based simulation technology in dealing with more complex AGV systems are successfully proved, but also the scientific approach to establishing more advanced and comprehensive models of complex AGV systems is established. The achievement of these has successfully filled the present research gap in the field of AGVs.

10.2 Unique Contributions to the Area

This thesis promotes the reliability and availability research of AGVs mainly via the following scientific contributions:

- The comprehensive FMECA of AGVs has been conducted, which provides the most up-to-date tabular analysis of the failure modes of AGV subsystems. This achievement filled the research gap in the area of reliability analysis of AGVs.

- The FTA of the missions of AGVs has been performed based on the knowledge derived from the FMECA, which provides an innovative top-down approach to assessing the reliability of AGV missions. The achieved approach enables the investigation of the impact of AGV subsystem failures on mission phases of AGVs and from the investigation results, the critical AGV subsystems and mission phases can be successfully identified.

- A comprehensive PN-based modelling technology has been developed in this thesis for modelling the operation of AGV systems at different levels of complexity. As opposed to existing AGV simulation models, the PN-based models developed in this thesis consider more factors simultaneously that may affect the performance of AGV systems. This greatly promotes the scientific research of AGV simulation technology and enables the simulation results to closely reflect actual AGV systems and their operation and maintenance.

- The performance of AGV system is investigated in more detail in this thesis than previously by considering the impact of AGV failures, which are often ignored in previous research. The research in this thesis has proved that the influence of AGV failures on the system performance is significant and not negligible.

- The risk and reliability of the application of multi-load AGVs is investigated in this thesis for the first time. This fills the research gap and has potential to accelerate the design and application of multi-load AGVs in the future.

- An innovative GA-based multi-objective optimisation technique, which considers both AGV system performance and cost, was developed in the thesis dedicatedly for optimising the design, operation and maintenance of complex AGV systems early in the phase of concept design. The successful research of such a technique will reduce the risk and improve the economic return of AGV systems.

10.3 Suggestions for Future Work

The research reported in this thesis has provided valid solutions for a variety of issues in the field of AGV. However, discrepancy still exists between the theoretical research and the actual operation of AGV systems. To reduce the gap further, the following research is suggested to be conducted in the future:

1. The thesis has successfully established various AGV research approaches based on the data available in the open literature. But as the data available for the research is very limited at present, the research conclusions obtained based on this data still need to be further verified by using more reliability, operation and maintenance data from the AGV industry.

2. Research on the design, maintenance and operation of large-scale AGV systems is essential as such systems are increasingly adopted by industry. Such work may require the aid of High-Performance Computing (HPC) facilities in order to undertake optimisation.

3. Since the operation of some AGV systems requires frequent human involvement and interaction between human and AGVs, human's behaviour will have an impact on the performance of the AGV systems. However, this factor has not been considered in the research of this thesis. The influence of such a factor should be studied in the future.

4. Nowadays, more advanced maintenance strategies, such as condition-based maintenance, have been developed for further improving the availability of industrial facilities. They will be applied to the asset management of AGVs sooner or later. Therefore, how these new maintenance strategies affect the performance of AGV systems should be investigated in the future.

5. The future AGVs may be designed to possess versatile functions for meeting different requirements over time in their service life. Consequently, both single-load and multi-load AGVs may operate simultaneously in the same AGV system in the future. How the performance of the AGV system can be maximised by optimising the composition of them is also an issue that should be researched in the future.

6. In order to increase the impact of the proposed technique and ease the extensive

application of it in the future, the developed modelling and optimisation approaches will be encoded into a software package. With the aid of this software, the relevant industries are able to readily assess and improve the design and operation of their AGV systems.

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Appendix A. Python codes for GA optimisation

```
# GA code

#parameters & cost
# Simulation results from excel files

def findP(cor,road,repairT,backup,period,numAGV,cAGV):
    directory=0
    if cor==1: # corrective
        if road==1:
        if road == 2:
    elif cor==0:      # no corrective
        if backup==0:
    return (performance,numF)

def get_fitness(guess):
    Na=numMAGV[int(guess[0:3],2)]                    # number of AGV
    Cap=capAGV[int(guess[3:5],2)]                   #loading capacity of AGV
    Per=periodofPM[int(guess[5:8],2)                  # period of PM
    RW=widepath[int(guess[8],2)]                    # road width
    RT=repairtime[int(guess[9],2)]                  # repairtime
    Nb=NumBackup[int(guess[10:13],2)]                # number of backup AGV
    NCM=corrective [int(guess[13],2)]                # correctivemaintenace or not
    Cw=CW[int(guess[8],2)]
    if NCM==0 and RT==20:
        Cms=20000
        Ne=Ne1
    else:
        Cms=4000
        Ne=Ne2
    output = list(findP(NCM, RW, RT, Nb, Per, Na, Cap))
    Mission =output[0]
    Nfail=output[1]
    Cla=ClA*(1+Cap/4)
    if RT==20:
        Cc=Cc1
        Ne=Ne1
    if RT==100:
        Cc=Cc2
        Ne=Ne2
    Cost = Na *Cla+ Na*Per*Cp + Nb*Cla*NCM + Nb*NCM*Per*Cp + Nfail*Cc+ RW*Cw +
Ne*Ce + Cms
    fitness=Mission*w/Cost #minimise...............
    return   (Cost,Mission)

def generate_parent(length):
    genes = []
    while len(genes) < length:
        i=str(random.choice(geneSet))
        genes.append(i)
    return ''.join(genes)

def mutate(parent):
    index = random.randrange(0, len(parent))
    childGenes = list(parent)
    newGene = str(random.choice(geneSet))
    alternate = str(random.choice(geneSet))
```

```
        childGenes[index] = alternate \
            if newGene == childGenes[index] \
            else newGene
        return ''.join(childGenes)

def display(guess):
        timeDiff = datetime.datetime.now() - startTime
        fitness = get_fitness(guess)

def crossover(a,b):
        midpoint=random.randint(0,length)
        R1=list(str(a))
        R2=list(str(b))
        child=[]
        j=0
        while j<=length-1:
            if (j <= midpoint):
                child.extend(R1[j])
            if (j > midpoint):
                child.extend(R2[j])
            j=j+1
        return ''.join(child)

while i<=population:
        p=generate_parent(length)
        if    p[0:3]=='111'or int(p[10:13],2)>4 or (int(p[8],2)==1 and int(p[13],2)==0) or(int(p[13],2)==0
and int(p[5:8],2)>5) or (int(p[13],2)==1 and int(p[10:13],2)>0):
            continue
        P.append(p)
        i=i+1

while True:
        itr += 1
        F=[]
        mpool=[]
        l=0
        ll=0
        lll=0

        while l<=population:
            temp=list(get_fitness(P[l]))
            if temp[0]<=600000 and temp[1]>=92000:
                f = -temp[0] / temp[1]*3
            else:
                f = 0
            F.append(f)
            l=l+1

        meanFit=sum(F)/len(F)
        meanFitlist.append(meanFit)
        worst= min(F)

        while ll<=population:
            hh=int(math.exp(F[ll]-min(F)))
            k=0
            if F[ll]==0:
                hh=-1
            while k<=hh:
                mpool.append(P[ll])
                k=k+1
```

```
            ll=ll+1

        while s<=population:
            ran1=random.choice(mpool)
            ratec=random.random()
            ratem=random.random()
            child=ran1
            if ratec<=crate:
                while True:
                    ran2 = random.choice(mpool)
                    child = crossover(ran1,ran2)                    # constraints
                    if child[0:3] == '111' or int(child[10:13], 2) > 4 or (int(child[8], 2) == 1 and
int(child[13], 2) == 0) or (
                            int(child[13], 2) == 0 and int(child[5:8], 2) > 5) or (int(child[13], 2) == 1
and int(child[10:13], 2) > 0):
                        continue
                    else:
                        break
            if ratem<=mrate:
                while True:
                    child = mutate(child)
                    if child[0:3] == '111' or int(child[10:13], 2) > 4 or (int(child[8], 2) == 1 and
int(child[13], 2) == 0) or (
                            int(child[13], 2) == 0 and int(child[5:8], 2) > 5) or (int(child[13], 2) == 1
and int(child[10:13], 2) > 0):
                        continue
                    else:
                        break

        while lll<=population:
            temp=list(get_fitness(P[lll]))
            if temp[0]<=600000 and temp[1]>=92000:
                f = -temp[0] / temp[1]*3
            else:
                f = 0
            F.append(f)

        evaluate=sum(F)/len(F)
        evaluatelist.append(evaluate)
        itrlist.append(itr)
        evaList.append(evaluate)

        if ii >=10:
            Aver=sum(evaList[ii-5:ii])/5
            if abs(Aver-evaList[ii]) <=0.0001:
                break
```

Appendix B. Simulation results for GA optimisation

Table B.1 Simulation results for narrow-path AGV systems with onsite corrective maintenance when loading capacity is 1

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	1	1	8687.329	8687.329	4.951	4.951
2	1	1	17227.147	17227.147	9.945	9.945
3	1	1	25663.259	25663.259	14.958	14.958
4	1	1	34017.220	34017.220	19.896	19.896
5	1	1	42328.003	42328.003	24.835	24.835
6	1	1	50582.652	50582.652	29.856	29.856
7	1	1	58811.530	58811.530	34.782	34.782
1	1	2	4331.072	8662.144	2.256	4.513
2	1	2	8586.236	17172.473	4.521	9.041
3	1	2	12793.051	25586.103	6.808	13.617
4	1	2	16956.875	33913.750	9.093	18.187
5	1	2	21096.321	42192.643	11.351	22.701
6	1	2	25218.214	50436.428	13.564	27.128
7	1	2	29309.794	58619.588	15.962	31.924
1	1	3	2877.849	8633.547	1.366	4.098
2	1	3	5707.077	17121.232	2.712	8.136
3	1	3	8499.035	25497.104	4.082	12.247
4	1	3	11269.173	33807.518	5.477	16.430
5	1	3	14017.394	42052.183	6.856	20.569
6	1	3	16752.070	50256.210	8.188	24.564
7	1	3	19466.780	58400.340	9.600	28.800
1	1	4	2150.710	8602.839	0.937	3.748
2	1	4	4263.321	17053.285	1.876	7.503
3	1	4	6351.259	25405.036	2.824	11.296
4	1	4	8422.459	33689.837	3.716	14.865
5	1	4	10475.658	41902.632	4.721	18.883
6	1	4	12521.916	50087.664	5.592	22.368
7	1	4	14559.360	58237.440	6.546	26.184
1	1	6	1427.610	8565.658	0.415	2.488
2	1	6	2830.525	16983.152	0.839	5.032
3	1	6	4217.859	25307.154	1.269	7.616
4	1	6	5591.065	33546.388	1.665	9.988
5	1	6	6955.879	41735.272	2.108	12.646
6	1	6	8314.972	49889.832	2.494	14.964
7	1	6	9657.448	57944.688	3.052	18.312
1	1	12	696.665	8359.980	0.047	0.560
2	1	12	1380.896	16570.752	0.118	1.420
3	1	12	2056.907	24682.888	0.169	2.032
4	1	12	2726.588	32719.060	0.241	2.892
5	1	12	3393.920	40727.044	0.277	3.320
6	1	12	4051.986	48623.832	0.394	4.728
7	1	12	4712.446	56549.352	0.440	5.280
1	1	26	295.543	7684.127	0.005	0.130
2	1	26	586.149	15239.865	0.010	0.251
3	1	26	872.673	22689.498	0.018	0.468
4	1	26	1157.276	30089.167	0.019	0.494
5	1	26	1440.009	37440.225	0.021	0.555
6	1	26	1720.358	44729.308	0.028	0.728
7	1	26	2003.582	52093.132	0.022	0.572
1	1	52	123.059	6399.051	0.001	0.035
2	1	52	244.056	12690.912	0.001	0.035
3	1	52	363.425	18898.117	0.001	0.052
4	1	52	481.586	25042.455	0.002	0.121
5	1	52	599.558	31177.033	0.000	0.017
6	1	52	716.468	37256.336	0.006	0.312
7	1	52	834.308	43384.016	0.002	0.104

Table B.2 Simulation results for narrow-path AGV systems with onsite corrective maintenance when loading capacity is 2

