Agent-Based Material Transportation Scheduling of AGV Systems and Its Manufacturing Applications

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List of Abbreviations

AGV	Automated Guided Vehicle
FMS	Flexible Manufacturing System
MAS	Multi Agent System
HMS	Holonic Manufacturing System
MTS	Material Transportation System
FIPA	Foundation of Intelligent Physical Agents
DAI	Distributed Artificial Intelligence
AGVA	AGV Agent
MA	Machine Agent
TA	Monitor and Coordinate Agent
CNP	Contract Net Protocol
CFP	Call for Proposals
VRP	Vehicle Routing Problem
CA	Combinatorial Auctions
BGP	Bid Generation Problem
WDP	Winner Determination Problem
MIP	Mixed Integer Programming
DES	Discrete Event Simulation
RSM	Response Surface Methodology
ANOVA	Analysis of Variance
NOV	Number of Vehicle
CAP	Vehicle loading capacity
STH	System Throughput
MFT	Mean Flow Time
FLT	Percentage of Fully Loaded Travel
PWT	Pickup Waiting Time
ETDT	Effective Total Distance Travel

Abstract

The impacts of market and supply-chain globalizations have led not only to the increasingly demanding customers but also stiffer competition and fluctuating market. In order to adapt into such scenarios, an advanced manufacturing system needs to incorporate Agile Manufacturing paradigm that will enable the system to exploit dynamic factors in a timely manner. In addressing those requirements, there is a trend of employing distributed architecture to control manufacturing operation. One of the best concepts to explain distributed architecture is Holonic Manufacturing System (HMS) that can be realized by using Multi Agent System (MAS) technology.

The central focus of this research is to propose an efficient scheduling method for dynamic and autonomous Material Transportation System (MTS) based on MAS architecture. Automated Guided Vehicle System (AGVS) is used as a working example for MTS. Several substantial research problems have been studied in the thesis. (i) Existing task assignment protocol does not consider dynamism of AGV operation. This prevents the entity from making optimal assignment thus resulting in underperformance of the entire system. This is addressed in Chapter 4; (ii) Existing researches on distributed task assignment don't contemplate the deployment of vehicle with multiple-loading capacity. This is discussed in Chapter 5; (iii) Most of the research models for AGV system design used simplified cases for evaluation. In order to design a realistic distributed AGV operation, it is necessary to consider a realistic production environment with multiple performance objectives. This is addressed in Chapter 6.

The effectiveness of the proposed method is evaluated using worked example and realistic case study. The results show that the proposed method can yield better performance compared to the conventional method.

Acknowledgement

First of all, I would like to dedicate my gratitude to my research advisor, Professor Tomohiro Murata, for his priceless supervision and guidance during my Doctoral program. In addition to his knowledgeable advices, Professor Murata has also been very kind, supportive, open-minded and patience in supervising the research work. It is an honor to have spent 3½ years studying in his Laboratory.

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Chapter 1

Introduction

1.1 Background and Motivation

The changing natures of market demand and supply chain due to globalization factor have driven the economics and industrial organizations worldwide to enhance their competitiveness. Nowadays, manufacturing industries face stiff competition from around the globe. This forces the industrial enterprises to increase production efficiency as well as to have flexibility in coping with dynamic demand changes and fluctuations which can be attributed as an agile manufacturing system. Moreover, with the increasing needs for an organization to operate worldwide, each of the manufacturing subsidiaries must be given certain degree of autonomy for decision making particularly to deal with local issues. Common manufacturing sectors that need to deal with the scenarios include automotive and semiconductor sectors.

For years, organizations are utilizing centralized architecture to control their manufacturing systems. One of the main advantages of centralized architecture is that it could provide global optimization capability as decisions are made based on system-wide information. However, there are several notable drawbacks of centralized control system particularly when dealing with dynamic and stochastic manufacturing environments. As it needs system-wide information, this architecture typically requires long computational time that may not be feasible for real-time system especially in dealing with unexpected events such as express jobs order or resource failures.

Furthermore, centralized controller occasionally reacts sensitively to information updates. Thus, minor information changes of system variables could have impact on schedules of other entities resulting in high system nervousness.

In order to overcome the limitations of a monolithic system, there is an increasing trend that researchers and practitioners to employ decentralized architecture to control manufacturing operation. This is due to the fact that decentralized control architecture possesses certain advantages over centralized approach. Decentralized control architecture typically requires lower computational effort, contains multiple decision-making entities that eliminate single-node system failure weakness and provide parallel information processing capability. In realizing the concept, there are many implementation methodologies proposed to realize decentralized industrial control system.

There are some concepts that can be referred to implement decentralized manufacturing control architecture. One of the widely-used concepts is Holonic Manufacturing System (HMS) [1]. In employing HMS, specific manufacturing system could be decomposed into independent functional components. Motivations in adopting holonic paradigm to control manufacturing system come from the benefits attained by holonic characteristics within living organization which include stability in facing disturbance and adaptability in managing changes [1], [2]. Among recent researches related to HMS could be found in several papers [3], [4], [5].

Material transportation is one of the most critical functional components in manufacturing system. It is due to the reasons that customers are demanding for shorter delivery time, lower transportation charge and higher service reliability. This put the organizations under continuous pressure to implement various operational approaches and policies to achieve both aims. Among the recent approaches taken are having smaller transportation batch size and higher delivery frequencies. Furthermore, there is also an increasing demand for company to be adaptive in accommodating dynamic factors such as express transportation request for high-priority order and arrangement rescheduling in a real-time manner. This drives the company to have high system reliability so as to smoothly realize scheduled transportation plan.

Considering broader perspectives of Material Transportation System (MTS), there is also a trend of recent researches employing distributed control architecture in addressing those transportation requirements [6], [7], [8]. In employing distributed-controlled MTS, each transportation entity could have the autonomy in making decision to accomplish its job. To a certain degree, this successfully provides flexibility attribute for the system. Nevertheless, the main drawback of distributed control MTS is that it can't provide competitive system performance compared to the centralized approach. It is due to the fact that decision-making in a distributed system normally is being made based on local information. This restricts the decision-maker from searching the global optimum solution.

As such, it is necessary to establish efficient cooperative distributed problem solving mechanism in order to improve the entire performance. Contract Net Protocol (CNP) is a prominent task-sharing protocol for distributed control architecture due to its capability in supporting high-level communication and does not require complex computational requirement. Nevertheless, the protocol does not fully accommodate dynamic factors within MTS operation planning and scheduling thus leading to un-optimized performance. This brings the need to customize the conventional protocol so as to increase the MTS performance.

1.2 General Research Aims

In order to establish an effective material transportation system, it is necessary to identify important aims need to be achieved. General research aims intended to be addressed are:

- To determine generic functional attributes required to establish advanced vehicle-based MTS. These are critical in designing appropriate system architecture and functionality in order to fulfill the requirements.
- To establish decentralized Material Transportation System consists of autonomous transportation entities based on Multi-Agent System

(MAS) architecture. By employing MAS, each of the transportation entities could be represented by an intelligent agent so as to provide them with decision-making capability.

- To model the operation of autonomous Automated Guided Vehicles (AGVs) in manufacturing workplace as working examples. Specific focus is given on the establishment of working architecture and the problem solving and optimization mechanism.
- To investigate and identify current technical limitations of distributed-controlled AGVs operation in achieving competitive performance and to propose appropriate methodologies to solve existing limitations.
- To analyze the efficiency of proposed methods in comparison to the conventional methods. As the main concern of distributed control architecture is regarding its performance, comparison will take into account the resulting performance of the proposed methodologies.

The following chapters will provide discussion on how the stated goals are going to be accomplished.

1.3 Research Goals

The central goal of this research is to develop an efficient material transportation scheduling method for autonomous AGVs based on Multi Agent System architecture taking into account generic requirements and general research aims of an advanced AGV system.

The proposed system takes inspiration from the HMS concept that highlights the advantages of a distributed control system. In order to realize the proposal, manufacturing environments are selected as the case applications. The goal has been decomposed into three main objectives as the following:

G1) To propose an efficient multi agents architecture and fundamental communication protocol that are capable to accommodate dynamic transportation factors. This could be realized by enabling each of the decision makers (DM) to allow multiple-round bidding process and distinguish potential vehicle candidates based on their respective locations. In order to testify that the established MAS architecture could provide competitive performance, analysis was conducted to measure the resulting performance when the proposed method is implemented. Detail discussion is included in Chapter 4.

G2) One of the critical and difficult aspects in managing decentralized-controlled MTS is regarding the transportation scheduling procedure. The scheduling problem increases when each of the vehicles is equipped with multiple-loading capacity i.e. the ability to carry aboard multiple transportation loads. Optimizing such problem can be categorized under combinatorial optimization problem. In distributed control architecture, one of the highly potential techniques is the market-based auction algorithm. The proposal to achieve the objective is provided in Chapter 5.

G3) Simulation approach is a suitable way to demonstrate the effectiveness of a proposed idea in a realistic manufacturing workplace. The main goal of the study is to determine the best combination of number of vehicle, vehicle loading capacity and job arrival rate for a manufacturing system to achieve critical objective function. This could be realized by utilizing both Discrete Event Simulation (DES) and Response Surface Methodologies (RSM) methods. While DES could be used to obtain the resultants of specific combination of design parameters, RSM could be used to analyse the relationships between the parameters and related response variables. This shortcoming is elaborated in Chapter 6.

1.4 Dissertation Organization

This dissertation is organized into seven chapters.

Chapter 1 presents an overview for the study. This includes research background and motivation. Moreover, key research aims were explained and consequently general research goals were constituted. Besides, dissertation organization is also clarified in this chapter.

Chapter 2 provides a literature review on the theoretical components required to accomplish research objectives. These include overview on i)

MTS for manufacturing industry; ii) AGV technology; iii) MAS technology; iv) Contract Net Protocol (CNP); and v) Combinatorial Auctions (CA) method.

Chapter 3 states the functionality requirements for advanced AGV that this thesis intends to address. Key technical problems were then identified. Accordingly, AGV control architecture based on MAS architecture was proposed.

Chapter 4 addresses the protocol to manage two important dynamic factors in AGVs operation. The factors are dynamic status of vehicle availability and the positioning advantage of certain vehicles in handling a particular transportation request. In addressing both factors, an Improved Contract Net Protocol (ICNP) mechanism has been proposed. Experiments have been carried out to demonstrate the effectiveness of the proposed protocol where three important transportation–related performance indicators were measured. Variations of number of AGV are used and the result proves that the ICNP outperformed Standard CNP (SCNP) method significantly.

Chapter 5 proposes a market-based method to schedule a group of autonomous AGVs with multiple-loading capacity. The main goal is to overcome the weakness of conventional auction where only one job could be allocated in a single auction. Main problem inherits combinatory attributes and were decomposed into several sub-problems. Knapsack problem model was utilized to formalize AGV's capacity utilization. Meanwhile, combinatorial auctions mechanism was used in order to realize the task assignment protocol for the multi-load AGV scheduling. The functions have been divided into three components: bid generation, winner determination and auction coordination. Mixed Integer Programming (MIP) is used to obtain the solution.

Performance analyses of AGV with 3-, 5- and 7-loading capacities have been carried out with variation of number of AGV. The result depicts that the proposed method could enable multi-load AGV to yield competitive system performance. Deployment of vehicle with bigger loading capacity directly contributes to improve throughput and waiting time.