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	2	1	10581.507	10581.507	4.952	4.952
2	2	1	20982.767	20982.767	9.873	9.873
3	2	1	31234.504	31234.504	14.846	14.846
4	2	1	41385.240	41385.240	19.758	19.758
5	2	1	51449.057	51449.057	24.733	24.733
6	2	1	61453.764	61453.764	29.718	29.718
7	2	1	71419.566	71419.566	34.588	34.588
1	2	2	5276.954	10553.907	2.275	4.551
2	2	2	10465.690	20931.381	4.476	8.953
3	2	2	15575.936	31151.871	6.789	13.578
4	2	2	20637.589	41275.178	9.019	18.038
5	2	2	25658.059	51316.118	11.290	22.581
6	2	2	30646.672	61293.344	13.600	27.200
7	2	2	35608.528	71217.056	16.006	32.012
1	2	3	3508.677	10526.030	1.375	4.125
2	2	3	6956.879	20870.636	2.734	8.203
3	2	3	10358.207	31074.621	4.082	12.245
4	2	3	13724.344	41173.032	5.424	16.273
5	2	3	17063.082	51189.246	6.811	20.433
6	2	3	20379.572	61138.716	8.146	24.438
7	2	3	23689.790	71069.370	9.486	28.458
1	2	4	2623.904	10495.616	0.936	3.744
2	2	4	5201.569	20806.276	1.873	7.492
3	2	4	7743.630	30974.521	2.813	11.253
4	2	4	10260.609	41042.437	3.724	14.895
5	2	4	12756.903	51027.613	4.675	18.701
6	2	4	15232.234	60928.936	5.628	22.512
7	2	4	17708.576	70834.304	6.500	26.000
1	2	6	1745.675	10474.050	0.412	2.472
2	2	6	3458.831	20752.986	0.850	5.100
3	2	6	5150.045	30900.270	1.230	7.382
4	2	6	6823.032	40938.194	1.685	10.108
5	2	6	8484.344	50906.062	2.090	12.542
6	2	6	10139.522	60837.132	2.510	15.060
7	2	6	11776.276	70657.656	2.926	17.556
1	2	12	853.370	10240.440	0.055	0.656
2	2	12	1690.377	20284.520	0.121	1.448
3	2	12	2517.796	30213.548	0.175	2.096
4	2	12	3334.551	40014.608	0.231	2.776
5	2	12	4147.583	49770.996	0.292	3.508
6	2	12	4953.268	59439.216	0.386	4.632
7	2	12	5759.308	69111.696	0.420	5.040
1	2	26	362.557	9426.491	0.005	0.130
2	2	26	718.359	18677.334	0.009	0.234
3	2	26	1069.147	27797.831	0.016	0.416
4	2	26	1417.272	36849.081	0.017	0.451
5	2	26	1761.760	45805.769	0.022	0.572
6	2	26	2103.386	54688.036	0.026	0.676
7	2	26	2444.104	63546.704	0.034	0.884
1	2	52	150.798	7841.479	0.001	0.052
2	2	52	299.150	15555.800	0.001	0.052
3	2	52	445.112	23145.807	0.001	0.035
4	2	52	589.693	30664.053	0.002	0.121
5	2	52	732.788	38104.993	0.002	0.121
6	2	52	876.286	45566.872	0.002	0.104
7	2	52	1017.006	52884.312	0.004	0.208

Table B.3 Simulation results for narrow-path AGV systems with onsite corrective maintenance when loading capacity is 3

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	3	1	12194.900	12194.900	4.914	4.914
2	3	1	24162.350	24162.350	9.841	9.841
3	3	1	35957.898	35957.898	14.768	14.768
4	3	1	47618.911	47618.911	19.693	19.693
5	3	1	59173.240	59173.240	24.610	24.610
6	3	1	70653.730	70653.730	29.660	29.660
7	3	1	82077.158	82077.158	34.468	34.468
1	3	2	6082.710	12165.420	2.256	4.513
2	3	2	12054.895	24109.790	4.499	8.997
3	3	2	17946.614	35893.229	6.722	13.443
4	3	2	23759.868	47519.735	8.994	17.989
5	3	2	29523.269	59046.537	11.268	22.535
6	3	2	35265.244	70530.488	13.430	26.860
7	3	2	40951.328	81902.656	15.786	31.572
1	3	3	4047.588	12142.763	1.352	4.055
2	3	3	8021.337	24064.011	2.722	8.166
3	3	3	11938.584	35815.751	4.055	12.166
4	3	3	15809.695	47429.084	5.402	16.206
5	3	3	19644.294	58932.882	6.764	20.292
6	3	3	23455.634	70366.902	8.086	24.258
7	3	3	27245.122	81735.366	9.552	28.656
1	3	4	3026.975	12107.901	0.938	3.752
2	3	4	5997.596	23990.385	1.868	7.472
3	3	4	8927.043	35708.173	2.804	11.216
4	3	4	11820.757	47283.027	3.757	15.027
5	3	4	14691.310	58765.241	4.684	18.735
6	3	4	17525.224	70100.896	5.648	22.592
7	3	4	20379.416	81517.664	6.492	25.968
1	3	6	2016.375	12098.248	0.428	2.568
2	3	6	3996.466	23978.798	0.828	4.968
3	3	6	5942.717	35656.304	1.284	7.706
4	3	6	7870.227	47221.362	1.703	10.218
5	3	6	9781.187	58687.122	2.115	12.692
6	3	6	11691.416	70148.496	2.418	14.508
7	3	6	13580.674	81484.044	2.844	17.064
1	3	12	988.414	11860.968	0.054	0.644
2	3	12	1959.408	23512.892	0.098	1.180
3	3	12	2912.354	34948.248	0.177	2.124
4	3	12	3855.505	46266.060	0.242	2.904
5	3	12	4793.839	57526.072	0.280	3.360
6	3	12	5720.162	68641.944	0.400	4.800
7	3	12	6649.534	79794.408	0.402	4.824
1	3	26	419.946	10918.605	0.003	0.078
2	3	26	831.842	21627.901	0.009	0.243
3	3	26	1238.170	32192.429	0.013	0.329
4	3	26	1639.117	42617.042	0.017	0.442
5	3	26	2037.049	52963.274	0.025	0.641
6	3	26	2432.010	63232.260	0.032	0.832
7	3	26	2825.316	73458.216	0.030	0.780
1	3	52	174.882	9093.864	0.001	0.035
2	3	52	346.357	18010.547	0.000	0.000
3	3	52	515.164	26788.528	0.001	0.035
4	3	52	681.985	35463.203	0.002	0.104
5	3	52	847.910	44091.303	0.003	0.139
6	3	52	1010.944	52569.088	0.004	0.208
7	3	52	1175.272	61114.144	0.002	0.104

Table B.4 Simulation results for narrow-path AGV systems with onsite corrective maintenance when loading capacity is 4

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	4	1	13662.804	13662.804	4.902	4.902
2	4	1	27071.181	27071.181	9.797	9.797
3	4	1	40265.284	40265.284	14.669	14.669
4	4	1	53302.697	53302.697	19.606	19.606
5	4	1	66209.074	66209.074	24.439	24.439
6	4	1	78976.864	78976.864	29.436	29.436
7	4	1	91773.832	91773.832	34.008	34.008
1	4	2	6823.490	13646.980	2.227	4.454
2	4	2	13510.646	27021.291	4.499	8.998
3	4	2	20096.192	40192.383	6.754	13.509
4	4	2	26597.666	53195.332	9.014	18.028
5	4	2	33051.292	66102.583	11.187	22.373
6	4	2	39458.820	78917.640	13.494	26.988
7	4	2	45784.438	91568.876	15.714	31.428
1	4	3	4539.218	13617.655	1.358	4.073
2	4	3	8994.510	26983.531	2.706	8.118
3	4	3	13382.670	40148.011	4.030	12.090
4	4	3	17707.502	53122.507	5.419	16.258
5	4	3	21993.285	65979.854	6.778	20.334
6	4	3	26234.700	78704.100	8.164	24.492
7	4	3	30480.756	91442.268	9.396	28.188
1	4	4	3396.037	13584.149	0.935	3.739
2	4	4	6729.659	26918.636	1.860	7.440
3	4	4	10012.547	40050.189	2.792	11.168
4	4	4	13249.295	52997.179	3.753	15.011
5	4	4	16460.369	65841.475	4.678	18.712
6	4	4	19648.604	78594.416	5.566	22.264
7	4	4	22808.210	91232.840	6.478	25.912
1	4	6	2266.776	13600.654	0.416	2.494
2	4	6	4491.349	26948.092	0.826	4.958
3	4	6	6681.496	40088.976	1.215	7.288
4	4	6	8841.495	53048.968	1.632	9.792
5	4	6	10977.835	65867.012	2.066	12.394
6	4	6	13097.708	78586.248	2.524	15.144
7	4	6	15211.380	91268.280	2.884	17.304
1	4	12	1112.883	13354.600	0.055	0.660
2	4	12	2204.078	26448.932	0.110	1.320
3	4	12	3277.274	39327.292	0.169	2.028
4	4	12	4336.158	52033.896	0.230	2.764
5	4	12	5385.101	64621.208	0.299	3.584
6	4	12	6430.414	77164.968	0.348	4.176
7	4	12	7460.070	89520.840	0.422	5.064
1	4	26	472.712	12290.503	0.007	0.191
2	4	26	936.895	24359.261	0.008	0.217
3	4	26	1393.283	36225.367	0.013	0.338
4	4	26	1843.383	47927.949	0.019	0.503
5	4	26	2290.550	59554.291	0.022	0.563
6	4	26	2733.192	71062.992	0.042	1.092
7	4	26	3173.728	82516.928	0.022	0.572
1	4	52	196.799	10233.565	0.000	0.017
2	4	52	389.973	20278.596	0.001	0.035
3	4	52	579.525	30135.317	0.001	0.035
4	4	52	767.352	39902.304	0.001	0.052
5	4	52	953.046	49558.375	0.002	0.104
6	4	52	1138.172	59184.944	0.000	0.000
7	4	52	1319.780	68628.560	0.004	0.208

Table B.5 Simulation results for narrow-path AGV systems with offsite corrective maintenance when loading capacity is 1

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	1	1	8022.898	8022.898	4.534	4.534
2	1	1	15928.844	15928.844	8.994	8.994
3	1	1	23718.792	23718.792	13.572	13.572
4	1	1	31474.924	31474.924	18.022	18.022
5	1	1	39183.650	39183.650	22.432	22.432
6	1	1	46814.884	46814.884	27.198	27.198
7	1	1	54498.854	54498.854	31.418	31.418
1	1	2	4038.638	8077.276	2.080	4.160
2	1	2	8002.246	16004.492	4.188	8.376
3	1	2	11931.164	23862.328	6.282	12.564
4	1	2	15786.928	31573.856	8.368	16.736
5	1	2	19659.614	39319.228	10.434	20.868
6	1	2	23488.150	46976.300	12.582	25.164
7	1	2	27389.168	54778.336	14.512	29.024
1	1	3	2687.710	8063.130	1.314	3.942
2	1	3	5347.110	16041.330	2.564	7.692
3	1	3	7995.492	23986.476	3.804	11.412
4	1	3	10584.010	31752.030	5.114	15.342
5	1	3	13152.922	39458.766	6.378	19.134
6	1	3	15724.412	47173.236	7.638	22.914
7	1	3	18302.242	54906.726	8.896	26.688
1	1	4	2032.106	8128.424	0.890	3.560
2	1	4	4022.906	16091.624	1.790	7.160
3	1	4	5989.400	23957.600	2.750	11.000
4	1	4	7930.982	31723.928	3.628	14.512
5	1	4	9900.446	39601.784	4.504	18.016
6	1	4	11805.160	47220.640	5.494	21.976
7	1	4	13767.688	55070.752	6.352	25.408
1	1	6	1378.826	8272.956	0.408	2.448
2	1	6	2736.060	16416.360	0.822	4.932
3	1	6	4075.580	24453.480	1.276	7.656
4	1	6	5408.490	32450.940	1.634	9.804
5	1	6	6725.086	40350.516	2.052	12.312
6	1	6	8045.196	48271.176	2.428	14.568
7	1	6	9373.884	56243.304	2.812	16.872
1	1	12	690.878	8290.536	0.066	0.792
2	1	12	1374.278	16491.336	0.118	1.416
3	1	12	2040.026	24480.312	0.192	2.304
4	1	12	2714.124	32569.488	0.218	2.616
5	1	12	3369.704	40436.448	0.316	3.792
6	1	12	4027.624	48331.488	0.350	4.200
7	1	12	4680.602	56167.224	0.416	4.992
1	1	26	295.966	7695.116	0.000	0.000
2	1	26	586.124	15239.224	0.006	0.156
3	1	26	872.596	22687.496	0.010	0.260
4	1	26	1156.430	30067.180	0.034	0.884
5	1	26	1439.370	37423.620	0.032	0.832
6	1	26	1720.674	44737.524	0.022	0.572
7	1	26	2001.276	52033.176	0.028	0.728
1	1	52	122.966	6394.232	0.000	0.000
2	1	52	243.892	12682.384	0.000	0.000
3	1	52	363.144	18883.488	0.000	0.000
4	1	52	481.858	25056.616	0.000	0.000
5	1	52	599.674	31183.048	0.000	0.000
6	1	52	716.508	37258.416	0.000	0.000
7	1	52	833.230	43327.960	0.002	0.104