Chapter 6 presents the simulation of the proposed AGV system for a realistic manufacturing operation. The main goal is to provide an effective tool to design AGV operational system. The problem is defined as to determine the best combination of AGV design variables (number of vehicle and vehicle loading capacity) in delivering transportation requests to achieve desired target performance. The experiment case is based on data of a tire manufacturing factory involving multiple transportation objectives:

i) Mean flow time.

ii) Average pickup waiting time.

iii) Total distance travelled.

In optimizing the performance, combination of Discrete Event Simulation and Response Surface Methodology (RSM) were employed. The result obtained shows that determining proper variables combination is critical to acquire desired level of performance particularly when plural conflicting objectives were involved. Deliverable of this chapter includes the fleet-sizing decision support mechanism to design an AGV system.

Chapter 7 summarizes the thesis by discussing the novelty and contribution of the study particularly on the implementation of autonomous multi-load AGVs. Additionally, this chapter also includes possible future research directions.

Chapter 2

Literature Review and Problems Description

There are continuous debates on the implementation of centralized and distributed MTS within production systems. Centralized control possesses major disadvantage in terms of the required computational effort as the central controller is the bottleneck of the system's information processing, which occasionally is inefficient in terms of amount of computation and communication. Nevertheless, distributed control does not bound to this disadvantage as decision-making could be carried out in distributed and parallel manner. However, it typically results in suboptimal performance as decision is made only based on local information.

In addressing the issue, there is an increasing trend that researchers in Distributed Artificial Intelligence (DAI) discipline were recently investigating the potential of non-engineering methods to solve distributed resource allocation problem. Subsequently, the methods could be combined with more established engineering method.

This chapter focuses on the technologies need to be studied in order to establish an autonomous AGV system. This chapter provides the research background and discusses on the theoretical aspects needed to develop an efficient material transportation schedule. These include the overviews on MTS for manufacturing industry, AGV technology, MAS technology, Contract Net Protocol (CNP) and Combinatorial Auctions methods.

2.1 Realizing Distributed Control Paradigm using Holonic Manufacturing System

2.1.1 Introduction of Holonic Manufacturing System

Holon is basically derived from Greek words defined as something that is simultaneously a whole and a part. The term was coined as a mean to explain the hybrid nature of sub-wholes in a realistic system. Aspired by the proposed concept, Holonic Manufacturing System was originated under the framework of the Intelligent Manufacturing System (IMS) programme [9].

Almost inseparable, Product-Resource-Order-Staff Architecture (PROSA) [1] is typically used as the reference architecture for HMS. When it was first designed, the main goal is to provide manufacturing industry the benefits that holonic organization gives to living organisms such as adaptability, stability in confronting disturbance and efficient use of available resources. Aside from PROSA, another well-known reference architecture for HMS is known as ADACOR [2].

2.1.2 Holonic Manufacturing System Architecture

Inspired by the concept of having autonomous agents representing functional entities in a manufacturing system, HMS was established mainly to provide high autonomy, flexibility, reliability and modularity for a manufacturing system.

The uniqueness of HMS is that it is capable to combine the features of both hierarchical and heterarchical organizational structures. Furthermore, in parallel with the definition, holonic system provides a concept of an evolving system where HMS can facilitates the understanding and development of complex systems from simple components.

With regards to the PROSA architecture, a manufacturing system can be divided into three main holons as also shown in Fig. 2.1:

i) *resource holon* – consists of production resources (e.g.: machines, material handling, tools, equipments, personnel, floor space etc.) and the information processing needed to control the resources.

Resource holon comprises of both manufacturing system and the manufacturing control system.

ii) *product holon* – contains the information on products and respective processes needed in producing the goods. This includes product engineering design, product lifecycle, bill of materials etc.

iii) *order holon* – comprises of production jobs in the system. The holon manages the physical products being produced and the corresponding logistical information. *Order holon* may represents customer orders, maintenance orders, repair orders etc.

Meanwhile ADACOR architecture divided manufacturing system into: i) *product holon*; ii) *task holon*; iii) *supervisor holon*; and iv) *operational holons* [2]. As the ADACOR's product, task and operational holons share similarities to the PROSA's product, order and resource holons, its supervisor holon is responsible for holon coordination and conflict resolution. Since introduced, both PROSA and ADACOR reference architectures have been picked by numerous researches in proposing autonomous manufacturing system [3], [4].

It is commonly accepted that material transportation is one of the important components of a manufacturing system. Due to their importance, PROSA architecture included *AGV-fleet* and *Conveyor* holons as examples to carry out material transportation jobs [1]. Meanwhile, ADACOR stated more generalized *Transporter Resources* holon as part of the Operational Holon [2].

Some of the recent researches related to material transportation based on HMS architecture could be found in several papers [3], [5], [10]. This research focuses on developing Material Transportation Holon that operates within the HMS framework.

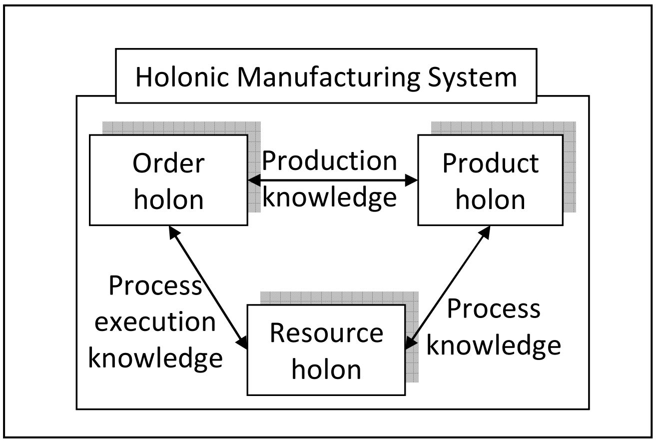

Fig. 2.1. Basic components of Holonic Manufacturing System [1]

2.2 Deployment of Automated Guided Vehicle (AGV) as MTS in Manufacturing Industry

2.2.1 MTS for Manufacturing Industry

MTS refers to any system developed specifically to satisfy transport requests in moving materials from one location to another location. MTS may consist of a set of transportation equipment. There are several categories of transportation equipment typically employed in a manufacturing facility based on their attributes as illustrated in Fig. 2.2.

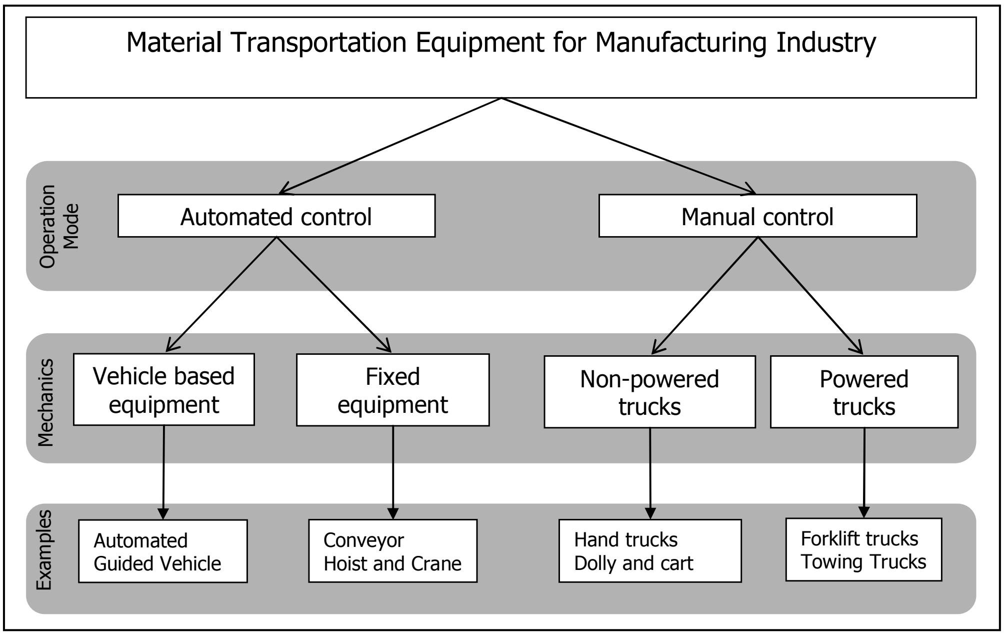

Fig. 2.2. Category of Material Transportation Equipment

Due to their different characteristics, each of the equipment could provide best performance under several different conditions. As such, it is critical to determine the best equipment to suit specific set of transportation requirements. Table 2.1 provides the suitability examples of the transportation equipment with regard to different type of shop floor layouts.

Table 2.1. Types of MTS equipment associated with factory layout [11].

Layout type	Characteristics	Typical Material Handling Equipment
Process	Variation in products & processing, low to medium production	Manual hand truck, forklift truck
	Variation in products & processing, medium to high production	Forklift truck, AGV
Product	Limited product variety, high production rate	Product flow: conveyors Incoming/ outgoing: AGV
Cellular	Variation in products & processing, low to medium production	Hand truck, forklift truck
	Variation in products & processing, medium to high production	Forklift truck, AGV
Fixed Position	Large product size, low production rate	Crane, hoist, industrial truck

Moreover, with regards to the research scope, there are several conditions of which AGV may become the best transportation equipment in a specific environment. Among the conditions are:

- Production with low to medium amount of transportation requirements.

  Fixed path conveyor typically used to cater the needs of high transport requirements. As such, in cases where the requirements are in the low to medium range, an AGV system will suit well. Meanwhile, manually operated equipment is suitable for very low throughput.

- Shop floor with flexible layout requirement.

  Whenever a factory required a flexible shop floor particularly is the layout is subject to expansion or constant change, an AGV system might be the best solution. This is due to the fact that AGV system is more adaptable to change compared to the other fixed equipment.

- Shop floor with process-based layout.

  Factory with a process-based layout group the machineries based on their processing functionalities. Process-based layout is typically utilized to produce high variation products in low or medium quantities. Due to both the high product variation and their respective quantities, AGV is a preferred material transportation option.

- Relatively long transportation distance.

  Another factor affecting the selection of transportation equipment is the transportation distance. AGV is suitable for long distance transportation. In cases where distances between pickup and delivery nodes are more than 60 meters, AGV could operate efficiently [12].

AGV is a general term of transport equipment that refers to the utilization of driverless vehicle use to move materials from a station to another without human intervention. There are several general types of AGV typically used in a manufacturing and warehouse facilities which include:

- Tow AGV – also known as Tugger AGV that pulls non-driven wheeled carts containing transport loads. Often regarded as the most productive form of AGV.
- Unitload AGV – is the form of traditional AGV where loads are put on top of the vehicle. Roller conveyor is frequently installed on the vehicle to facilitate handling process.
- Forklift AGV – is a vehicle with forklift equipment. It is regarded as the most versatile AGV.

- Customized AGV – that is built to suit specific conditions such as Clamp AGV and the low-cost Automated Guided Cart.

Recently, numerous AGVs have been developed to transport products with various weight and size ranges. These include small-sized product such as mails [13] as well as heavy and large cargo container [14]. Thus, product size is not a major constraint in opting for AGV over the other equipment as the main transportation equipment.

2.2.2 Overview on AGV Technologies

Upon having the background idea and understand the AGV utilization, there is a need to identify the technologies needed to establish an AGV operation. There are several technologies need to be considered. The technological aspects involve are:

i) Physical design aspect.

ii) Operational design aspect.

Among the important components for physical design are vehicle design, navigational technology, communication facilities and control architecture.

Vehicle design concerns with how the AGV should be physically built particularly from mechanical and electrical/ electronic point of views. In designing the vehicle, there are many aspects need to be taken into account such as expected payload, vehicle control system, safety mechanism, utilization rate, automation integration and so on.