Table B.6 Simulation results for narrow-path AGV systems with offsite corrective maintenance when loading capacity is 2

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	2	1	9755.492	9755.492	4.542	4.542
2	2	1	19387.216	19387.216	9.078	9.078
3	2	1	28881.794	28881.794	13.498	13.498
4	2	1	38250.468	38250.468	18.036	18.036
5	2	1	47593.336	47593.336	22.590	22.590
6	2	1	56856.870	56856.870	27.000	27.000
7	2	1	66101.904	66101.904	31.414	31.414
1	2	2	4915.674	9831.348	2.092	4.184
2	2	2	9733.112	19466.224	4.180	8.360
3	2	2	14512.862	29025.724	6.244	12.488
4	2	2	19229.106	38458.212	8.308	16.616
5	2	2	23914.578	47829.156	10.460	20.920
6	2	2	28529.860	57059.720	12.572	25.144
7	2	2	33154.062	66308.124	14.682	29.364
1	2	3	3282.950	9848.850	1.300	3.900
2	2	3	6534.406	19603.218	2.496	7.488
3	2	3	9715.772	29147.316	3.784	11.352
4	2	3	12868.324	38604.972	5.078	15.234
5	2	3	16006.582	48019.746	6.382	19.146
6	2	3	19115.666	57346.998	7.606	22.818
7	2	3	22200.958	66602.874	8.928	26.784
1	2	4	2477.484	9909.936	0.894	3.576
2	2	4	4887.360	19549.440	1.826	7.304
3	2	4	7292.980	29171.920	2.722	10.888
4	2	4	9671.270	38685.080	3.608	14.432
5	2	4	12041.978	48167.912	4.524	18.096
6	2	4	14391.118	57564.472	5.364	21.456
7	2	4	16703.196	66812.784	6.292	25.168
1	2	6	1689.794	10138.764	0.392	2.352
2	2	6	3337.780	20026.680	0.866	5.196
3	2	6	4966.296	29797.776	1.300	7.800
4	2	6	6577.446	39464.676	1.708	10.248
5	2	6	8182.194	49093.164	2.106	12.636
6	2	6	9804.926	58829.556	2.478	14.868
7	2	6	11374.980	68249.880	2.920	17.520
1	2	12	847.580	10170.960	0.060	0.720
2	2	12	1681.318	20175.816	0.122	1.464
3	2	12	2500.666	30007.992	0.188	2.256
4	2	12	3311.530	39738.360	0.252	3.024
5	2	12	4123.566	49482.792	0.272	3.264
6	2	12	4924.896	59098.752	0.348	4.176
7	2	12	5732.116	68785.392	0.348	4.176
1	2	26	362.520	9425.520	0.002	0.052
2	2	26	718.520	18681.520	0.002	0.052
3	2	26	1070.318	27828.268	0.010	0.260
4	2	26	1416.400	36826.400	0.028	0.728
5	2	26	1760.504	45773.104	0.020	0.520
6	2	26	2103.738	54697.188	0.034	0.884
7	2	26	2443.502	63531.052	0.044	1.144
1	2	52	150.256	7813.312	0.002	0.104
2	2	52	298.596	15526.992	0.000	0.000
3	2	52	445.158	23148.216	0.002	0.104
4	2	52	589.708	30664.816	0.000	0.000
5	2	52	732.824	38106.848	0.000	0.000
6	2	52	875.528	45527.456	0.002	0.104
7	2	52	1017.396	52904.592	0.002	0.104

Table B.7 Simulation results for narrow-path AGV systems with offsite corrective maintenance when loading capacity is 3

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	3	1	11299.130	11299.130	4.524	4.524
2	3	1	22374.344	22374.344	9.028	9.028
3	3	1	33335.592	33335.592	13.584	13.584
4	3	1	44135.890	44135.890	18.110	18.110
5	3	1	54854.288	54854.288	22.620	22.620
6	3	1	65488.756	65488.756	27.068	27.068
7	3	1	76129.934	76129.934	31.564	31.564
1	3	2	5655.352	11310.704	2.124	4.248
2	3	2	11231.382	22462.764	4.214	8.428
3	3	2	16712.750	33425.500	6.388	12.776
4	3	2	22195.726	44391.452	8.360	16.720
5	3	2	27604.798	55209.596	10.428	20.856
6	3	2	32896.784	65793.568	12.612	25.224
7	3	2	38227.492	76454.984	14.710	29.420
1	3	3	3785.868	11357.604	1.306	3.918
2	3	3	7536.908	22610.724	2.592	7.776
3	3	3	11199.504	33598.512	3.826	11.478
4	3	3	14846.144	44538.432	5.156	15.468
5	3	3	18460.488	55381.464	6.374	19.122
6	3	3	22057.580	66172.740	7.592	22.776
7	3	3	25656.374	76969.122	8.812	26.436
1	3	4	2865.380	11461.520	0.878	3.512
2	3	4	5680.762	22723.048	1.776	7.104
3	3	4	8452.272	33809.088	2.628	10.512
4	3	4	11174.022	44696.088	3.610	14.440
5	3	4	13896.830	55587.320	4.522	18.088
6	3	4	16566.330	66265.320	5.450	21.800
7	3	4	19286.816	77147.264	6.234	24.936
1	3	6	1956.276	11737.656	0.386	2.316
2	3	6	3851.704	23110.224	0.852	5.112
3	3	6	5743.818	34462.908	1.270	7.620
4	3	6	7641.026	45846.156	1.558	9.348
5	3	6	9458.000	56748.000	2.114	12.684
6	3	6	11309.882	67859.292	2.498	14.988
7	3	6	13143.422	78860.532	2.898	17.388
1	3	12	978.180	11738.160	0.072	0.864
2	3	12	1950.918	23411.016	0.094	1.128
3	3	12	2899.928	34799.136	0.170	2.040
4	3	12	3830.508	45966.096	0.248	2.976
5	3	12	4768.352	57220.224	0.276	3.312
6	3	12	5679.856	68158.272	0.378	4.536
7	3	12	6615.246	79382.952	0.388	4.656
1	3	26	420.072	10921.872	0.006	0.156
2	3	26	832.096	21634.496	0.006	0.156
3	3	26	1237.856	32184.256	0.012	0.312
4	3	26	1639.548	42628.248	0.020	0.520
5	3	26	2034.706	52902.356	0.028	0.728
6	3	26	2430.406	63190.556	0.034	0.884
7	3	26	2826.842	73497.892	0.022	0.572
1	3	52	174.430	9070.360	0.000	0.000
2	3	52	346.618	18024.136	0.000	0.000
3	3	52	515.356	26798.512	0.000	0.000
4	3	52	681.852	35456.304	0.000	0.000
5	3	52	847.950	44093.400	0.008	0.416
6	3	52	1012.864	52668.928	0.000	0.000
7	3	52	1176.190	61161.880	0.004	0.208

Table B.8 Simulation results for narrow-path AGV systems with offsite corrective maintenance when loading capacity is 4

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	4	1	12700.326	12700.326	4.494	4.494
2	4	1	25184.980	25184.980	9.044	9.044
3	4	1	37452.066	37452.066	13.554	13.554
4	4	1	49539.974	49539.974	18.138	18.138
5	4	1	61577.110	61577.110	22.656	22.656
6	4	1	73610.236	73610.236	27.034	27.034
7	4	1	85437.424	85437.424	31.620	31.620
1	4	2	6373.080	12746.160	2.138	4.276
2	4	2	12647.972	25295.944	4.236	8.472
3	4	2	18828.094	37656.188	6.302	12.604
4	4	2	24930.968	49861.936	8.346	16.692
5	4	2	30954.392	61908.784	10.416	20.832
6	4	2	36948.160	73896.320	12.550	25.100
7	4	2	42977.468	85954.936	14.534	29.068
1	4	3	4271.868	12815.604	1.280	3.840
2	4	3	8461.792	25385.376	2.554	7.662
3	4	3	12620.060	37860.180	3.808	11.424
4	4	3	16684.394	50053.182	5.118	15.354
5	4	3	20748.292	62244.876	6.310	18.930
6	4	3	24780.396	74341.188	7.608	22.824
7	4	3	28749.504	86248.512	8.976	26.928
1	4	4	3216.380	12865.520	0.888	3.552
2	4	4	6356.572	25426.288	1.846	7.384
3	4	4	9494.886	37979.544	2.656	10.624
4	4	4	12574.322	50297.288	3.552	14.208
5	4	4	15590.306	62361.224	4.470	17.880
6	4	4	18622.492	74489.968	5.420	21.680
7	4	4	21628.820	86515.280	6.210	24.840
1	4	6	2197.078	13182.468	0.422	2.532
2	4	6	4334.612	26007.672	0.888	5.328
3	4	6	6478.552	38871.312	1.204	7.224
4	4	6	8538.214	51229.284	1.758	10.548
5	4	6	10677.024	64062.144	1.968	11.808
6	4	6	12708.492	76250.952	2.466	14.796
7	4	6	14737.118	88422.708	2.922	17.532
1	4	12	1107.192	13286.304	0.058	0.696
2	4	12	2195.406	26344.872	0.104	1.248
3	4	12	3276.498	39317.976	0.114	1.368
4	4	12	4300.142	51601.704	0.260	3.120
5	4	12	5363.950	64367.400	0.304	3.648
6	4	12	6388.794	76665.528	0.378	4.536
7	4	12	7431.446	89177.352	0.362	4.344
1	4	26	473.144	12301.744	0.002	0.052
2	4	26	936.648	24352.848	0.020	0.520
3	4	26	1393.814	36239.164	0.012	0.312
4	4	26	1844.912	47967.712	0.012	0.312
5	4	26	2288.916	59511.816	0.022	0.572
6	4	26	2730.922	71003.972	0.046	1.196
7	4	26	3172.044	82473.144	0.030	0.780
1	4	52	196.286	10206.872	0.000	0.000
2	4	52	389.824	20270.848	0.000	0.000
3	4	52	580.176	30169.152	0.004	0.208
4	4	52	767.004	39884.208	0.004	0.208
5	4	52	952.522	49531.144	0.000	0.000
6	4	52	1137.138	59131.176	0.000	0.000
7	4	52	1321.406	68713.112	0.006	0.312

Table B.9 Simulation results for wide-path AGV systems with onsite corrective maintenance when loading capacity is 1