Control and communication facilities design is the manifestation of the control architecture for the transportation system. Analyzing the needs to have appropriate control architecture (e.g.: centralized, distributed control etc.) will result in requiring of different technology for communication and information exchange.

Navigational technology is another aspect need to be carefully designed. Among the matters need to be addressed include traffic control, navigation track/ guide and safety requirement.

With regards to the navigation track, there are two available approaches:

i) Fixed path – traditionally, fixed paths are installed on or beneath the floor to guide AGV navigation. Some of fixed path technologies are guide tape, laser target navigation, gyroscopic navigation and wired sensors.

ii) Flexible path – currently, with the advancement of camera-based vision system, Vision-Guided AGV (VGAGV) uses cameras to move around. VGAGV provides better features particularly for occupational safety and *human-like* movement. When equipped with database system, VGAGV has the ability to map and analyze the shop floor layout without prior training. In order to ensure human safety, the VGAGV could be equipped with cameras allowing 360^{o} view and advanced collision avoidance system.

Meanwhile, the operational design consideration should involve the AGV economics, transportation scheduling optimization and layout optimization. AGV economics refers to the strategic planning of deploying AGV in a specific workplace.

Meanwhile, transportation scheduling covers short to medium term material transportation planning. As it deals with day-to-day operation, it is important to ensure that the vehicle fleet is operating at an optimum level. As such, numerous demand and production factors need to be analyzed. As various dynamic factors exist in a shop floor, AGV need to have the capability to response whenever changes need to be made. Transportation scheduling problem could be divided into two main sub-problems, which are: i) task assignment and ii) conflict-free vehicle routing.

Another important theme is on optimizing the layout. Important issues include assigning zones for each vehicle as well as positioning of vehicle buffer and maintenance area. The discussion is summarized in Fig. 2.3. Additionally, extensive review on AGV researches could also be found in several papers [15], [16].

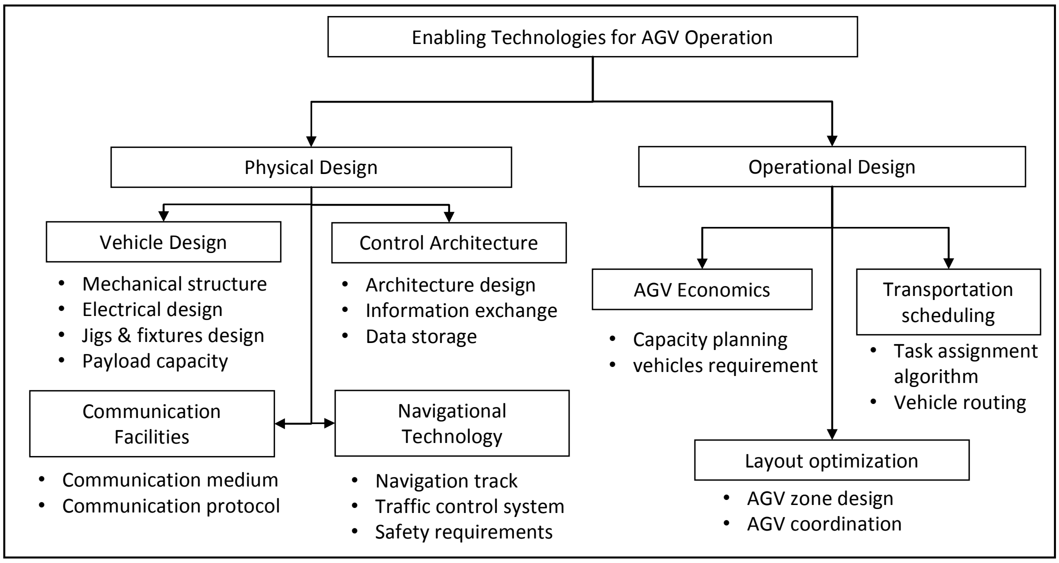

Fig. 2.3. Enabling Technologies for AGV Operation

2.2.3 Scheduling and Routing of Autonomous AGVs using Vehicle Routing Problem

Generally, AGV scheduling inherits the characteristics of the more established theory of Vehicle Routing Problem (VRP). VRP is categorized as a combinatorial optimization problem. Its objective is to delegate transportation jobs to a fleet of vehicles in an appropriate order so that the jobs could be completed in time [16]. Typically, transportation cost and time are also considered in the minimization functions. There are several methods could be utilized to solve VRP model. Mixed Integer Programming [17], [18], [19] and heuristic methods [17], [20], [21] are among the most commonly used to solve VRP and its variants.

Nevertheless, in dealing with autonomous AGVs, there is also a need to focus on how vehicles could navigate safely. Autonomous AGVs possesses unique characteristics where their routes may not be controlled by single centralized controller. Therefore, there is another need to build a conflict-free routing mechanism. Singh and Tiwari [22] proposed a conflict-free vehicle routing mechanism based on multi agent architecture.

In this research, a generalized variant of VRP, specifically Vehicle Routing Problem with Time Windows (VRPTW) has been adopted to implement AGV scheduling. Mathematical approach was used to obtain the solution.

2.2.4 Performance Measurements of MTS in a Manufacturing Industry

Performance indicators (PIs) are typically utilized to measure the successfulness of a particular proposed method to achieve stated objectives. It is important to select appropriate PIs so as to measure critical aspects resulted from the implemented proposal. Some of the PIs used in this research are categorized as the following:

i) Related to production performance

- System throughput (STH) refers to the total output produced in a specific time period. Throughput is defined as the summation of the jobs completed by the system.
- Average pickup waiting time (AWT) that measures the time difference between actual vehicle arrival times and the earliest pickup time.

ii) Related to vehicle performance

- Percentage of fully loaded travel (FLT) that is useful to measure how AGV's capacity is used in the experiment.
- Standard deviation of FLT is necessary to analyse the variation of FLT between vehicles.
- AGV traveling distance that may be used to measure the efficiency of vehicle utilization.

iii) Related to computational effort required

- Computational time is effective in comparing the required computational effort in order for the proposed method to obtain final solutions.

2.3 Developing Autonomous Control System based on Multi Agent Architecture

2.3.1 Principle of Intelligent Agent

Agent is defined as autonomous problem-solving entity, which by nature continuously senses, communicates and reacts in order to satisfy specified goal within an operation environment [23], [24]. While the concept of agent has been viewed from various perspectives, this thesis used the definition by [24] where essentially, agent could be categorized as the following:

- Purely Reactive Agent should be equipped with sensor to detect changes in the environment and response accordingly through actuator as illustrated in Fig. 2.4. Agent's function is based on *condition-action* rule: *if-then* action where *action*: $E \rightarrow Ac$ where E is the set of environment states and Ac is the set of agent's actions. One of an example for the Purely Reactive Agent is thermostat of which the main purpose is to maintain room temperature by turning on the heating or cooling system accordingly.

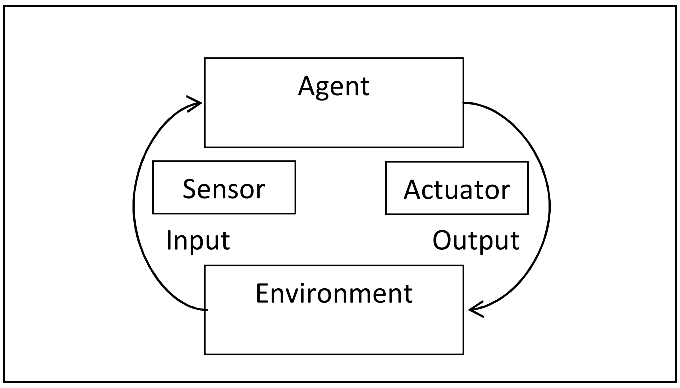

Fig. 2.4. Structure for Purely Reactive Agent [24].

- Agent with Perception – the agent consists of a fairly high level internal architecture of a reactive agent. Agent's decision function is separated into perception and action subsystems. '*See*' module represents the agent's ability to monitor changes in its environment, whereas the '*action*' module represents the decision making process of the agent where objective functions could be stored. The output of *see* function is based on the mapped environment states where *see*: $E \rightarrow Per$ and *action*: *Per** → *A* which defines the percepts, *Per* to actions, *A* accordingly. The concept agent is graphically depicted in Fig. 2.5.

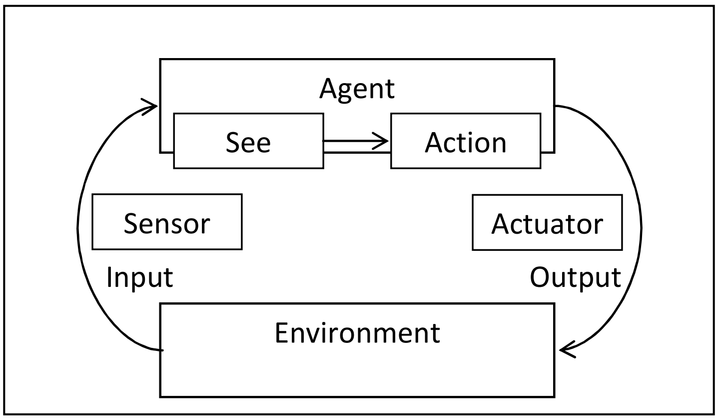

Fig. 2.5. Structure for Agent with Perception [24]

- Agent with State – the agent is equipped with internal data structure that is used to store information. This allows the agent to have better decision-making capability by changing the agent's *action* function. As the perception function remains *see*: *E* → *Per*, the action-selection complies to *action: I* → *Ac* where *I* may represents the set of all internal states. *Next* function is used to map the internal state and percept to an internal state as *next*: *I* * *Per* → *I*. Fig. 2.6 illustrates the concept.

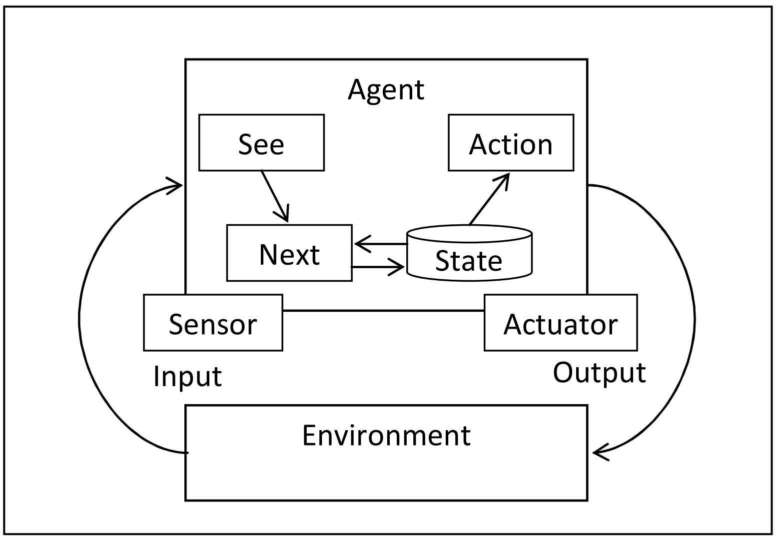

Fig. 2.6. Structure for Agent with Internal State [24]

2.3.2 Types of Multi Agent Architecture

The concept of Multi Agent System (MAS) is established when multiple intelligent agents are systematically planned to cooperate in the same working environment to achieve specific goal. Essentially, the architecture for multi agent system (MAS) can be categorized into three main types as the following [25]:

i) a contract-net system

In a contract-net system, delegation of a composite job among agents is conducted by establishing contract among themselves. Typically, multiple jobs are shared among agents within the same environment leading to the creation of a network of contracts, hence the name *'contract-net'*. Agent that has job availability initiates the task-sharing protocol by broadcasting Call for Proposals (CFP). Agents that received CFP will then bid to offer the service to the initiating agent. Best bid will be selected and the winning agent will serve the initiating agent. Details of the protocol are provided in Section 2.2.3.

ii) specification-sharing system

Specification-sharing system is based on the idea where agents supply the information regarding their capabilities and needs to the others. Based on the acquired information, activities are carried out with mutual understanding. Survey shows limited numbers of engineering applications are based on specification-sharing system. Nevertheless, system proposed by [26] could be regarded as having the attributes of specification-sharing system [27].

iii) federated system

The differences between federated MAS and the other two types are federated system has hierarchical agent structures where coordinators are deployed to supervise groups of local agents. Therefore, local agents only communicate within their federation while inter-federation communications are carried out by coordinators.