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	1	1	8687.549	8687.549	4.984	4.984
2	1	1	17374.168	17374.168	9.921	9.921
3	1	1	26059.618	26059.618	14.912	14.912
4	1	1	34745.287	34745.287	19.858	19.858
5	1	1	43431.022	43431.022	24.821	24.821
6	1	1	52132.324	52132.324	29.658	29.658
7	1	1	60799.888	60799.888	34.774	34.774
1	1	2	4328.612	8657.224	2.268	4.536
2	1	2	8658.794	17317.588	4.536	9.072
3	1	2	12991.878	25983.756	6.766	13.532
4	1	2	17318.220	34636.440	9.152	18.304
5	1	2	21652.296	43304.592	11.308	22.616
6	1	2	25984.462	51968.924	13.606	27.212
7	1	2	30297.820	60595.640	15.846	31.692
1	1	3	2875.324	8625.972	1.390	4.170
2	1	3	5752.706	17258.118	2.728	8.184
3	1	3	8633.874	25901.622	4.046	12.138
4	1	3	11511.204	34533.612	5.474	16.422
5	1	3	14383.994	43151.982	6.942	20.826
6	1	3	17273.404	51820.212	8.160	24.480
7	1	3	20142.434	60427.302	9.514	28.542
1	1	4	2147.306	8589.224	0.946	3.784
2	1	4	4300.312	17201.248	1.900	7.600
3	1	4	6450.972	25803.888	2.824	11.296
4	1	4	8596.432	34385.728	3.774	15.096
5	1	4	10755.378	43021.512	4.630	18.520
6	1	4	12910.296	51641.184	5.608	22.432
7	1	4	15047.178	60188.712	6.624	26.496
1	1	6	1425.618	8553.708	0.426	2.556
2	1	6	2857.556	17145.336	0.800	4.800
3	1	6	4284.342	25706.052	1.222	7.332
4	1	6	5712.580	34275.480	1.674	10.044
5	1	6	7134.578	42807.468	2.136	12.816
6	1	6	8566.948	51401.688	2.506	15.036
7	1	6	9994.930	59969.580	2.868	17.208
1	1	12	696.072	8352.868	0.064	0.772
2	1	12	1393.447	16721.360	0.115	1.380
3	1	12	2088.936	25067.232	0.173	2.080
4	1	12	2785.517	33426.208	0.219	2.628
5	1	12	3481.333	41776.000	0.297	3.560
6	1	12	4177.710	50132.520	0.346	4.152
7	1	12	4873.004	58476.048	0.424	5.088
1	1	26	295.603	7685.687	0.005	0.121
2	1	26	591.484	15378.584	0.009	0.234
3	1	26	886.682	23053.732	0.011	0.277
4	1	26	1182.095	30734.470	0.019	0.503
5	1	26	1478.702	38446.252	0.024	0.633
6	1	26	1773.592	46113.392	0.036	0.936
7	1	26	2068.408	53778.608	0.032	0.832
1	1	52	123.057	6398.981	0.000	0.000
2	1	52	246.364	12810.911	0.001	0.035
3	1	52	368.886	19182.055	0.000	0.017
4	1	52	492.263	25597.659	0.001	0.035
5	1	52	615.284	31994.751	0.003	0.173
6	1	52	738.428	38398.256	0.002	0.104
7	1	52	861.408	44793.216	0.002	0.104

Table B.10 Simulation results for wide-path AGV systems with onsite corrective maintenance when loading capacity is 2

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	2	1	10583.551	10583.551	4.935	4.935
2	2	1	21164.471	21164.471	9.886	9.886
3	2	1	31744.213	31744.213	14.850	14.850
4	2	1	42328.635	42328.635	19.818	19.818
5	2	1	52905.626	52905.626	24.754	24.754
6	2	1	63498.232	63498.232	29.554	29.554
7	2	1	74091.610	74091.610	34.644	34.644
1	2	2	5278.334	10556.668	2.276	4.552
2	2	2	10557.400	21114.800	4.546	9.092
3	2	2	15818.558	31637.116	6.852	13.704
4	2	2	21105.968	42211.936	9.080	18.160
5	2	2	26393.124	52786.248	11.298	22.596
6	2	2	31675.654	63351.308	13.474	26.948
7	2	2	36947.758	73895.516	15.870	31.740
1	2	3	3510.758	10532.274	1.378	4.134
2	2	3	7017.278	21051.834	2.736	8.208
3	2	3	10523.716	31571.148	4.146	12.438
4	2	3	14037.438	42112.314	5.466	16.398
5	2	3	17554.790	52664.370	6.684	20.052
6	2	3	21058.354	63175.062	8.178	24.534
7	2	3	24566.892	73700.676	9.512	28.536
1	2	4	2626.414	10505.656	0.932	3.728
2	2	4	5254.354	21017.416	1.832	7.328
3	2	4	7869.688	31478.752	2.818	11.272
4	2	4	10490.138	41960.552	3.742	14.968
5	2	4	13118.588	52474.352	4.690	18.760
6	2	4	15740.270	62961.080	5.644	22.576
7	2	4	18370.964	73483.856	6.454	25.816
1	2	6	1745.204	10471.224	0.400	2.400
2	2	6	3490.220	20941.320	0.822	4.932
3	2	6	5240.842	31445.052	1.178	7.068
4	2	6	6984.742	41908.452	1.598	9.588
5	2	6	8730.266	52381.596	2.020	12.120
6	2	6	10473.664	62841.984	2.486	14.916
7	2	6	12215.740	73294.440	2.958	17.748
1	2	12	853.905	10246.860	0.054	0.644
2	2	12	1706.568	20478.812	0.117	1.408
3	2	12	2560.135	30721.616	0.173	2.072
4	2	12	3413.255	40959.064	0.229	2.744
5	2	12	4262.350	51148.200	0.302	3.624
6	2	12	5119.968	61439.616	0.332	3.984
7	2	12	5976.194	71714.328	0.356	4.272
1	2	26	362.539	9426.014	0.005	0.130
2	2	26	724.591	18839.357	0.011	0.295
3	2	26	1087.336	28270.736	0.013	0.329
4	2	26	1450.224	37705.824	0.019	0.494
5	2	26	1812.488	47124.697	0.020	0.529
6	2	26	2175.106	56552.756	0.022	0.572
7	2	26	2538.194	65993.044	0.028	0.728
1	2	52	150.850	7844.200	0.000	0.017
2	2	52	301.662	15686.441	0.000	0.000
3	2	52	452.589	23534.628	0.002	0.087
4	2	52	603.577	31386.004	0.001	0.035
5	2	52	754.424	39230.048	0.001	0.052
6	2	52	906.248	47124.896	0.002	0.104
7	2	52	1055.616	54892.032	0.004	0.208

Table B.11 Simulation results for wide-path AGV systems with onsite corrective maintenance when loading capacity is 3

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	3	1	12197.899	12197.899	4.897	4.897
2	3	1	24386.541	24386.541	9.833	9.833
3	3	1	36576.687	36576.687	14.756	14.756
4	3	1	48784.848	48784.848	19.604	19.604
5	3	1	60972.654	60972.654	24.582	24.582
6	3	1	73162.896	73162.896	29.538	29.538
7	3	1	85358.708	85358.708	34.274	34.274
1	3	2	6088.174	12176.348	2.254	4.508
2	3	2	12162.228	24324.456	4.538	9.076
3	3	2	18259.936	36519.872	6.744	13.488
4	3	2	24335.168	48670.336	8.996	17.992
5	3	2	30416.032	60832.064	11.260	22.520
6	3	2	36514.450	73028.900	13.446	26.892
7	3	2	42595.534	85191.068	15.866	31.732
1	3	3	4050.284	12150.852	1.342	4.026
2	3	3	8093.058	24279.174	2.688	8.064
3	3	3	12142.224	36426.672	4.054	12.162
4	3	3	16189.678	48569.034	5.424	16.272
5	3	3	20243.836	60731.508	6.792	20.376
6	3	3	24286.990	72860.970	8.080	24.240
7	3	3	28348.552	85045.656	9.394	28.182
1	3	4	3028.368	12113.472	0.940	3.760
2	3	4	6058.116	24232.464	1.862	7.448
3	3	4	9084.268	36337.072	2.808	11.232
4	3	4	12103.366	48413.464	3.784	15.136
5	3	4	15147.928	60591.712	4.598	18.392
6	3	4	18161.336	72645.344	5.608	22.432
7	3	4	21182.374	84729.496	6.594	26.376
1	3	6	2018.686	12112.116	0.394	2.364
2	3	6	4035.168	24211.008	0.842	5.052
3	3	6	6054.612	36327.672	1.238	7.428
4	3	6	8067.372	48404.232	1.666	9.996
5	3	6	10084.594	60507.564	2.072	12.432
6	3	6	12095.424	72572.544	2.552	15.312
7	3	6	14120.428	84722.568	2.888	17.328
1	3	12	988.785	11865.420	0.053	0.636
2	3	12	1977.519	23730.232	0.105	1.260
3	3	12	2965.268	35583.216	0.167	2.000
4	3	12	3949.722	47396.664	0.242	2.904
5	3	12	4940.092	59281.104	0.284	3.408
6	3	12	5930.534	71166.408	0.308	3.696
7	3	12	6920.048	83040.576	0.396	4.752
1	3	26	420.126	10923.267	0.004	0.104
2	3	26	838.966	21813.125	0.011	0.286
3	3	26	1259.736	32753.127	0.012	0.303
4	3	26	1679.553	43668.369	0.019	0.485
5	3	26	2099.948	54598.639	0.022	0.563
6	3	26	2519.556	65508.456	0.028	0.728
7	3	26	2939.072	76415.872	0.040	1.040
1	3	52	174.763	9087.693	0.001	0.035
2	3	52	349.517	18174.867	0.000	0.017
3	3	52	524.210	27258.937	0.001	0.069
4	3	52	698.858	36340.599	0.002	0.087
5	3	52	874.130	45454.743	0.000	0.017
6	3	52	1049.362	54566.824	0.002	0.104
7	3	52	1223.628	63628.656	0.000	0.000

Table B.12 Simulation results for wide-path AGV systems with onsite corrective maintenance when loading capacity is 4

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
5	4	3	22715.268	68145.804	6.660	19.980
6	4	3	27236.682	81710.046	8.174	24.522
7	4	3	31769.360	95308.080	9.506	28.518
1	4	4	3396.216	13584.864	0.918	3.672
2	4	4	6794.682	27178.728	1.846	7.384
3	4	4	10198.504	40794.016	2.792	11.168
4	4	4	13588.918	54355.672	3.714	14.856
5	4	4	16991.918	67967.672	4.640	18.560
6	4	4	20385.928	81543.712	5.588	22.352
7	4	4	23774.428	95097.712	6.512	26.048
1	4	6	2263.722	13582.332	0.426	2.556
2	4	6	4528.764	27172.584	0.864	5.184
3	4	6	6803.454	40820.724	1.234	7.404
4	4	6	9068.818	54412.908	1.718	10.308
5	4	6	11320.322	67921.932	2.158	12.948
6	4	6	13599.606	81597.636	2.514	15.084
7	4	6	15863.562	95181.372	2.938	17.628
1	4	12	1113.527	13362.324	0.050	0.600
2	4	12	2224.319	26691.824	0.127	1.528
3	4	12	3336.139	40033.664	0.180	2.156
4	4	12	4454.920	53459.040	0.196	2.352
5	4	12	5566.012	66792.144	0.270	3.240
6	4	12	6674.898	80098.776	0.366	4.392
7	4	12	7784.170	93410.040	0.470	5.640
1	4	26	473.329	12306.563	0.004	0.113
2	4	26	946.787	24616.453	0.007	0.173
3	4	26	1419.220	36899.729	0.016	0.416
4	4	26	1892.469	49204.185	0.015	0.390
5	4	26	2364.768	61483.977	0.023	0.598
6	4	26	2837.232	73768.032	0.028	0.728
7	4	26	3312.216	86117.616	0.026	0.676
1	4	52	196.746	10230.792	0.001	0.035
2	4	52	393.867	20481.101	0.000	0.000
3	4	52	590.474	30704.665	0.002	0.104
4	4	52	787.395	40944.523	0.004	0.191
5	4	52	983.807	51157.947	0.002	0.104
6	4	52	1181.436	61434.672	0.004	0.208
7	4	52	1377.876	71649.552	0.000	0.000
5	4	3	22715.268	68145.804	6.660	19.980
6	4	3	27236.682	81710.046	8.174	24.522
7	4	3	31769.360	95308.080	9.506	28.518
1	4	4	3396.216	13584.864	0.918	3.672
2	4	4	6794.682	27178.728	1.846	7.384
3	4	4	10198.504	40794.016	2.792	11.168
4	4	4	13588.918	54355.672	3.714	14.856
5	4	4	16991.918	67967.672	4.640	18.560
6	4	4	20385.928	81543.712	5.588	22.352
7	4	4	23774.428	95097.712	6.512	26.048
1	4	6	2263.722	13582.332	0.426	2.556
2	4	6	4528.764	27172.584	0.864	5.184
3	4	6	6803.454	40820.724	1.234	7.404
4	4	6	9068.818	54412.908	1.718	10.308
5	4	6	11320.322	67921.932	2.158	12.948
6	4	6	13599.606	81597.636	2.514	15.084
7	4	6	15863.562	95181.372	2.938	17.628
1	4	12	1113.527	13362.324	0.050	0.600

Table B.13 Simulation results for wide-path AGV systems with offsite corrective maintenance when loading capacity is 1

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	1	1	8016.842	8016.842	4.552	4.552
2	1	1	16016.932	16016.932	9.006	9.006
3	1	1	24081.456	24081.456	13.482	13.482
4	1	1	32114.462	32114.462	18.086	18.086
5	1	1	40138.686	40138.686	22.588	22.588
6	1	1	48260.758	48260.758	26.940	26.940
7	1	1	56180.322	56180.322	31.590	31.590
1	1	2	4035.038	8070.076	2.090	4.180
2	1	2	8031.280	16062.560	4.174	8.348
3	1	2	12093.420	24186.840	6.272	12.544
4	1	2	16101.240	32202.480	8.434	16.868
5	1	2	20173.186	40346.372	10.454	20.908
6	1	2	24166.454	48332.908	12.518	25.036
7	1	2	28195.344	56390.688	14.740	29.480
1	1	3	2702.180	8106.540	1.282	3.846
2	1	3	5397.034	16191.102	2.586	7.758
3	1	3	8074.862	24224.586	3.866	11.598
4	1	3	10811.184	32433.552	5.088	15.264
5	1	3	13488.526	40465.578	6.368	19.104
6	1	3	16168.288	48504.864	7.638	22.914
7	1	3	18896.614	56689.842	8.826	26.478
1	1	4	2027.670	8110.680	0.882	3.528
2	1	4	4051.876	16207.504	1.762	7.048
3	1	4	6093.480	24373.920	2.710	10.840
4	1	4	8102.518	32410.072	3.620	14.480
5	1	4	10117.514	40470.056	4.516	18.064
6	1	4	12181.968	48727.872	5.320	21.280
7	1	4	14162.192	56648.768	6.368	25.472
1	1	6	1381.322	8287.932	0.390	2.340
2	1	6	2750.404	16502.424	0.850	5.100
3	1	6	4144.996	24869.976	1.202	7.212
4	1	6	5518.020	33108.120	1.630	9.780
5	1	6	6884.744	41308.464	2.124	12.744
6	1	6	8284.896	49709.376	2.464	14.784
7	1	6	9645.510	57873.060	2.888	17.328
1	1	12	690.682	8288.184	0.046	0.552
2	1	12	1383.398	16600.776	0.114	1.368
3	1	12	2075.748	24908.976	0.180	2.160
4	1	12	2768.366	33220.392	0.246	2.952
5	1	12	3463.284	41559.408	0.288	3.456
6	1	12	4148.916	49786.992	0.386	4.632
7	1	12	4839.498	58073.976	0.440	5.280
1	1	26	295.834	7691.684	0.000	0.000
2	1	26	590.490	15352.740	0.010	0.260
3	1	26	886.430	23047.180	0.018	0.468
4	1	26	1182.038	30732.988	0.022	0.572
5	1	26	1477.770	38422.020	0.016	0.416
6	1	26	1772.216	46077.616	0.018	0.468
7	1	26	2069.460	53805.960	0.022	0.572
1	1	52	123.088	6400.576	0.000	0.000
2	1	52	246.200	12802.400	0.000	0.000
3	1	52	368.946	19185.192	0.000	0.000
4	1	52	492.674	25619.048	0.004	0.208
5	1	52	615.470	32004.440	0.000	0.000
6	1	52	737.686	38359.672	0.000	0.000
7	1	52	861.002	44772.104	0.004	0.208

Table B.14 Simulation results for wide-path AGV systems with offsite corrective maintenance when loading capacity is 2

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	2	1	9750.080	9750.080	4.512	4.512
2	2	1	19545.898	19545.898	9.026	9.026
3	2	1	29327.950	29327.950	13.452	13.452
4	2	1	39042.748	39042.748	18.058	18.058
5	2	1	48849.210	48849.210	22.618	22.618
6	2	1	58638.520	58638.520	27.138	27.138
7	2	1	68438.420	68438.420	31.484	31.484
1	2	2	4922.718	9845.436	2.102	4.204
2	2	2	9793.584	19587.168	4.220	8.440
3	2	2	14715.046	29430.092	6.264	12.528
4	2	2	19617.408	39234.816	8.344	16.688
5	2	2	24558.608	49117.216	10.438	20.876
6	2	2	29454.896	58909.792	12.578	25.156
7	2	2	34352.950	68705.900	14.624	29.248
1	2	3	3297.706	9893.118	1.252	3.756
2	2	3	6574.464	19723.392	2.554	7.662
3	2	3	9878.604	29635.812	3.816	11.448
4	2	3	13146.922	39440.766	5.088	15.264
5	2	3	16466.434	49399.302	6.344	19.032
6	2	3	19723.150	59169.450	7.614	22.842
7	2	3	22978.990	68936.970	9.000	27.000
1	2	4	2470.428	9881.712	0.896	3.584
2	2	4	4975.756	19903.024	1.732	6.928
3	2	4	7408.150	29632.600	2.682	10.728
4	2	4	9896.264	39585.056	3.576	14.304
5	2	4	12364.496	49457.984	4.464	17.856
6	2	4	14816.182	59264.728	5.490	21.960
7	2	4	17307.048	69228.192	6.306	25.224
1	2	6	1693.284	10159.704	0.394	2.364
2	2	6	3373.008	20238.048	0.820	4.920
3	2	6	5066.036	30396.216	1.190	7.140
4	2	6	6756.390	40538.340	1.636	9.816
5	2	6	8413.498	50480.988	2.122	12.732
6	2	6	10117.018	60702.108	2.498	14.988
7	2	6	11818.118	70908.708	2.838	17.028
1	2	12	846.258	10155.096	0.054	0.648
2	2	12	1698.358	20380.296	0.110	1.320
3	2	12	2547.402	30568.824	0.156	1.872
4	2	12	3391.950	40703.400	0.244	2.928
5	2	12	4234.814	50817.768	0.298	3.576
6	2	12	5086.812	61041.744	0.330	3.960
7	2	12	5937.118	71245.416	0.414	4.968
1	2	26	363.052	9439.352	0.000	0.000
2	2	26	725.150	18853.900	0.002	0.052
3	2	26	1086.428	28247.128	0.012	0.312
4	2	26	1448.946	37672.596	0.018	0.468
5	2	26	1812.902	47135.452	0.024	0.624
6	2	26	2174.736	56543.136	0.022	0.572
7	2	26	2535.342	65918.892	0.026	0.676
1	2	52	150.774	7840.248	0.000	0.000
2	2	52	301.992	15703.584	0.000	0.000
3	2	52	452.750	23543.000	0.002	0.104
4	2	52	603.404	31377.008	0.000	0.000
5	2	52	754.490	39233.480	0.000	0.000
6	2	52	905.456	47083.712	0.004	0.208
7	2	52	1056.474	54936.648	0.000	0.000

Table B.15 Simulation results for wide-path AGV systems with offsite corrective maintenance when loading capacity is 3

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	3	1	11298.640	11298.640	4.492	4.492
2	3	1	22560.104	22560.104	9.034	9.034
3	3	1	33821.142	33821.142	13.604	13.604
4	3	1	45062.484	45062.484	18.152	18.152
5	3	1	56425.520	56425.520	22.676	22.676
6	3	1	67794.514	67794.514	27.002	27.002
7	3	1	79016.402	79016.402	31.588	31.588
1	3	2	5676.732	11353.464	2.122	4.244
2	3	2	11364.152	22728.304	4.148	8.296
3	3	2	17011.848	34023.696	6.286	12.572
4	3	2	22705.512	45411.024	8.330	16.660
5	3	2	28359.660	56719.320	10.440	20.880
6	3	2	34027.888	68055.776	12.564	25.128
7	3	2	39761.966	79523.932	14.480	28.960
1	3	3	3806.434	11419.302	1.268	3.804
2	3	3	7574.302	22722.906	2.612	7.836
3	3	3	11381.702	34145.106	3.882	11.646
4	3	3	15214.682	45644.046	5.076	15.228
5	3	3	19021.306	57063.918	6.340	19.020
6	3	3	22782.326	68346.978	7.660	22.980
7	3	3	26627.960	79883.880	8.816	26.448
1	3	4	2846.572	11386.288	0.926	3.704
2	3	4	5739.306	22957.224	1.768	7.072
3	3	4	8592.086	34368.344	2.700	10.800
4	3	4	11399.694	45598.776	3.704	14.816
5	3	4	14275.190	57100.760	4.562	18.248
6	3	4	17149.276	68597.104	5.440	21.760
7	3	4	19980.972	79923.888	6.366	25.464
1	3	6	1952.212	11713.272	0.420	2.520
2	3	6	3894.424	23366.544	0.820	4.920
3	3	6	5860.802	35164.812	1.208	7.248
4	3	6	7809.990	46859.940	1.650	9.900
5	3	6	9748.882	58493.292	2.068	12.408
6	3	6	11696.174	70177.044	2.532	15.192
7	3	6	13681.300	82087.800	2.846	17.076
1	3	12	981.310	11775.720	0.060	0.720
2	3	12	1963.326	23559.912	0.110	1.320
3	3	12	2943.002	35316.024	0.184	2.208
4	3	12	3935.234	47222.808	0.230	2.760
5	3	12	4911.940	58943.280	0.304	3.648
6	3	12	5897.832	70773.984	0.320	3.840
7	3	12	6877.708	82532.496	0.404	4.848
1	3	26	419.694	10912.044	0.000	0.000
2	3	26	839.208	21819.408	0.018	0.468
3	3	26	1259.312	32742.112	0.012	0.312
4	3	26	1680.364	43689.464	0.018	0.468
5	3	26	2098.718	54566.668	0.020	0.520
6	3	26	2519.230	65499.980	0.032	0.832
7	3	26	2939.698	76432.148	0.032	0.832
1	3	52	174.594	9078.888	0.000	0.000
2	3	52	349.792	18189.184	0.000	0.000
3	3	52	524.472	27272.544	0.000	0.000
4	3	52	699.416	36369.632	0.000	0.000
5	3	52	873.766	45435.832	0.002	0.104
6	3	52	1048.634	54528.968	0.000	0.000
7	3	52	1224.382	63667.864	0.002	0.104

Table B.16 Simulation results for wide-path AGV systems with offsite corrective maintenance when loading capacity is 4

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year	Average Number of Failures Between Neighbouring Periodic Maintenance	Total Number of Failures per Year
1	4	1	12693.102	12693.102	4.552	4.552
2	4	1	25407.552	25407.552	9.002	9.002
3	4	1	38100.776	38100.776	13.494	13.494
4	4	1	50798.330	50798.330	18.034	18.034
5	4	1	63490.406	63490.406	22.554	22.554
6	4	1	76140.844	76140.844	27.114	27.114
7	4	1	88871.548	88871.548	31.586	31.586
1	4	2	6387.966	12775.932	2.094	4.188
2	4	2	12774.846	25549.692	4.146	8.292
3	4	2	19174.640	38349.280	6.178	12.356
4	4	2	25544.410	51088.820	8.302	16.604
5	4	2	31935.422	63870.844	10.464	20.928
6	4	2	38298.766	76597.532	12.488	24.976
7	4	2	44635.192	89270.384	14.656	29.312
1	4	3	4268.266	12804.798	1.298	3.894
2	4	3	8556.174	25668.522	2.572	7.716
3	4	3	12828.578	38485.734	3.800	11.400
4	4	3	17150.908	51452.724	4.970	14.910
5	4	3	21385.226	64155.678	6.334	19.002
6	4	3	25690.768	77072.304	7.566	22.698
7	4	3	29963.770	89891.310	8.900	26.700
1	4	4	3216.976	12867.904	0.892	3.568
2	4	4	6433.714	25734.856	1.778	7.112
3	4	4	9658.860	38635.440	2.726	10.904
4	4	4	12872.926	51491.704	3.642	14.568
5	4	4	16074.046	64296.184	4.570	18.280
6	4	4	19317.036	77268.144	5.366	21.464
7	4	4	22525.908	90103.632	6.276	25.104
1	4	6	2195.964	13175.784	0.400	2.400
2	4	6	4393.840	26363.040	0.830	4.980
3	4	6	6601.566	39609.396	1.198	7.188
4	4	6	8807.358	52844.148	1.616	9.696
5	4	6	11013.134	66078.804	2.010	12.060
6	4	6	13159.620	78957.720	2.580	15.480
7	4	6	15381.854	92291.124	2.830	16.980
1	4	12	1109.630	13315.560	0.042	0.504
2	4	12	2217.076	26604.912	0.102	1.224
3	4	12	3320.472	39845.664	0.166	1.992
4	4	12	4425.910	53110.920	0.232	2.784
5	4	12	5541.992	66503.904	0.256	3.072
6	4	12	6636.360	79636.320	0.354	4.248
7	4	12	7749.050	92988.600	0.398	4.776
1	4	26	472.132	12275.432	0.006	0.156
2	4	26	945.420	24580.920	0.012	0.312
3	4	26	1419.838	36915.788	0.016	0.416
4	4	26	1891.268	49172.968	0.022	0.572
5	4	26	2363.092	61440.392	0.020	0.520
6	4	26	2839.402	73824.452	0.026	0.676
7	4	26	3310.708	86078.408	0.038	0.988
1	4	52	196.766	10231.832	0.000	0.000
2	4	52	393.764	20475.728	0.002	0.104
3	4	52	590.962	30730.024	0.000	0.000
4	4	52	787.264	40937.728	0.004	0.208
5	4	52	984.250	51181.000	0.002	0.104
6	4	52	1180.678	61395.256	0.006	0.312
7	4	52	1377.910	71651.320	0.000	0.000