In this research, contract-net architecture is utilized particularly because i) it is suitable for engineering application with dynamic environment requiring real-time decision-making capability compared to specification-sharing system and ii) considering the size of the application, federated system might not be necessary. As such, communication could be less complicated and more straightforward.

2.3.3 Fundamental of Contract Net Protocol (CNP)

CNP is one of the communication protocols that are used for tasks delegation in Distributed Artificial Intelligence (DAI) systems. It was first introduced by Smith [28]. Due to its efficiency, Foundation of Intelligent Physical Agents (FIPA) of IEEE [29] has taken it as a standard to formalize communication protocol particularly between a group of nodes or agents within a system. Negotiation protocol that is based on Standard CNP (SCNP) consists of a sequence of four main steps as depicted in Fig. 2.7 [30]. Related agents must go through the following steps to negotiate each contract:

i. The initiator sends a CFP.

ii. Each participant reviews the CFP and responds accordingly.

iii. The initiator selects participant with the best bid and informs rejection of other bids.

iv. Selected participant notifies the initiator on task execution.

CNP is a systematic protocol where negotiation could be executed. Auction mechanism is suitable for allocating resource particularly when the information of the entire environment is not totally explored. Furthermore, auction algorithm has excellent computational efficiency and is regarded to be among the best in optimizing single commodity network problems [31].

However, existing researches focused on the application of CNP to suit static AGV operational environment making it less suitable to meet the requirements of dynamic AGV operations. Furthermore current approach does not fully utilize the latest information within a dynamic system. This leaves unaddressed technical shortcomings that will restrict realization of an effective distributed AGV system.

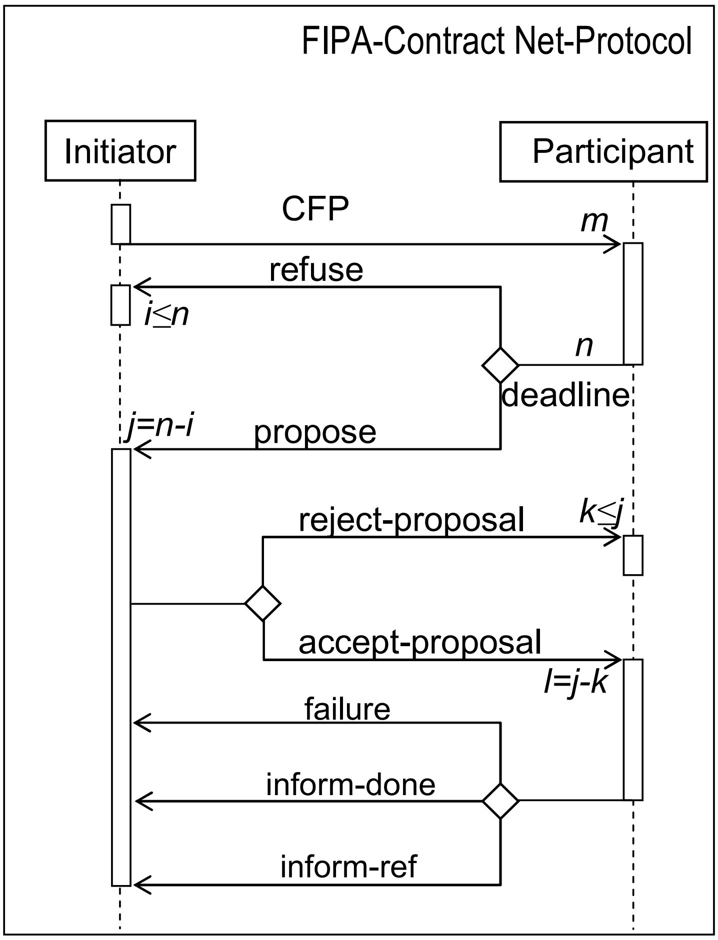

Fig. 2.7. Sequence of Contract Net Interaction Protocol

2.3.4 Agent Standards and Interoperability

There are several governing bodies that provide standards for intelligent agent and MAS. Two of the prominent bodies are the Foundation for Intelligent Physical Agent (FIPA), a standards organization of IEEE Computer Society [29] and the Agent Platform Special Interest Group (PSIG), a subgroup of Object Management Group [32].

FIPA has established 25 specifications as standards for agents system. The specifications can be categorized under five main themes: agent communication; agent transport; agent management; abstract architecture; and applications. FIPA regards agent communication as the core category at the heart of the FIPA multi-agent system model. Meanwhile, PSIG has more than 10 specifications particularly related to agent-based system modelling.

Other standardization bodies include AgentLink III, the European Coordination Action for Agent Based Computing [33] and US Defense Advanced Research Projects Agency (DARPA) that came with DARPA Agent Markup Language (DAML).

2.4 Scheduling of Distributed Resources using Combinatorial Auction

Combinatorial auctions (CA) refer to a systemic auction procedure that allows bidders to place a single bid on combinations of discrete items [34]. It could be employed when auctioneer has more than one item to be offered simultaneously. Originally utilized in economics and game-theory applications, there is now a growing number of researches applying the method to solve engineering problems such as airport slot allocation, scheduling in multi-rate wireless network, grip computing design and operating system memory allocation [35], [36], [37].

Compared to the traditional auction approach, CA has advantages on certain aspects particularly in enabling bidders to evaluate both complementary and substitutability attributes of the items put on auction. This could minimize the risks of only obtaining a subset of items that are not worth as much as the complete set. Based on the evaluation, bidders will then be able to submit a package of bid for the intended items.

When a bidder participates in auctions consist of multiple auctioneers with multiple items, the bidder needs the ability to assess the value for each item. Furthermore, if the bidder intends to bid for more than an item, there is a need to evaluate the consequences of acquiring an item to the others. Two important attributes are:

- Complementarity

  For a bidder, the value of an item can vary depending on other items that could be acquired. Thus, there exists complementarity attribute between items i_1 and i_2 where bidder a may put a value, $v(I)$ as of the following:

  $$v_a(\{i_1, i_2\}) > v_a(\{i_1\}) + v_a(\{i_2\})$$

- Substitutability

  Another important attribute need to be assessed is on the readiness of a bidder to accept alternative item should the best item couldn't be won. Substitutability can be expressed as the following:

  $$v_a(\{i_1, i_2\}) < v_a(\{i_1\}) + v_a(\{i_2\})$$

Looking from a material transportation viewpoint, both complementarity and substitutability attributes are critical particularly as tasks assignment will have consequent route establishment. Optimizing one assignment without considering others will still result in under optimized vehicle route. This could be overcome by evaluating multiple jobs simultaneously. As such, CA could be a suitable method to schedule the operation of autonomous AGVs.

2.5 Key Research Problems

Identification of critical research problems is necessary to ensure the system will be able to operate efficiently. It is necessary so that specific research objectives could be determined. The key research problems that have been studied in the thesis are as the following:

P1) Existing architecture and task assignment protocol does not consider dynamism of MTS operation. This prevents the entity from making optimal assignment thus resulting in underperformance of the entire system. In order to achieve competitive performance, there is a need for an assignment protocol that could exploit latest information within the system. Since transporters are moving entities, it is appropriate for the protocol to consider the location of transporters in evaluating task assignment as well as providing mechanism to re-evaluate assignments made.

P2) Existing researches on distributed-controlled MTS in particular AGV system don't contemplate the deployment of vehicle with multiple-loading capacity. Due to the fact that existing scheduling mechanism of distributed-controlled AGV is still depending on single-task allocation per auction, it is less suitable to be utilized when dealing with multi-capacity transporters as it hinders the entire assignments from being fully optimized where bidders could not evaluate the complementary or substitutability attributes among tasks.

P3) Most of the research models for AGV system design used simplified cases which may be useful to test the implementation of new idea. However, this might underestimate the effect of some decisive operation factors. In order to design a realistic AGV system, it is necessary to consider a realistic production environment. Furthermore, in a typical industrial environment, there are multiple operational criteria that need to be handled. As such, there is a need to determine the best combination of design variables taking into account related critical operational criteria.

2.6 Summary

The fundamental of important technologies required to develop an autonomous-controlled AGV system have been reviewed. The details on how the technologies were employed are explained in the respective chapters.

Chapter 3
MAS-Based MTS Architecture using Predictive-Reactive Approach

3.1 Introduction

3.1.1 Overview

Upon finishing the literature review, the trend for state-of-the-art researches and the corresponding important transportation attributes for advanced MTS could be extracted. Based on the attributes, key research problem could then be determined. Taking into account both aspects, an appropriate MTS control architecture based on MAS architecture could be proposed. The discussion in this chapter is divided into two main components:

i) Identification of generic attributes required by an advanced MTS system and existing problems need to be solved to realize it.

ii) Consequently, an autonomous MTS control architecture based on MAS that is capable to address both perspectives is proposed. The architecture is focused on enabling the MTS to conduct dynamic task assignment procedure.

3.1.2 Philosophy of Deploying Distributed and Autonomous MTS

Key philosophy of deploying MAS is to enable each entity the autonomy in planning and executing their responsibilities. This could be realized by providing them the intelligence to make decision independently based on their goal and current environment status. Besides, MAS enable the development of modular design application particularly for information processing and decision making functions. Compared to conventional MTS with centralized scheduler, the MAS-based MTS could provide new perspective as the following:

- Change management is localized – In dealing with dynamic environment, it is important for the system to continuously monitor the established schedule and dictate changes upon necessary. The drawback of conventional method is that minor changes may affect the transportation schedule of the whole fleet. Agent-based MTS minimize the impact chain by localizing the change only to the related machines and vehicles thus minimizing system nervousness.
- Information traffic load and processing is localized – Compared to the traditional system with centralized decision maker (CDM) that requires system-wide information, the proposed MAS approach consists of multiple decision makers (DM). This enables the information traffic to be localized within a specific DM thus eliminates the need for a decision maker to process unneeded information.
- Eliminate single-point failure – This will increase the entire system fault-tolerant capability. As the entities have the autonomy in making decision, any failure could be isolated.

3.1.3 Realizing Dynamic Task Assignment based on Predictive-Reactive Approach

In a realistic world, scheduling or task assignment is a continuous and ongoing process. This is due to the fact that more often than not, established initial plan need to be revised due to the changing circumstances cause by various dynamic factors. While initial plan could be derived using predictive scheduling, the process of revising an earlier schedule triggered by dynamic events is termed as reactive scheduling.

Predictive-reactive scheduling is regarded as the most widely used approach to manage dynamic factors within a manufacturing system [38]. It refers to scheduling and re-scheduling processes where initial schedule could be amended as a response to real-time event. This chapter aims to provide a task assignment protocol inheriting predictive-reactive characteristics that also has the function to react to dynamic events related to AGV operation.

3.2 Functional Attributes of an Advanced AGV System

There are several functional attributes required of an advanced MTS system. The features were highlighted in numerous recent papers. In this research, three main attributes for advanced MTS were studied in detail.

- Ability to exploit dynamic changes within a system.

  One of the critical attributes is the ability for a system to exploit changes dynamically so that the changes are beneficial for the system. There are a number of dynamic factors exist within a manufacturing system such as demand changes, random jobs arrival, resource breakdowns, transportation deadlocks, operation delays and material reworks. Taking into account these factors, an efficient MTS should provide necessary features to address the issues. This can be achieved by having flexible and appropriate conflict-resolution protocol among functional units. Therefore, there is a need to enhance the design of the protocol so that important dynamic factors could be addressed.

- Managing vehicle with multiple capacity efficiently.

  Manufacturing industry in particular has been receiving the benefits of MTS, especially AGVs for years. Nevertheless, significant enhancements could still be made. One of the reasons is that most of the existing autonomous AGVs operate based on single task assignment per auction method. While this might be useful for single-loading capacity, it could lead to suboptimal performance as it does not have the ability to evaluate complementarity attribute among transportation requests. This limits the fleet's capability in achieving high performance especially when number of deliveries or distance travelled factor is taken into account.

- Establishment of MTS system design to address multiple-objective transportation problem.

MTS system design is a crucial issue particularly as it requires huge capital investment. In order to provide a realistic MTS system design, it is necessary to consider a realistic industrial environment. Furthermore, in a typical industrial environment, there are multiple operational criteria that need to be handled. As such, there is a need to determine the best combination of design variables.

3.3 Development of Autonomous MTS Architecture based on MAS

Based on the discussion on the required attributes and related problems in realizing an advanced MTS, this section proposes an MTS control architecture based on MAS.

3.3.1 Fundamental of MAS

In this thesis, intelligent agent is defined as a goal-oriented autonomous computational entity, which continuously senses, communicates and reacts accordingly within an operation environment [39]. As such, each entity is equipped with a certain degree of learning ability and is responsible in making decisions on behalf of a respective physical entity in a manufacturing system.

Meanwhile, the concept of MAS arises when multiple agents are systematically planned to cooperate in the same working environment to achieve specific goals. In establishing appropriate MAS, there are four main agent elements that need to be planned:

i. Multi-agent system architecture.

ii. Definition of agent’s functionality.

iii. Communication protocol for executing jobs.

iv. Agent’s reward system consisting bidding functions.

Fundamental MTS operational control of task assignment and routing are mapped into the MAS framework. Task assignment is executed using auction-based negotiation protocol between agents. In order to provide a certain degree of freedom for the transporters to plan and decide its own operation, the agent-based control system is embodied into each vehicle.

In order to establish a distributed architecture for MTS operation, it is necessary to identify the task assignment requirements. Fig. 3.1 summarizes the stages of material transportation planning and the proposed task assignment method. This research uses job shop machine schedule as the system input.

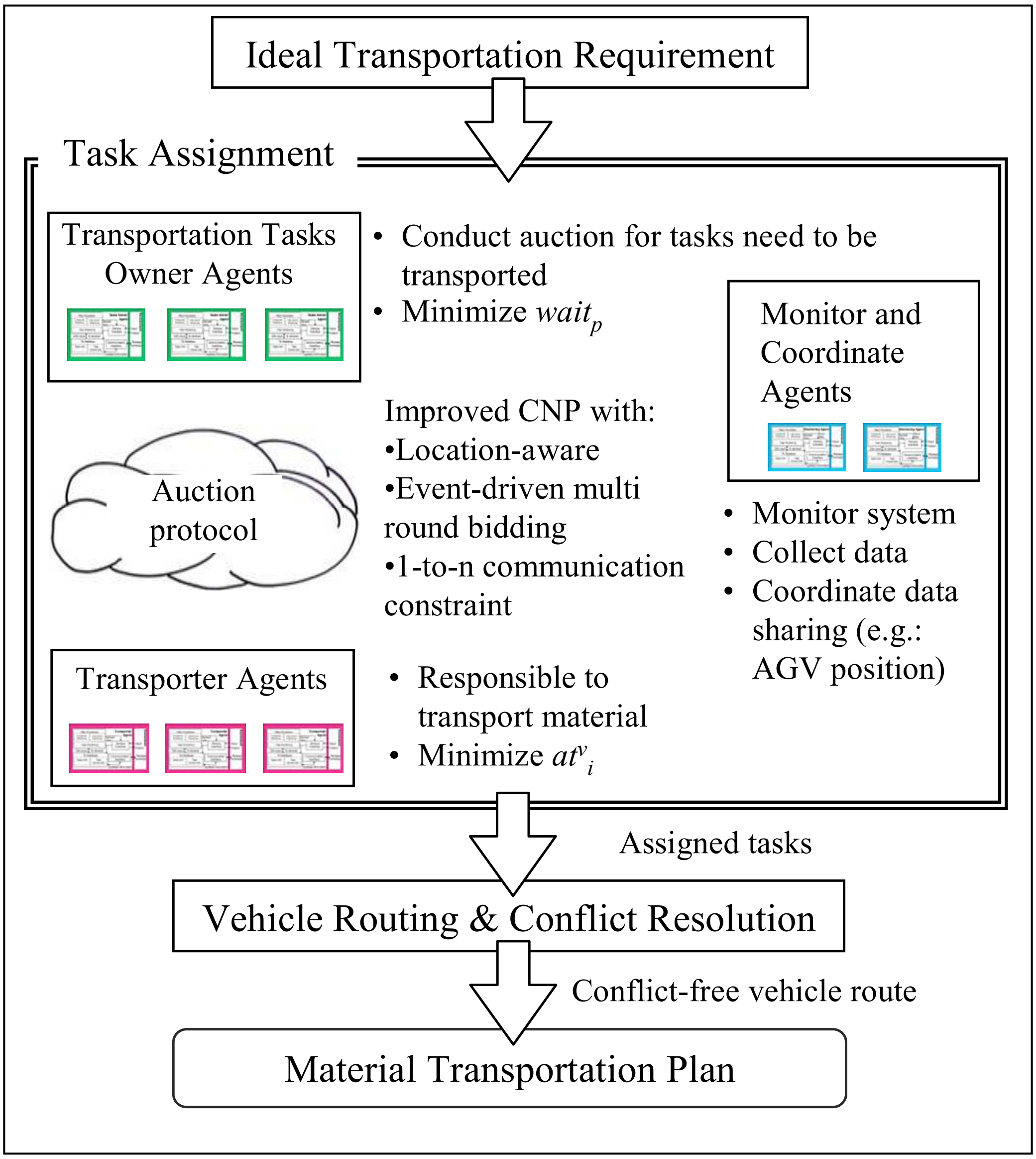

Fig. 3.1. Proposed Task Assignment Method within Material Transportation Planning

The central idea to establish transportation assignment is by utilizing auction-based protocol to handle task assignment procedure. Based on standard Contract Net Protocol (CNP), an Improved CNP (ICNP) is proposed in order to enhance communication protocol between Transporter Agent and Transportation Tasks Owner Agent to accommodate the procedure.

ICNP is equipped with event-driven multi-round proposal capability and the communication is conducted in a bounded communication range. Apart from Transporter Agent and Transportation Tasks Owner Agent, Monitor and Coordinate Agent is deployed to monitor and to ensure the system operates efficiently. In realizing the entire mechanism, multi-agent architecture is proposed.

3.3.2 Proposed MAS Architecture for Autonomous MTS

There are variations of agent-based control architecture applied for task assignment purpose [23], [40], [41], [42]. However, most of the architectures were not based on auction mechanism and are developed to suit static environment. Thus, a unique multi-agent architecture is needed to satisfy the complete set of requirements for distributed MTS operation.

Basically there are three types of agent deployed within the system namely as Transporter Agent, Transportation Tasks Owner Agent and Monitor and Coordinate Agent. All of the agents are equipped with specific set of functions. Related notations are shown in Table 3.1.

3.3.3 Agents Configuration and Functionality

There are three types of agents deployed in order to enable dynamic transportation task assignment. The agents are as the following:

- **Transporter Agent Configuration**

  Each Transporter Agent represents an individual vehicle, which is designed to enable independent control for its respective transporters. Transporter Agent is engaged in transportation assignment, responsible for delivery of requests and plan the required routing in completing the job. In order to carry out its job, it is equipped with a set of modules in supporting vehicle's transportation functions shown in Fig. 3.2.

Table 3.1. Notation (MTS)

Sets	
I	Set of transport requests
V	Set of transporters
P	Set of transportation tasks owners

System Parameters	
td_i	delivery time for transport request-i
tv_i	loading time for transport request -i
tw_i	unloading time for transport request -i
tu_i	machine setup time for transport request -i ($tu_i = tv_i + tw_i$)
$tr^v{}_i$	time duration for transporter -v to pick transport request -i
$tp^p{}_i$	expected holding time of transport request -i

Decision Variables	
α_i^p	binary variable for assignment status of transport request -i where $\alpha_i^p = \begin{cases} 1, \text{if task - i is assigned} \\ 0, \text{if task - i is not assigned} \end{cases}$
β_i^v	binary variable representing status of transport request -i assigned to transporter-v where $\beta_i^v = \begin{cases} 1, \text{if task - i is assigned} \\ 0, \text{if task - i is not assigned} \end{cases}$
$at^v{}_i$	expected arrival time of vehicle-v for transport request -i
ct_v	time needed to transport all tasks assigned to transporter -v
$tt^v{}_i$	transportation time for transport request -i ($tt^v{}_i = tr^v{}_i + td_i$)
te_i	earliest pickup start time for transport request -i
J_p	total number of operations processed by Transportation Tasks Owner-p
tva_i	starting time of loading of transport request -i
$tpa^p{}_i$	starting time of machine processing of transport request -i
$tta^v{}_i$	starting time of transportation of transport request -i
C_i	job completion time for transport request -i
O_{ij}	operation time of transport request -i
AWT	average waiting time
$wait_p$	total waiting time for Transportation Tasks Owner-p

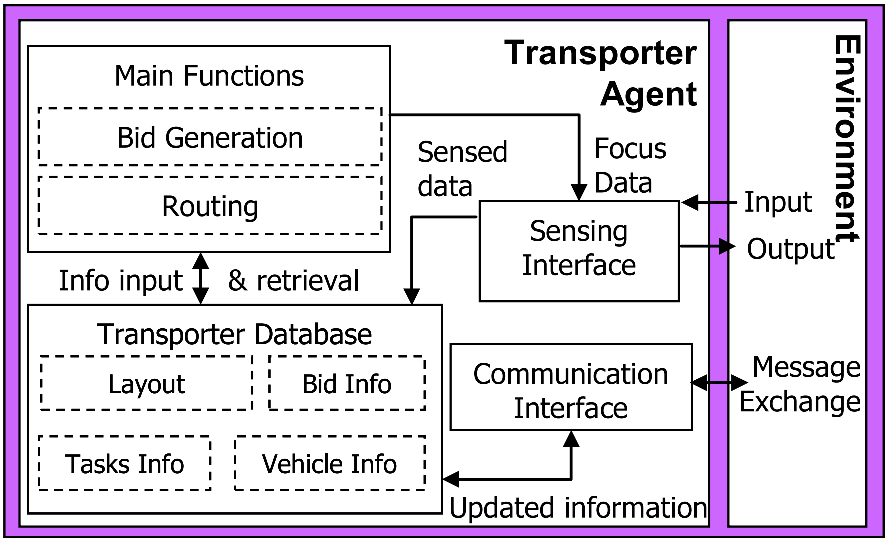

Fig. 3.2. Agent configuration for Transporter Agent

Task assignment and vehicle routing are the two main functions that need to be established in order to have an efficient MTS. Conventionally, both aspects can be planned sequentially with task assignment function precedes the vehicle routing function where the output of task assignment is used as the input for vehicle routing. Based on our survey, vehicle routing has been well studied by other researchers. Thus, this research opted to focus the improvement on job assignment problem and adopted vehicle routing method proposed by Singh and Tiwari [22].