Table B.17 Simulation results for narrow-path AGV systems without corrective maintenance and backup AGVs when loading capacity is 1

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	1	1	1639.880	1639.880
2	1	1	3171.594	3171.594
3	1	1	4861.298	4861.298
4	1	1	6284.384	6284.384
5	1	1	7817.162	7817.162
6	1	1	9411.108	9411.108
7	1	1	10837.380	10837.380
1	1	2	1600.023	3200.047
2	1	2	3211.859	6423.719
3	1	2	4748.258	9496.516
4	1	2	6303.531	12607.062
5	1	2	7875.340	15750.681
6	1	2	9400.220	18800.440
7	1	2	10896.986	21793.972
1	1	3	1600.660	4801.980
2	1	3	3116.706	9350.118
3	1	3	4695.106	14085.318
4	1	3	6263.862	18791.586
5	1	3	7908.432	23725.296
6	1	3	9381.378	28144.134
7	1	3	10856.338	32569.014
1	1	4	1502.904	6011.616
2	1	4	3103.298	12413.192
3	1	4	4555.032	18220.128
4	1	4	6126.884	24507.536
5	1	4	7556.018	30224.072
6	1	4	9035.598	36142.392
7	1	4	10628.504	42514.016
1	1	6	1280.446	7682.676
2	1	6	2527.380	15164.280
3	1	6	3790.134	22740.804
4	1	6	4993.250	29959.500
5	1	6	6231.938	37391.628
6	1	6	7469.374	44816.244
7	1	6	8743.202	52459.212
1	1	12	689.212	8270.544
2	1	12	1361.642	16339.704
3	1	12	2038.596	24463.152
4	1	12	2699.114	32389.368
5	1	12	3361.430	40337.160
6	1	12	4016.780	48201.360
7	1	12	4660.354	55924.248

Table B.18 Simulation results for narrow-path AGV systems without corrective maintenance and backup AGVs when loading capacity is 2

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	2	1	1918.452	1918.452
2	2	1	3822.934	3822.934
3	2	1	5785.136	5785.136
4	2	1	7799.014	7799.014
5	2	1	9655.776	9655.776
6	2	1	11422.474	11422.474
7	2	1	13319.784	13319.784
1	2	2	1960.522	3921.044
2	2	2	3863.940	7727.880
3	2	2	5731.072	11462.144
4	2	2	7646.556	15293.112
5	2	2	9594.290	19188.580
6	2	2	11442.502	22885.004
7	2	2	13379.266	26758.532
1	2	3	1966.974	5900.922
2	2	3	3903.594	11710.782
3	2	3	5792.686	17378.058
4	2	3	7763.806	23291.418
5	2	3	9514.560	28543.680
6	2	3	11622.850	34868.550
7	2	3	13381.942	40145.826
1	2	4	1953.098	7812.392
2	2	4	3796.502	15186.008
3	2	4	5648.474	22593.896
4	2	4	7442.704	29770.816
5	2	4	9313.904	37255.616
6	2	4	11135.304	44541.216
7	2	4	12929.420	51717.680
1	2	6	1596.082	9576.492
2	2	6	3104.434	18626.604
3	2	6	4644.862	27869.172
4	2	6	6180.860	37085.160
5	2	6	7643.662	45861.972
6	2	6	9148.204	54889.224
7	2	6	10660.404	63962.424
1	2	12	850.172	10202.064
2	2	12	1676.250	20115.000
3	2	12	2492.250	29907.000
4	2	12	3308.144	39697.728
5	2	12	4105.418	49265.016
6	2	12	4904.842	58858.104
7	2	12	5694.942	68339.304

Table B.19 Simulation results for narrow-path AGV systems without corrective maintenance and backup AGVs when loading capacity is 3

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	3	1	2283.172	2283.172
2	3	1	4541.570	4541.570
3	3	1	6735.802	6735.802
4	3	1	8899.858	8899.858
5	3	1	11172.730	11172.730
6	3	1	13091.510	13091.510
7	3	1	15205.795	15205.795
1	3	2	2300.284	4600.568
2	3	2	4499.206	8998.412
3	3	2	6687.942	13375.884
4	3	2	8994.455	17988.910
5	3	2	11189.766	22379.532
6	3	2	13160.335	26320.670
7	3	2	15208.315	30416.630
1	3	3	2220.186	6660.558
2	3	3	4489.588	13468.764
3	3	3	6776.132	20328.396
4	3	3	8890.422	26671.266
5	3	3	10925.235	32775.705
6	3	3	13336.235	40008.705
7	3	3	15610.960	46832.880
1	3	4	2241.278	8965.112
2	3	4	4397.434	17589.736
3	3	4	6510.710	26042.840
4	3	4	8683.370	34733.480
5	3	4	10670.605	42682.420
6	3	4	12755.130	51020.520
7	3	4	14950.190	59800.760
1	3	6	1838.264	11029.584
2	3	6	3614.276	21685.656
3	3	6	5404.774	32428.644
4	3	6	7161.316	42967.896
5	3	6	8896.976	53381.856
6	3	6	10577.152	63462.912
7	3	6	12306.444	73838.664
1	3	12	982.892	11794.704
2	3	12	1939.426	23273.112
3	3	12	2889.014	34668.168
4	3	12	3819.120	45829.440
5	3	12	4750.018	57000.216
6	3	12	5675.168	68102.016
7	3	12	6587.984	79055.808

Table B.20 Simulation results for narrow-path AGV systems without corrective maintenance and backup AGVs when loading capacity is 4

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	4	1	2566.646	2566.646
2	4	1	5172.466	5172.466
3	4	1	7551.994	7551.994
4	4	1	10044.540	10044.540
5	4	1	12446.670	12446.670
6	4	1	14771.045	14771.045
7	4	1	17417.500	17417.500
1	4	2	2493.516	4987.032
2	4	2	5037.282	10074.564
3	4	2	7725.020	15450.040
4	4	2	9911.408	19822.816
5	4	2	12436.054	24872.108
6	4	2	14964.310	29928.620
7	4	2	17271.990	34543.980
1	4	3	2557.034	7671.102
2	4	3	5136.734	15410.202
3	4	3	7536.566	22609.698
4	4	3	9984.518	29953.554
5	4	3	12459.772	37379.316
6	4	3	14768.200	44304.600
7	4	3	17370.140	52110.420
1	4	4	2506.798	10027.192
2	4	4	4962.740	19850.960
3	4	4	7387.460	29549.840
4	4	4	9782.214	39128.856
5	4	4	12001.948	48007.792
6	4	4	14501.130	58004.520
7	4	4	16686.975	66747.900
1	4	6	2068.134	12408.804
2	4	6	4065.484	24392.904
3	4	6	6069.074	36414.444
4	4	6	8040.400	48242.400
5	4	6	9926.574	59559.444
6	4	6	11916.522	71499.132
7	4	6	13847.260	83083.560
1	4	12	1108.150	13297.800
2	4	12	2187.874	26254.488
3	4	12	3260.940	39131.280
4	4	12	4295.440	51545.280
5	4	12	5328.628	63943.536
6	4	12	6373.090	76477.080
7	4	12	7404.492	88853.904

Table B.21 Simulation results for narrow-path AGV systems without corrective maintenance but with one backup AGV when loading capacity is 1

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	1	1	3246.634	3246.634
2	1	1	4754.630	4754.630
3	1	1	6317.664	6317.664
4	1	1	7917.900	7917.900
5	1	1	9360.196	9360.196
6	1	1	10943.926	10943.926
7	1	1	12554.076	12554.076
1	1	2	3177.420	6354.839
2	1	2	4765.988	9531.976
3	1	2	6331.811	12663.622
4	1	2	7872.968	15745.936
5	1	2	9376.447	18752.895
6	1	2	11049.584	22099.168
7	1	2	12499.534	24999.068
1	1	3	2711.814	8135.442
2	1	3	4521.304	13563.912
3	1	3	6062.742	18188.226
4	1	3	7782.248	23346.744
5	1	3	9363.584	28090.752
6	1	3	10803.314	32409.942
7	1	3	12364.320	37092.960
1	1	4	2126.682	8506.728
2	1	4	3894.758	15579.032
3	1	4	5530.670	22122.680
4	1	4	7107.638	28430.552
5	1	4	8602.386	34409.544
6	1	4	10170.954	40683.816
7	1	4	11596.404	46385.616
1	1	6	1426.542	8559.252
2	1	6	2800.658	16803.948
3	1	6	4126.304	24757.824
4	1	6	5448.022	32688.132
5	1	6	6725.644	40353.864
6	1	6	8006.626	48039.756
7	1	6	9235.606	55413.636
1	1	12	697.300	8367.600
2	1	12	1380.740	16568.880
3	1	12	2057.746	24692.952
4	1	12	2722.292	32667.504
5	1	12	3391.760	40701.120
6	1	12	4053.404	48640.848
7	1	12	4707.286	56487.432

Table B.22 Simulation results for narrow-path AGV systems without corrective maintenance but with one backup AGV when loading capacity is 2

Number of AGV	**Loading Capacity**	**Times of Periodic Maintenance per Year**	**Average Number of Items Delivered Between Neighbouring Periodic Maintenance**	**Total Number of Items Delivered per Year**
1	2	1	3874.132	3874.132
2	2	1	5904.274	5904.274
3	2	1	7756.092	7756.092
4	2	1	9630.130	9630.130
5	2	1	11496.474	11496.474
6	2	1	13321.618	13321.618
7	2	1	15351.804	15351.804
1	2	2	3922.564	7845.128
2	2	2	5813.556	11627.112
3	2	2	7743.858	15487.716
4	2	2	9645.788	19291.576
5	2	2	11550.536	23101.072
6	2	2	13432.338	26864.676
7	2	2	15278.890	30557.780
1	2	3	3287.508	9862.524
2	2	3	5473.540	16420.620
3	2	3	7388.460	22165.380
4	2	3	9453.666	28360.998
5	2	3	11314.598	33943.794
6	2	3	13184.208	39552.624
7	2	3	15008.730	45026.190
1	2	4	2583.158	10332.632
2	2	4	4741.852	18967.408
3	2	4	6738.546	26954.184
4	2	4	8703.306	34813.224
5	2	4	10559.938	42239.752
6	2	4	12446.686	49786.744
7	2	4	14454.470	57817.880
1	2	6	1746.498	10478.988
2	2	6	3423.090	20538.540
3	2	6	5063.778	30382.668
4	2	6	6637.450	39824.700
5	2	6	8151.568	48909.408
6	2	6	9739.026	58434.156
7	2	6	11253.718	67522.308
1	2	12	854.650	10255.800
2	2	12	1690.714	20288.568
3	2	12	2517.226	30206.712
4	2	12	3332.036	39984.432
5	2	12	4144.872	49738.464
6	2	12	4949.252	59391.024
7	2	12	5749.776	68997.312

Table B.23 Simulation results for narrow-path AGV systems without corrective maintenance but with one backup AGV when loading capacity is 3