In order to support autonomous vehicle operation, dedicated agent configuration equipped with required sub-modules has been designed. Transporter Agent has the capability to decide on which operation should be selected for delivery based on some specific criteria. In serving transportation request, the agent will attempt to achieve its main objective that is to minimize its arrival time for task it is bidding for. Upon receiving Calls for Proposal (CFP), each agent determines its at^{v}_{ij} to pick-up the announced task as defined in (Eq. 3.1) to (Eq. 3.5) where tr^{v}_{ij} represents time duration needed for the vehicle to retrieve the offered task; ct_v is the time needed to complete the transportation of all tasks assigned to transporter-v. Furthermore, i refers to a transportation request need to be moved.

$$\text{Min } at_i^v \quad (3.1)$$

$$\text{s.t. } at_i^v = tr_i^v + ct_v \quad (3.2)$$

$$ct_v = \sum_{i=1}^{I} \left[\left(tta_i^v + (tr_i^v + td_i) + (tv_i + tw_i) \right) \beta_i^v \right] \quad (3.3)$$

$$\beta_i^v = 1, \forall i \quad (3.4)$$

$$tr_i^v > ct_v \quad (3.5)$$

- **Transportation Tasks Owner Agent Configuration**

Transportation Tasks Owner Agent represents the interest of task owners and equip them with decision making capability. The agents with configuration as in Fig. 3.3 are responsible to initiate CFP, evaluate bids and assign delivery task to the most suitable vehicle. Essentially its main objective is to maximize the overall throughput. Therefore, Transportation Tasks Owner Agent have the ability to decide which participant should be awarded with the contract. In achieving the objective, the agents are equipped with a set of decision-making modules to evaluate the decision criteria.

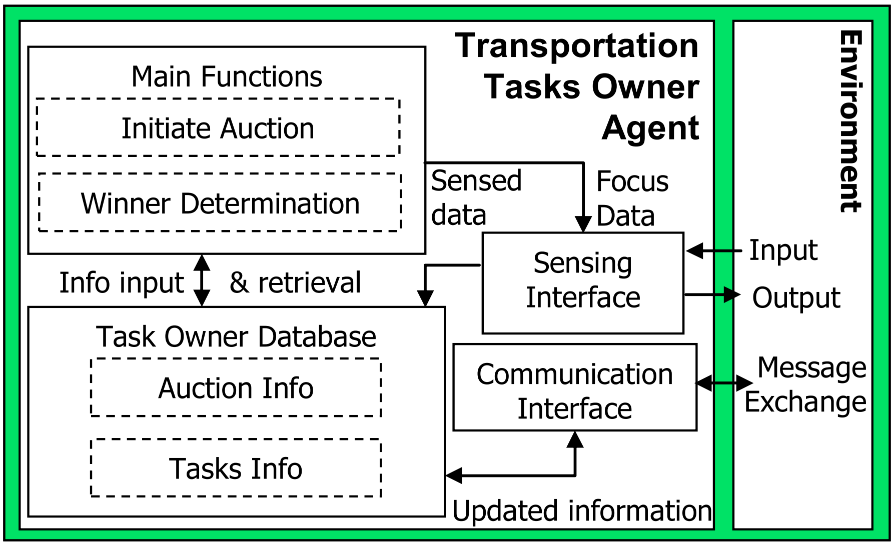

Fig. 3.3. Agent configuration for Transportation Tasks Owner Agent

This research proposes an Improved CNP (ICNP) to manage two important dynamic factors in AGVs operation. The factors are:

i) dynamic status of vehicle's capacity availability

ii) the positioning advantage of certain vehicles in handling a particular transportation request.

As such, Transportation Tasks Owner Agent is equipped with the modules to support both requirements. The details are discussed in Chapter 4. Transportation Tasks Owner Agents are also responsible for interacting with TA to update job completion status and to receive production orders from production management system.

Transportation Tasks Owner Agent is responsible to minimize $wait_p$ for all of the tasks as defined in (Eqs. 3.6 and 3.7) and average load-pickup waiting time for each operation (*AWT*) as in (Eq. 3.8) are used as the performance indicators where tva_i is the loading start time of transport request-*i* which is also the actual starting time of loading operation.

$$\text{Min } wait_p \quad \ldots\ldots\ldots\ldots \quad (3.6)$$

$$\text{s.t. } wait_p = \sum_{i=1}^{I} (tva_i^v - te_i)\alpha_i^p \quad \ldots\ldots\ldots\ldots \quad (3.7)$$

$$AWT = \sum_{p=1}^{P} \left(\frac{wait_p}{J_p} \right) \quad \ldots\ldots\ldots\ldots \quad (3.8)$$

- **Monitor and Coordinate Agent Configuration**

Since agents store information, plan and react based on local knowledge, it lacks an entire view on the system. Hence, there is a need to establish an approach on how to trace system operation and performance. An agent needs to be assigned to take charge on these functions. Monitor and Coordinate Agent as illustrated in Fig. 3.4, resides at a *monitoring base* i.e. a dedicated computer located in shop floor.

Fundamentally, the agent is responsible to monitor the entire Transportation Tasks Owner Agents and Transporter Agents. This could further facilitate any fault-tolerant mechanism to solve machine or vehicle failure. Additionally, Monitor and Coordinate Agent responsibles to provide Transportation Tasks Owner Agent the information of transporters that are eligible to bid for a specific transport request. The detail is discussed in Chapter 4.

Moreover, Monitor and Coordinate Agent also stores system data such as job input and output data. Monitor and Coordinate Agent may interacts with Transportation Tasks Owner Agent and Transporter Agent during task assignment process. In addition, Monitor and Coordinate Agent holds job completion time, C_i which can be expressed as in (Eq. 3.9) and (Eq. 3.10) where O_i refers to the operation time for i^{th} job.

$$C_i = \sum_{i=1}^{I} O_i \quad (3.9)$$

$$O_i = tu_i \alpha_i^p + tp_i^p \alpha_i^p + tt_i^v \beta_i^v \quad (3.10)$$

Practical-wise, in order to avoid single-point failure, mirror agent of Monitor and Coordinate Agent need to be established in a replicated monitoring base as a backup. Both agents possess the same functions, are connected and synchronized with each other at a specified time interval.

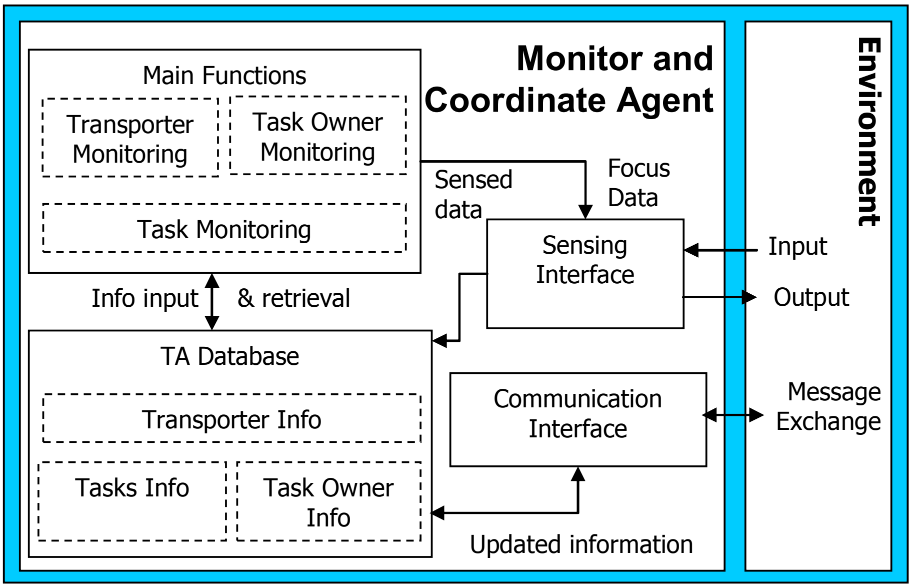

Fig. 3.4. Agent configuration for Monitor and Coordinate Agent

3.4 Key Research Objectives and Approaches

In developing efficient MAS for MTS, key research objectives have been determined. Consequently, necessary approaches to fulfill the objectives have been identified. The discussion is summarized in Table 3.2.

Table 3.2. Key research objectives and approaches

	Section 3 Dynamic Protocol	Section 4 Multi Loading Capacity	Section 5 System Design
Key Objectives	To enhance Contract Net Protocol (CNP) to: 1.Exploit dynamism of AGV position 2.Enable revisable bidding	To enhance task assignment protocol to: 1. Optimize the performance of multi-load AGV 2. Assign multiple tasks per auction through multi-initiator to multi-participant communication	To provide an effective tool to decide design parameter of MAS-based AGV system for dominance-based multi-objective problem.
Main Approaches	Enhance CNP with: 1. Location-aware 2. Utilize Monitor and Coordinate Agent to facilitate location-aware protocol 3. Event-based multi-round bidding features 4. Modify time constraint to realize event-based bidding	1. Formalize Knapsack Problem model to optimize utilization of AGV loading capacity 2. Extend Vehicle Routing Problem with Time Window for Multi-Load AGV 3. Utilize Combinatorial auction with Exclusive OR (XOR) bidding rule 4. Introduce Auction Agent to resolve task assignment conflicts	Establish simulation approach of MAS-based AGV system design: 1. Provide simulation procedure & tool of the MAS-based AGV system 2. Utilize RSM method for optimizing design parameters' values

3.5 Summary

This chapter has laid the foundation of an advanced Vehicle-based Material Transportation System. MAS-based MTS control architecture is used to realize the system. The architecture will be used in the following discussion.

Chapter 4

Enhancement of CNP with Location-Aware and Event-based Multi Round Bidding Features

4.1 Introduction

For years, majority of the researches in AGV scheduling has been based on centralized planning method. In a centralized approach, schedule for the entire fleet is planned by a single decision-maker that has all of the system information. While the approach typically possesses the advantages of global optimization capability, the method comes with major shortcomings as well. Occasionally, centralized method becomes very difficult to cope with unforeseen circumstances such as unexpected express requests and machine breakdown as it takes long computation time to obtain the route planning of large scale systems [43], [44], [45].

Looking from MTS point of view, AGV system is made up of several functional units that are operating independently, thus each may have their own preferences in achieving the objective function. This emulates the concept of independent units that should be given certain degree of freedom to decide whether to cooperate with other units or not. Therefore, it is not necessary for one individual vehicle to share all their information (such as tasks currently assigned, battery level etc.) in case cooperation is not needed. This contradicts the characteristics of centralized control that requires information of the entire system prior to the computation.

In addressing dynamic and real-time operation criteria, this chapter introduces a distributed task assignment method for autonomous AGV based on auction method. Multi agent system (MAS) as proposed in Chapter 3 is employed to realize the distributed environment and Contract Net Protocol (CNP) is used to facilitate auction-based task assignment method.

The discussion in this chapter is focus on the development of an improved protocol to exploit dynamic transportation factors within the system and to overcome existing limitation.

4.2 MAS Architecture for Autonomous AGV

4.2.1 Overview

As there are several approaches of developing MAS architecture for task assignment and scheduling, there is a need to clarify the architecture that is needed to fulfill the requirements of a dynamic AGV system that operates within a manufacturing environment. A unique system architecture has been established in this research in order to map AGV control requirements into the agent-based framework. As discussed in Chapter 3, there are three agent types needed for MTS. In order to adapt the idea for AGV system, basically there are three types of agent deployed within the system namely as:

- AGV Agent (AGVA) that responsible as Transporter Agent.
- Machine Agent (MA) that responsible as Transportation Tasks Owner Agent.
- Monitor and Coordinate Agent (TA).

The respective agent strcutures are shown in Fig. 4.1 The related functions stated in Chapter 3 have been modified accordingly to suit specific problem case requirement. As such, the notations shown in Table 4.1 will act as the guide for the entire dissertation.

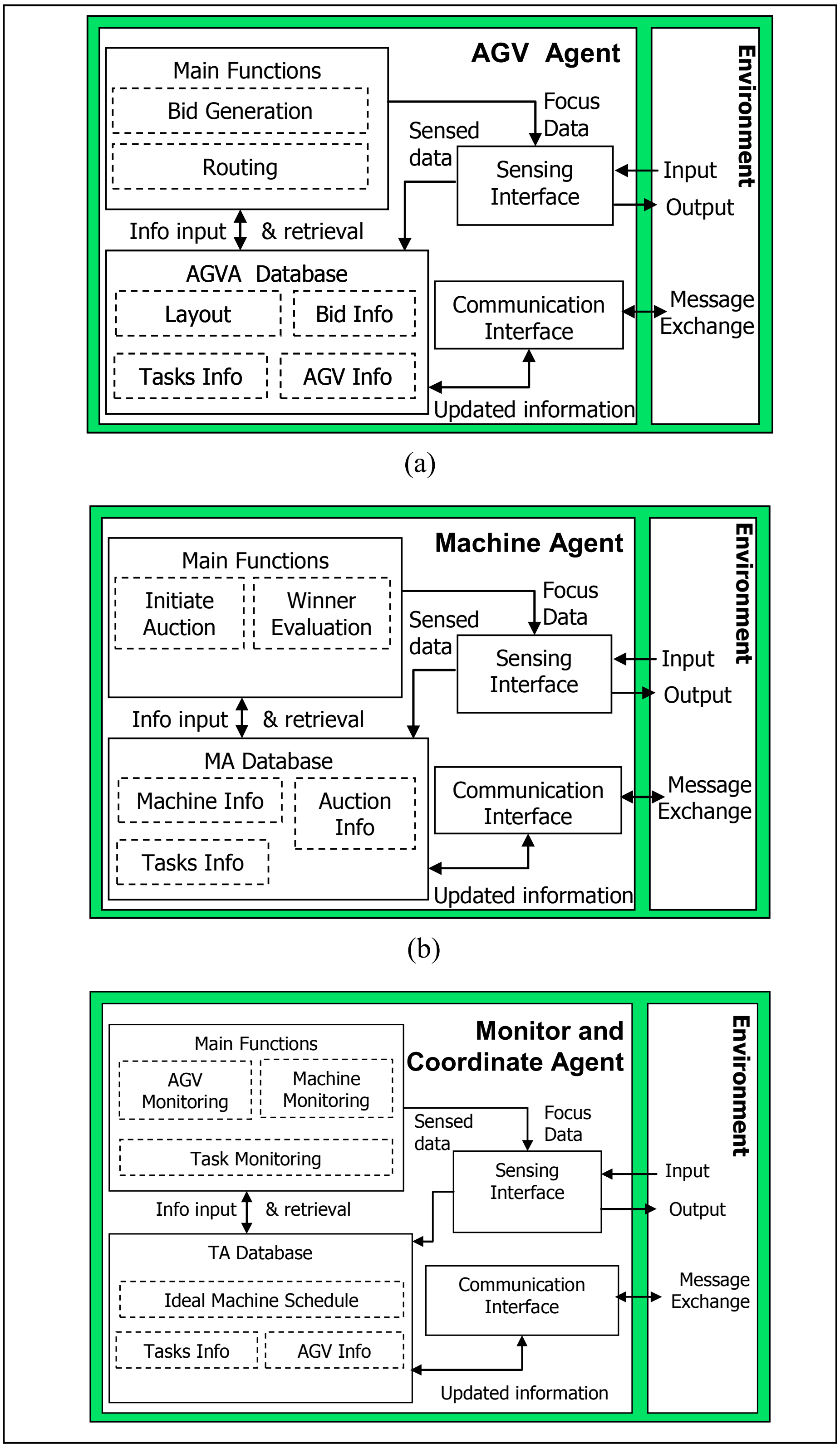

Fig. 4.1 (a) AGVA structure

(b) MA structure

(c) TA structure

Table 4.1. Notation

Sets	
IJ	Set of operations
A	Set of agents
B	Set of bids
X	Set of AGVs
M	Set of machines
L	Set of lanes/ arcs/ ordered pair of vertices
T	Set of time periods

System Parameters	
td_{ij}	delivery time for operation-*ij*
tv_{ij}	loading time for operation-*ij*
tw_{ij}	unloading time for operation-*ij*
tu_{ij}	machine setup time for operation -*ij* ($tu_{ij} = tv_{ij} + tw_{ij}$)
tr^{x}_{ij}	time duration for AGV to pick operation-*ij*
tp^{m}_{ij}	machine processing time of operation-*ij*
d^{x}_{ij}	shortest node-to-node distance to transport load-*ij*
sd	cost for AGV to travel for a unit length
cp_{x}	Total loading capacity of AGV-*x*
p_{ij}	Pickup station for operation-*ij*
e_{ij}	Destination station for operation-*ij*

Binary Variables	
α^{m}_{ij}	binary variable for assignment status of operation-*ij* where $\alpha^{m}_{ij} = \begin{cases} 1, \text{if operation - ij is assigned} \\ 0, \text{if operation - ij is not assigned} \end{cases}$
β^{x}_{ij}	binary variable representing status of operation-*ij* assigned to AGV-*x* where $\beta^{x}_{ij} = \begin{cases} 1, \text{if operation - ij is assigned} \\ 0, \text{if operation - ij is not assigned} \end{cases}$
ce^{x}_{m}	binary variable representing either AGV-*x* is capable to carry new load when it is at machine-*m* where

	$ce_{ax} = \begin{cases} 0, \text{if } cc_{ax} = cp_{ax} \\ 1, \text{if } cc_{ax} < cp_{ax} \end{cases}$
δ^x_{mn}	binary variable assigned to AGV-*x* where $\delta^x_{mn} = \begin{cases} 1, \text{if AGV - x travels from node - m to - n} \\ 0, \text{if otherwise} \end{cases}$
ξ^x_b	binary variable representing status of bid-*b* $\xi^x_b = \begin{cases} 1, \text{if the active bid is the optimal bid} \\ 0, \text{if otherwise} \end{cases}$

Decision variables	
at^x_{ij}	expected arrival time of vehicle-*x* for operation-*ij*
ct_x	time needed to transport all tasks assigned to AGV-*x*
tt^x_{ij}	transportation time for operation-*ij* ($tt^x_{ij} = tr^x_{ij} + td_{ij}$)
te_{ij}	earliest pickup start time for operation-*ij*
tl_{ij}	latest delivery start time without delaying the entire job sequence
rt_j	released time of job-*j*
mt_j	remaining time of the respective job-*j*
dt_j	due time of job-*j*
J_m	total number of operations processed by machine-*m*
tva_{ij}	starting time of loading of operation-*ij*
tpa^m_{ij}	starting time of machine processing of operation-*ij*
tta^x_{ij}	starting time of transportation of operation-*ij*
C_i	job completion time
O_{ij}	operation time of operation-*ij*
cc^x_m	current occupied capacity of AGV-*x* at machine-*m*
cl^x_m	quantity of pickup / delivery for AGV-*x* at machine-*m*
ad^x_{ij}	difference between te_{ij} and AGV's at^x_{ij}.
q_m	quantity of transportation request (loading or unloading) at machine *m*.
ct_x	time needed by AGV to complete the transportation of all loaded tasks.
tb_{ij}	end of bidding time for operation-*ij*
tn_{ij}	end of bid evaluation time for operation-*ij*
ta_{ij}	end of auctioning time for operation-*ij*

$tpb_{m,ij}$	end time of processing of operation –*ij*

Performance Variables	
PLT	percentage of average loaded travel
$loaded_x$	percentage of loaded travel for AGV-*x*
AWT	average waiting time
$wait_m$	total waiting time for machine-*m*
STH	system throughput
TOT	total production time
fs	vehicle fleet size

4.2.2 Agents Functionality

Functionalities for the agents stated are as follows:

i) AGV Agent (AGVA)

AGVA will attempt to minimize its arrival time in serving the transportation request it is bidding for. As the agent received Calls for Proposal (CFP) from MA, each AGVA determines its $at^x{}_{ij}$ to pick-up the announced task as defined in (Eq. 4.1) that consists of $tr^x{}_{ij}$ that represents time duration needed for the AGV to retrieve the offered task and ct_x that refers to the time needed to complete the transportation of all tasks assigned to AGV-*x*. Furthermore, *i* refers to a job and *j* refers to a machine operation belong to the job. The function and related constraints are stated in (Eq. 4.1) to (Eq. 4.5).

$$\text{Min } at_{ij}^x \cdots\cdots \quad (4.1)$$

$$\text{s.t. } at_{ij}^x = tr_{ij}^x + ct_x \cdots\cdots \quad (4.2)$$

$$ct_x = \sum_{i=1}^{I}\sum_{j=1}^{J}\left[\left(tta_{ij}^x + (tr_{ij}^x + td_{ij}) + (tv_{ij} + tw_{ij})\right)\beta_{ij}^x\right] \quad (4.3)$$

$$\beta_{ij}^x = 1, \forall i, j \cdots\cdots \quad (4.4)$$

$$tr_{ij}^x > ct_x \cdots\cdots \quad (4.5)$$

ii) Machine Agent (MA)

MAs are deployed on all machines to equip the machines with decision making capability. The agent is responsible to minimize $wait_m$ for each tasks auction as defined in (Eqs. 4.6 and 4.8).

$$\text{Min } wait_m \quad \ldots \quad (4.6)$$

$$\text{s.t. } wait_m = \sum_{i=1}^{I}\sum_{j=1}^{J}(tva_{ij}^{x} - te_{ij})\alpha_{ij}^{m} \quad \ldots \quad (4.7)$$

$$AWT = \sum_{m=1}^{M}\left(\frac{wait_m}{J_m}\right) \quad \ldots \quad (4.8)$$

iii) Monitor and Coordinate Agent (TA).

TA is equipped with the function set defined in (Eqs. 4.9 and 4.10).

$$C_i = \sum_{i=1}^{I}\sum_{j=1}^{J}O_{ij} \quad \ldots \quad (4.9)$$

$$O_{ij} = tu_{ij}\alpha_{ij}^{m} + tp_{ij}^{m}\alpha_{ij}^{m} + tt_{ij}^{x}\beta_{ij}^{x} \quad \ldots \quad (4.10)$$

4.3 Addressing Dynamic Operation Environment using an ICNP

4.3.1 Requirements of CNP for Autonomous AGV Control

In order to realize an efficient distributed AGV control that is capable to suit high-performance production environment, it is necessary to define the characteristic of its communication requirement. The requirements include:

R1. SCNP is based on open-auction concept where all participants receive CFP and can bid for the task. While AGVs are moving entities, it is appropriate that task auction should only be made to the vehicles in acceptable position to bid for the task. SCNP does not fully address dynamism of AGV operation especially dealing with moving entities. The fact that the protocol does not take into account AGV location parameter makes it less capable to exploit possible advantage situations.