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	3	1	4596.458	4596.458
2	3	1	6793.630	6793.630
3	3	1	8910.380	8910.380
4	3	1	11186.192	11186.192
5	3	1	13258.640	13258.640
6	3	1	15468.415	15468.415
7	3	1	17598.040	17598.040
7	3	1	17598.040	17598.040
2	3	2	6738.240	13476.480
3	3	2	8920.835	17841.670
4	3	2	11040.810	22081.620
5	3	2	13512.204	27024.408
6	3	2	15557.600	31115.200
7	3	2	17609.040	35218.080
1	3	3	3830.750	11492.250
2	3	3	6341.830	19025.490
3	3	3	8625.076	25875.228
4	3	3	10912.460	32737.380
5	3	3	13219.420	39658.260
6	3	3	15233.145	45699.435
7	3	3	17401.215	52203.645
1	3	4	2990.252	11961.008
2	3	4	5536.252	22145.008
3	3	4	7842.700	31370.800
4	3	4	10030.745	40122.980
5	3	4	12299.945	49199.780
6	3	4	14467.275	57869.100
7	3	4	16382.830	65531.320
1	3	6	2017.658	12105.948
2	3	6	3959.246	23755.476
3	3	6	5826.666	34959.996
4	3	6	7655.844	45935.064
5	3	6	9475.000	56850.000
6	3	6	11260.212	67561.272
7	3	6	13024.276	78145.656
1	3	12	987.910	11854.920
2	3	12	1955.358	23464.296
3	3	12	2914.470	34973.640
4	3	12	3858.606	46303.272
5	3	12	4789.224	57470.688
6	3	12	5721.504	68658.048
7	3	12	6648.122	79777.464

Table B.24 Simulation results for narrow-path AGV systems without corrective maintenance but with one backup AGV when loading capacity is 4

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	4	1	5099.322	5099.322
2	4	1	7546.904	7546.904
3	4	1	10163.038	10163.038
4	4	1	12492.920	12492.920
5	4	1	15029.650	15029.650
6	4	1	17440.615	17440.615
7	4	1	20020.850	20020.850
1	4	2	5160.596	10321.192
2	4	2	7662.350	15324.700
3	4	2	10113.136	20226.272
4	4	2	12512.436	25024.872
5	4	2	15081.246	30162.492
6	4	2	17348.050	34696.100
7	4	2	19813.180	39626.360
1	4	3	4284.068	12852.204
2	4	3	7072.008	21216.024
3	4	3	9680.258	29040.774
4	4	3	12259.660	36778.980
5	4	3	14759.778	44279.334
6	4	3	17066.155	51198.465
7	4	3	19661.595	58984.785
1	4	4	3366.338	13465.352
2	4	4	6221.102	24884.408
3	4	4	8762.798	35051.192
4	4	4	11311.612	45246.448
5	4	4	13759.408	55037.632
6	4	4	16204.720	64818.880
7	4	4	18518.795	74075.180
1	4	6	2269.756	13618.536
2	4	6	4445.576	26673.456
3	4	6	6547.532	39285.192
4	4	6	8604.856	51629.136
5	4	6	10659.746	63958.476
6	4	6	12652.972	75917.832
7	4	6	14638.824	87832.944
1	4	12	1111.010	13332.120
2	4	12	2203.278	26439.336
3	4	12	3279.260	39351.120
4	4	12	4334.144	52009.728
5	4	12	5385.052	64620.624
6	4	12	6422.938	77075.256
7	4	12	7465.660	89587.920

Table B.25 Simulation results for narrow-path AGV systems without corrective maintenance but with two backup AGVs when loading capacity is 1

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	1	1	4829.610	4829.610
2	1	1	6428.156	6428.156
3	1	1	7850.350	7850.350
4	1	1	9493.666	9493.666
5	1	1	11011.168	11011.168
6	1	1	12375.496	12375.496
7	1	1	13978.794	13978.794
1	1	2	4148.690	8297.380
2	1	2	6335.047	12670.095
3	1	2	7929.835	15859.669
4	1	2	9436.194	18872.389
5	1	2	11027.209	22054.417
6	1	2	12499.000	24998.000
7	1	2	13990.382	27980.764
1	1	3	2874.756	8624.268
2	1	3	5390.382	16171.146
3	1	3	7271.372	21814.116
4	1	3	8918.458	26755.374
5	1	3	10612.576	31837.728
6	1	3	12233.884	36701.652
7	1	3	13787.096	41361.288
1	1	4	2151.238	8604.952
2	1	4	4226.584	16906.336
3	1	4	6064.910	24259.640
4	1	4	7813.318	31253.272
5	1	4	9441.524	37766.096
6	1	4	11050.066	44200.264
7	1	4	12542.088	50168.352
1	1	6	1426.986	8561.916
2	1	6	2833.694	17002.164
3	1	6	4199.966	25199.796
4	1	6	5556.006	33336.036
5	1	6	6896.734	41380.404
6	1	6	8199.210	49195.260
7	1	6	9504.130	57024.780
1	1	12	696.820	8361.840
2	1	12	1380.956	16571.472
3	1	12	2055.728	24668.736
4	1	12	2725.646	32707.752
5	1	12	3393.048	40716.576
6	1	12	4052.114	48625.368
7	1	12	4714.886	56578.632

Table B.26 Simulation results for narrow-path AGV systems without corrective maintenance but with two backup AGVs when loading capacity is 2

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	2	1	5938.980	5938.980
2	2	1	7946.936	7946.936
3	2	1	9657.908	9657.908
4	2	1	11498.806	11498.806
5	2	1	13407.714	13407.714
6	2	1	15344.436	15344.436
7	2	1	17120.722	17120.722
1	2	2	5058.478	10116.956
2	2	2	7686.990	15373.980
3	2	2	9698.958	19397.916
4	2	2	11516.615	23033.230
5	2	2	13604.808	27209.616
6	2	2	15268.476	30536.952
7	2	2	17256.342	34512.684
1	2	3	3499.604	10498.812
2	2	3	6583.756	19751.268
3	2	3	8934.618	26803.854
4	2	3	10990.026	32970.078
5	2	3	13018.426	39055.278
6	2	3	14857.902	44573.706
7	2	3	16500.735	49502.205
1	2	4	2622.968	10491.872
2	2	4	5151.350	20605.400
3	2	4	7426.424	29705.696
4	2	4	9521.510	38086.040
5	2	4	11553.994	46215.976
6	2	4	13501.040	54004.160
7	2	4	15366.450	61465.800
1	2	6	1744.140	10464.840
2	2	6	3460.904	20765.424
3	2	6	5134.294	30805.764
4	2	6	6795.634	40773.804
5	2	6	8407.030	50442.180
6	2	6	10007.484	60044.904
7	2	6	11558.798	69352.788
1	2	12	853.426	10241.112
2	2	12	1692.266	20307.192
3	2	12	2519.712	30236.544
4	2	12	3332.636	39991.632
5	2	12	4144.738	49736.856
6	2	12	4952.754	59433.048
7	2	12	5760.518	69126.216

Table B.27 Simulation results for narrow-path AGV systems without corrective maintenance but with two backup AGVs when loading capacity is 3

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	3	1	6721.346	6721.346
2	3	1	9090.470	9090.470
3	3	1	11337.366	11337.366
4	3	1	13349.774	13349.774
5	3	1	15600.366	15600.366
6	3	1	17763.375	17763.375
7	3	1	19909.110	19909.110
1	3	2	5860.270	11720.540
2	3	2	8899.606	17799.212
3	3	2	11266.855	22533.710
4	3	2	13211.550	26423.100
5	3	2	15748.316	31496.632
6	3	2	17709.870	35419.740
7	3	2	20107.110	40214.220
1	3	3	4029.964	12089.892
2	3	3	7610.858	22832.574
3	3	3	10195.478	30586.434
4	3	3	12631.992	37895.976
5	3	3	14848.090	44544.270
6	3	3	17204.470	51613.410
7	3	3	19520.090	58560.270
1	3	4	3029.192	12116.768
2	3	4	5943.050	23772.200
3	3	4	8586.072	34344.288
4	3	4	11029.215	44116.860
5	3	4	13348.835	53395.340
6	3	4	15424.275	61697.100
7	3	4	17855.690	71422.760
1	3	6	2019.828	12118.968
2	3	6	3997.058	23982.348
3	3	6	5928.262	35569.572
4	3	6	7832.400	46994.400
5	3	6	9712.960	58277.760
6	3	6	11556.062	69336.372
7	3	6	13350.274	80101.644
1	3	12	987.258	11847.096
2	3	12	1959.956	23519.472
3	3	12	2914.574	34974.888
4	3	12	3859.144	46309.728
5	3	12	4793.874	57526.488
6	3	12	5720.144	68641.728
7	3	12	6644.434	79733.208

Table B.28 Simulation results for narrow-path AGV systems without corrective maintenance but with two backup AGVs when loading capacity is 4

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	4	1	7822.142	7822.142
2	4	1	10005.830	10005.830
3	4	1	12629.222	12629.222
4	4	1	15000.912	15000.912
5	4	1	17429.774	17429.774
6	4	1	20007.065	20007.065
7	4	1	22264.450	22264.450
1	4	2	6534.364	13068.728
2	4	2	10078.952	20157.904
3	4	2	12566.764	25133.528
4	4	2	15116.576	30233.152
5	4	2	17519.916	35039.832
6	4	2	19870.005	39740.010
7	4	2	22611.550	45223.100
1	4	3	4527.566	13582.698
2	4	3	8574.502	25723.506
3	4	3	11640.508	34921.524
4	4	3	14253.370	42760.110
5	4	3	16850.766	50552.298
6	4	3	19419.495	58258.485
7	4	3	22120.005	66360.015
1	4	4	3397.464	13589.856
2	4	4	6675.956	26703.824
3	4	4	9616.382	38465.528
4	4	4	12373.224	49492.896
5	4	4	15011.460	60045.840
6	4	4	17387.890	69551.560
7	4	4	19856.185	79424.740
1	4	6	2274.450	13646.700
2	4	6	4482.212	26893.272
3	4	6	6658.400	39950.400
4	4	6	8804.702	52828.212
5	4	6	10876.666	65259.996
6	4	6	12959.432	77756.592
7	4	6	15041.114	90246.684
1	4	12	1113.570	13362.840
2	4	12	2204.828	26457.936
3	4	12	3279.220	39350.640
4	4	12	4335.456	52025.472
5	4	12	5389.616	64675.392
6	4	12	6424.730	77096.760
7	4	12	7463.350	89560.200

Table B.29 Simulation results for narrow-path AGV systems without corrective maintenance but with three backup AGVs when loading capacity is 1

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	1	1	6460.616	6460.616
2	1	1	7964.604	7964.604
3	1	1	9486.098	9486.098
4	1	1	11029.176	11029.176
5	1	1	12526.272	12526.272
6	1	1	14229.084	14229.084
7	1	1	15724.938	15724.938
1	1	2	4319.336	8638.671
2	1	2	7585.318	15170.635
3	1	2	9465.746	18931.493
4	1	2	11003.979	22007.957
5	1	2	12547.590	25095.181
6	1	2	14098.504	28197.008
7	1	2	15698.054	31396.108
1	1	3	2878.170	8634.510
2	1	3	5672.882	17018.646
3	1	3	8085.642	24256.926
4	1	3	10014.036	30042.108
5	1	3	11776.166	35328.498
6	1	3	13358.714	40076.142
7	1	3	14968.638	44905.914
1	1	4	2147.828	8591.312
2	1	4	4265.620	17062.480
3	1	4	6309.260	25237.040
4	1	4	8232.490	32929.960
5	1	4	9977.828	39911.312
6	1	4	11674.264	46697.056
7	1	4	13324.380	53297.520
1	1	6	1430.016	8580.096
2	1	6	2831.034	16986.204
3	1	6	4216.268	25297.608
4	1	6	5585.700	33514.200
5	1	6	6940.038	41640.228
6	1	6	8283.034	49698.204
7	1	6	9609.092	57654.552
1	1	12	284.422	3413.065
2	1	12	1381.252	16575.024
3	1	12	2057.668	24692.016
4	1	12	2725.664	32707.968
5	1	12	3392.210	40706.520
6	1	12	4051.832	48621.984
7	1	12	4711.840	56542.080

Table B.30 Simulation results for narrow-path AGV systems without corrective maintenance but with three backup AGVs when loading capacity is 2

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	2	1	7912.770	7912.770
2	2	1	9820.304	9820.304
3	2	1	11517.988	11517.988
4	2	1	13496.514	13496.514
5	2	1	15370.388	15370.388
6	2	1	17392.338	17392.338
7	2	1	19108.006	19108.006
1	2	2	5256.062	10512.124
2	2	2	9230.436	18460.872
3	2	2	11592.536	23185.072
4	2	2	13532.438	27064.876
5	2	2	15397.310	30794.620
6	2	2	17226.642	34453.284
7	2	2	19126.976	38253.952
1	2	3	3511.316	10533.948
2	2	3	6894.072	20682.216
3	2	3	9828.348	29485.044
4	2	3	12221.798	36665.394
5	2	3	14353.266	43059.798
6	2	3	16404.566	49213.698
7	2	3	18279.520	54838.560
1	2	4	2624.102	10496.408
2	2	4	5196.986	20787.944
3	2	4	7690.726	30762.904
4	2	4	10025.974	40103.896
5	2	4	12172.904	48691.616
6	2	4	14295.530	57182.120
7	2	4	16254.885	65019.540
1	2	6	1744.804	10468.824
2	2	6	3460.118	20760.708
3	2	6	5149.770	30898.620
4	2	6	6816.550	40899.300
5	2	6	8474.502	50847.012
6	2	6	10082.932	60497.592
7	2	6	11724.710	70348.260
1	2	12	852.742	10232.904
2	2	12	1692.060	20304.720
3	2	12	2518.658	30223.896
4	2	12	3335.272	40023.264
5	2	12	4148.654	49783.848
6	2	12	4951.162	59413.944
7	2	12	5753.972	69047.664

Table B.31 Simulation results for narrow-path AGV systems without corrective maintenance but with three backup AGVs when loading capacity is 3

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	3	1	9099.424	9099.424
2	3	1	11396.180	11396.180
3	3	1	13548.932	13548.932
4	3	1	15674.900	15674.900
5	3	1	17764.892	17764.892
6	3	1	20066.690	20066.690
7	3	1	22400.410	22400.410
1	3	2	6058.312	12116.624
2	3	2	10711.846	21423.692
3	3	2	13416.826	26833.652
4	3	2	15659.615	31319.230
5	3	2	17840.688	35681.376
6	3	2	19597.665	39195.330
7	3	2	22124.640	44249.280
1	3	3	4051.206	12153.618
2	3	3	7977.252	23931.756
3	3	3	11439.562	34318.686
4	3	3	14151.495	42454.485
5	3	3	16373.765	49121.295
6	3	3	18968.735	56906.205
7	3	3	21114.730	63344.190
1	3	4	3030.892	12123.568
2	3	4	6000.898	24003.592
3	3	4	8882.912	35531.648
4	3	4	11587.820	46351.280
5	3	4	14146.390	56585.560
6	3	4	16453.130	65812.520
7	3	4	18631.120	74524.480
1	3	6	2019.228	12115.368
2	3	6	3993.030	23958.180
3	3	6	5942.988	35657.928
4	3	6	7887.264	47323.584
5	3	6	9774.810	58648.860
6	3	6	11651.894	69911.364
7	3	6	13503.884	81023.304
1	3	12	987.436	11849.232
2	3	12	1955.866	23470.392
3	3	12	2911.694	34940.328
4	3	12	3857.424	46289.088
5	3	12	4792.426	57509.112
6	3	12	5722.108	68665.296
7	3	12	6643.228	79718.736

Table B.32 Simulation results for narrow-path AGV systems without corrective maintenance but with three backup AGVs when loading capacity is 4

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	4	1	10387.402	10387.402
2	4	1	12605.472	12605.472
3	4	1	15284.988	15284.988
4	4	1	17519.970	17519.970
5	4	1	19923.008	19923.008
6	4	1	22424.700	22424.700
7	4	1	24779.055	24779.055
1	4	2	6803.578	13607.156
2	4	2	12008.380	24016.760
3	4	2	15098.108	30196.216
4	4	2	17726.244	35452.488
5	4	2	19926.282	39852.564
6	4	2	22186.245	44372.490
7	4	2	24867.640	49735.280
1	4	3	4541.342	13624.026
2	4	3	8943.150	26829.450
3	4	3	12740.880	38222.640
4	4	3	15874.164	47622.492
5	4	3	18588.456	55765.368
6	4	3	21264.560	63793.680
7	4	3	23723.975	71171.925
1	4	4	3398.930	13595.720
2	4	4	6722.500	26890.000
3	4	4	9978.750	39915.000
4	4	4	12994.920	51979.680
5	4	4	15709.560	62838.240
6	4	4	18311.735	73246.940
7	4	4	20952.480	83809.920
1	4	6	2266.668	13600.008
2	4	6	4494.512	26967.072
3	4	6	6684.922	40109.532
4	4	6	8844.596	53067.576
5	4	6	10969.856	65819.136
6	4	6	13070.772	78424.632
7	4	6	15134.026	90804.156
1	4	12	1112.802	13353.624
2	4	12	2204.646	26455.752
3	4	12	3278.590	39343.080
4	4	12	4335.418	52025.016
5	4	12	5387.232	64646.784
6	4	12	6428.896	77146.752
7	4	12	7463.164	89557.968

Table B.33 Simulation results for narrow-path AGV systems without corrective maintenance but with four backup AGVs when loading capacity is 1

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	1	1	7726.184	7726.184
2	1	1	9671.110	9671.110
3	1	1	11121.782	11121.782
4	1	1	12544.486	12544.486
5	1	1	13992.444	13992.444
6	1	1	15812.530	15812.530
7	1	1	17092.586	17092.586
1	1	2	4327.918	8655.836
2	1	2	8317.969	16635.938
3	1	2	10755.999	21511.997
4	1	2	12540.766	25081.531
5	1	2	14075.772	28151.544
6	1	2	15763.926	31527.852
7	1	2	17100.210	34200.420
1	1	3	2878.106	8634.318
2	1	3	5697.716	17093.148
3	1	3	8419.326	25257.978
4	1	3	10714.332	32142.996
5	1	3	12690.634	38071.902
6	1	3	14478.204	43434.612
7	1	3	16183.670	48551.010
1	1	4	2147.852	8591.408
2	1	4	4263.698	17054.792
3	1	4	6351.252	25405.008
4	1	4	8396.364	33585.456
5	1	4	10306.730	41226.920
6	1	4	12159.806	48639.224
7	1	4	13852.212	55408.848
1	1	6	1427.938	8567.628
2	1	6	2831.074	16986.444
3	1	6	4217.236	25303.416
4	1	6	5588.350	33530.100
5	1	6	6955.212	41731.272
6	1	6	8313.436	49880.616
7	1	6	9647.190	57883.140
1	1	12	695.906	8350.872
2	1	12	1379.654	16555.848
3	1	12	2057.590	24691.080
4	1	12	2724.834	32698.008
5	1	12	3392.814	40713.768
6	1	12	4058.524	48702.288
7	1	12	4715.406	56584.872

Table B.34 Simulation results for narrow-path AGV systems without corrective maintenance but with four backup AGVs when loading capacity is 2

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	2	1	9563.152	9563.152
2	2	1	11774.968	11774.968
3	2	1	13584.336	13584.336
4	2	1	15624.352	15624.352
5	2	1	17196.284	17196.284
6	2	1	19263.000	19263.000
7	2	1	20990.622	20990.622
1	2	2	5279.048	10558.096
2	2	2	10136.912	20273.824
3	2	2	13257.955	26515.910
4	2	2	15354.615	30709.230
5	2	2	17118.836	34237.672
6	2	2	19213.580	38427.160
7	2	2	20826.168	41652.336
1	2	3	3511.266	10533.798
2	2	3	6954.802	20864.406
3	2	3	10218.934	30656.802
4	2	3	13081.684	39245.052
5	2	3	15436.784	46310.352
6	2	3	17600.524	52801.572
7	2	3	19870.868	59612.604
1	2	4	2622.602	10490.408
2	2	4	5200.768	20803.072
3	2	4	7738.032	30952.128
4	2	4	10221.140	40884.560
5	2	4	12548.662	50194.648
6	2	4	14822.685	59290.740
7	2	4	16843.140	67372.560
1	2	6	1746.666	10479.996
2	2	6	3457.600	20745.600
3	2	6	5146.402	30878.412
4	2	6	6817.332	40903.992
5	2	6	8479.334	50876.004
6	2	6	10121.402	60728.412
7	2	6	11769.120	70614.720
1	2	12	853.304	10239.648
2	2	12	1691.638	20299.656
3	2	12	2516.132	30193.584
4	2	12	3333.324	39999.888
5	2	12	4147.162	49765.944
6	2	12	4953.846	59446.152
7	2	12	5753.856	69046.272

Table B.35 Simulation results for narrow-path AGV systems without corrective maintenance but with four backup AGVs when loading capacity is 3

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	3	1	11063.884	11063.884
2	3	1	13610.818	13610.818
3	3	1	15747.334	15747.334
4	3	1	17834.546	17834.546
5	3	1	19922.574	19922.574
6	3	1	22248.900	22248.900
7	3	1	24269.080	24269.080
1	3	2	6079.322	12158.644
2	3	2	11695.886	23391.772
3	3	2	15289.615	30579.230
4	3	2	17775.918	35551.836
5	3	2	19961.880	39923.760
6	3	2	21877.105	43754.210
7	3	2	24588.630	49177.260
1	3	3	4043.572	12130.716
2	3	3	8019.344	24058.032
3	3	3	11822.960	35468.880
4	3	3	15123.750	45371.250
5	3	3	17891.060	53673.180
6	3	3	20261.925	60785.775
7	3	3	22870.000	68610.000
1	3	4	3030.556	12122.224
2	3	4	6004.038	24016.152
3	3	4	8929.262	35717.048
4	3	4	11766.020	47064.080
5	3	4	14475.115	57900.460
6	3	4	17053.575	68214.300
7	3	4	19444.240	77776.960
1	3	6	2015.574	12093.444
2	3	6	3993.940	23963.640
3	3	6	5950.430	35702.580
4	3	6	7874.260	47245.560
5	3	6	9786.810	58720.860
6	3	6	11667.726	70006.356
7	3	6	13548.272	81289.632
1	3	12	988.540	11862.480
2	3	12	1958.526	23502.312
3	3	12	2914.746	34976.952
4	3	12	3854.778	46257.336
5	3	12	4797.670	57572.040
6	3	12	5723.674	68684.088
7	3	12	6643.286	79719.432

Table B.36 Simulation results for narrow-path AGV systems without corrective maintenance but with four backup AGVs when loading capacity is 4

Number of AGV	Loading Capacity	Times of Periodic Maintenance per Year	Average Number of Items Delivered Between Neighbouring Periodic Maintenance	Total Number of Items Delivered per Year
1	4	1	12441.258	12441.258
2	4	1	15270.758	15270.758
3	4	1	17735.890	17735.890
4	4	1	20042.178	20042.178
5	4	1	22503.424	22503.424
6	4	1	24785.110	24785.110
7	4	1	27120.495	27120.495
1	4	2	6820.912	13641.824
2	4	2	13160.412	26320.824
3	4	2	17122.968	34245.936
4	4	2	19936.028	39872.056
5	4	2	22607.648	45215.296
6	4	2	24442.750	48885.500
7	4	2	27275.460	54550.920
1	4	3	4539.166	13617.498
2	4	3	8974.076	26922.228
3	4	3	13241.388	39724.164
4	4	3	16973.132	50919.396
5	4	3	20078.568	60235.704
6	4	3	22729.005	68187.015
7	4	3	25360.650	76081.950
1	4	4	3397.416	13589.664
2	4	4	6734.948	26939.792
3	4	4	9999.990	39999.960
4	4	4	13193.536	52774.144
5	4	4	16243.642	64974.568
6	4	4	19141.340	76565.360
7	4	4	21838.120	87352.480
1	4	6	2267.216	13603.296
2	4	6	4492.886	26957.316
3	4	6	6675.612	40053.672
4	4	6	8836.118	53016.708
5	4	6	10985.378	65912.268
6	4	6	13088.510	78531.060
7	4	6	15198.598	91191.588
1	4	12	1112.288	13347.456
2	4	12	2203.062	26436.744
3	4	12	3279.502	39354.024
4	4	12	4338.000	52056.000
5	4	12	5386.318	64635.816
6	4	12	6426.212	77114.544
7	4	12	7461.848	89542.176