R2. The protocol only allows single-round bidding. Bids evaluation will be made and contract will be awarded at the end of a single bidding period.

No revision could be made even if other participants are able to place better bid thereafter. This handicaps the protocol to exploit system's dynamism and make use of the latest information.

Therefore, this chapter proposes an integrated approach to fulfill the requirements discussed to enable distributed AGV's dynamic task assignment mechanism. Specific approach has been laid out to solve each of the requirements categorically.

4.3.2 Location-Aware Broadcasting of Transportation Request Availability

i) Location-Aware Task Announcement Broadcasting

One of the important dynamic factors need to be taken into account is regarding the vehicles' positions. Therefore, prior to have multi-pass bidding function, it is necessary that the proposed enhanced protocol has the feature to distinguish bidders within strategic location from the entire fleet. There are three main notable merits justifying the establishment of communication boundary in solving AGV task assignment problem:

- AGV operations occasionally deal with various uncertainty issues especially from timing perspective. One of the factors is due to the range of distance involves. There are possibilities that a vehicle may be blocked, delayed at a control point due to other's failure or totally breakdown. Limiting announcement coverage indirectly 'filters' potential recipients of the CFP. Therefore, only AGVs within strategic distance will be involved in the auction. This is important especially when dealing with large vehicles group.
- There are possibilities that more than one delivery operations are offered at the same time. Having an unlimited communication range would burden any single agent with unnecessary information processing tasks particularly from initiators that are not located within strategic distance to the vehicle.
- In terms of operational efficiency, it is good to localize AGV movement within a certain range of distance. Limiting the communication area could contribute towards localizing AGV to a specific area for most of

its time without totally restricting the vehicle to retrieve loads from different area if necessary.

However, there are also few demerits of employing bounded communication range as the condition may exposes MAs to several possibilities that may lead to lower performance. Among the possibilities include that:

- Since the CFP is only broadcasted within a specified communication range, most probably not all will receive the CFP. There is a possibility that any of the missed AGV could provide better solution compared to the vehicles that received CFP. This is particularly true if wide variation of performance measures such as AGV- CFP response time is taken into consideration.
- At any time, there could be no AGV is located within the communication range to response to the CFP announcement. In this case, MA has to wait until an AGV travels into its announcement range. This situation might delay the assignment as well as the actual pickup time.

Nevertheless, in our opinion, the merits possess more significant impact on the system compared to the demerits. As such, bounded communication range is applied by introducing location-aware algorithm to identify strategic vehicles before CFP is made.

In order to conduct a task assignment that is sensitive to the positions of the respective vehicles, the Initiator (MA) needs to enquire TA on the eligible candidates (AGVA) to receive the CFP. TA executes an algorithm to distinguish potential bidders based on their respective locations. The detail will then be send to the related MA. This is carried out before CFP is initiated. The communication sequence is depicted in Fig. 4.2 while the *Determine Eligible AGV* algorithm is as the following:

Step 1. Obtain current coordinate of AGV-x (lx_x, ly_x).

Step 2. Calculate the distance, dc_x between the pick-up station, p_{ij} and each AGV-x based on the Euclidean distance formulation as the following: $dc_x = \sqrt{(lx_{pij} - lx_x) + (ly_{pij} - ly_x)}$

Step 3. Determine the AGVs within specified broadcast range, br_m: $dc_x \leq br_m$.

Step 4. End

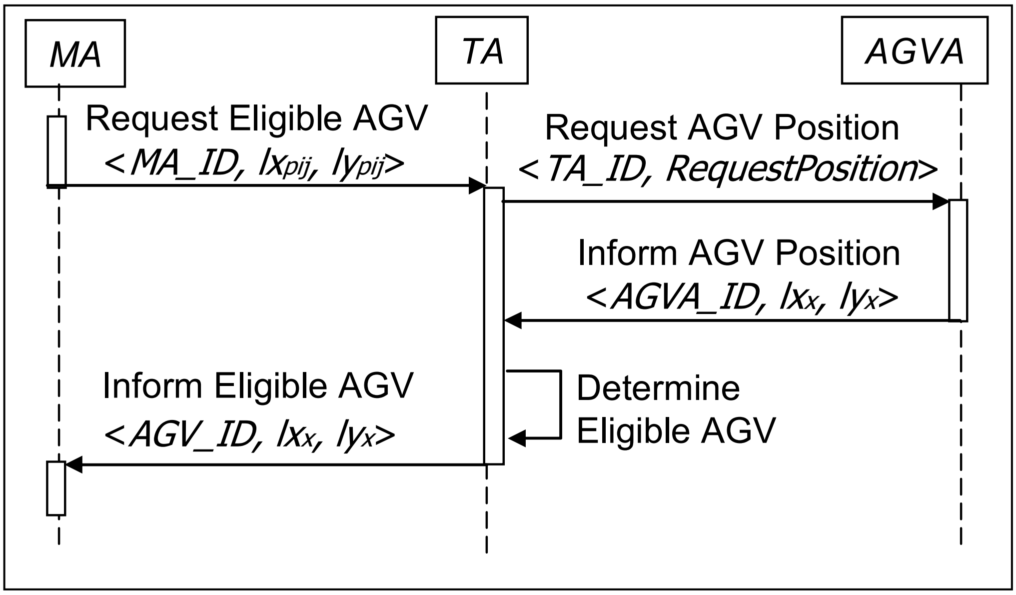

Fig. 4.2. Sequence diagram to identify potential CFP recipients.

ii) Communication Setup for Practical Application

Practical-wise, there are some points of discussion in employing the communication system in a production floor. Both wired and wireless networks could be utilized simultaneously. Wired network could be used to establish connection between Production Management System (PMS) to MA and MA-MA connections.

Wireless local area network (WLAN) is used as part of the agent communication platform particularly to accommodate AGVA-AGVA and AGVA-MA communications. In having WLAN platform, the message distance could be bounded to the coverage of IEEE 802.11 standard. Fig. 4.3 illustrates an example of agents' communication range.

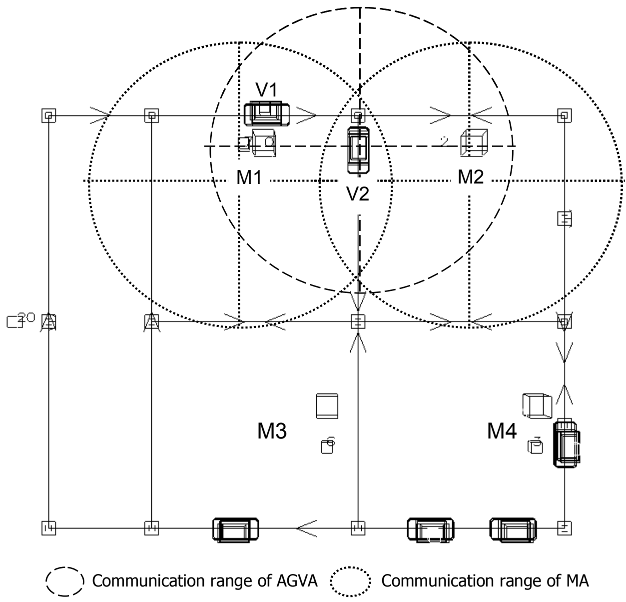

Fig. 4.3. Agents' communication range.

There is a concerning issue whenever bounded communication range is used particularly regarding the possibility to have an overlapped communication ranges. Since MA represents a machine, the entire system consists of multiple MAs which in turn could be multi initiators thus establishing a multi-initiators and multi-participants scenario. In order to avoid conflict, the system is designed so that AGV could only involve in one auction at a time. Once an AGV received broadcasted CFP, it will commit to the auction until the receiving of tentative reject message from MA or until it completes the delivery assigned.

iii) Locating and Updating the Positions of AGVs

Determination of an AGV position is closely related to the technology utilized for vehicle navigation system. As such, in order to explain the possible approaches to determine AGV positions, there may be necessary to include the discussion on the navigation system as well. Generally, the mechanisms can be categorized into three approaches as the following:

a. Vehicle-independent positioning system based on Inertial navigation system.

An inertial navigation system (INS) is a navigation system that uses a combination of computer (installed on-board of AGV), motion sensors (accelerometers) and rotation sensors (gyroscopes) to continuously calculate the position, orientation, and velocity of the AGV via dead reckoning without the need for external references.

b. Wireless Approach

- Local Positioning System (LPS)

  Local Positioning System (LPS) is a navigation system that provides location information within a specific area. Specific LPS that can be used for locating the AGV position is the Real-time Locating System that allows real-time tracking of an object. For the implementation within a factory, LPS may uses a set of beacons as the communication medium that include Wi-Fi access points or cellular base stations for communication purposes.

- Laser Target Navigation

  Retro-reflective tapes usually mounted on walls are used as the guide path. The AGV carries a laser transmitter and receiver on a rotating turret. The laser is sent off then received again the angle and distance could be calculated automatically and stored into the AGV's memory. The AGV has reflector map stored in memory and can correct its position based on errors between the expected and received measurements. It can then navigate to a destination target using the constantly updating position.

c. Fixed Path-Equipped Vehicle Positioning System

Sensors-Equipped Path: Wire-based navigation guidance is one of the oldest forms of AGV guidance. Usually, various types of sensor such as proximity and magnetic sensors could be used to track the position of an AGV.

4.3.3 Enabling CNP with Multi-Round Bidding

In realizing the protocol, there are two conditions in which task auction function would be invoked. The first condition is upon availability of any delivery task. In the context of this research, it would be triggered at the start of a machine process. MA is responsible to identify and broadcast messages to vehicles currently located within a specific distance to the machine. Then, the task auction will be conducted based on the proposed protocol.

The second condition is upon the availability of a vehicle. AGV that has just become available would announce its availability to machine agents. Should there be any available task waiting to be delivered, MA will send CFP of the task to the respective vehicle. AGV agent (AGVA) could then bid for the task.

Consider a situation where AGV v_1 (represented by *AGVA_1*) is transporting task t_1 to machine m_1 (represented by *MA_1*). In addition to that, t_2 at m_2 (represented by *MA_2*) has been tentatively assigned to v_1. While v_1 is still moving towards m_1, v_2 becomes available as it travels into m_2 communication range. It may provide better service by having earlier $at_{x,ij}$. In this case, modified CNP allows v_2 to bid for t_2 provided that it is still within auction period. If the latter bid is better than the earlier bid offered by *AGVA_1*, then *MA_2* may change the decision and award the contract to *AGVA_2*. This facilitates the interacting agents to look for the best solution available for each task. Fig. 4.4 shows the improved protocol (ICNP).

In order to call for proposals, Initiator (MA) will send delivery task specification. The analogy of the specification is SEND [*OperationID*] FROM [p_{ij}] TO [e_{ij}] WITHIN TIME [te_{ij}, tl_{ij}]. Bidders (*AGVAs*) will reply the CFP by providing earliest expected arrival time (to start pickup the task), at^x_{ij} and its next destination, *DestinationID* as the bid value which comply with (Eq. 4.1) to (Eq. 4.5). Structure for the bidding data submitted comply to the following tuple: < at^x_{ij}, *DestinationID* >.

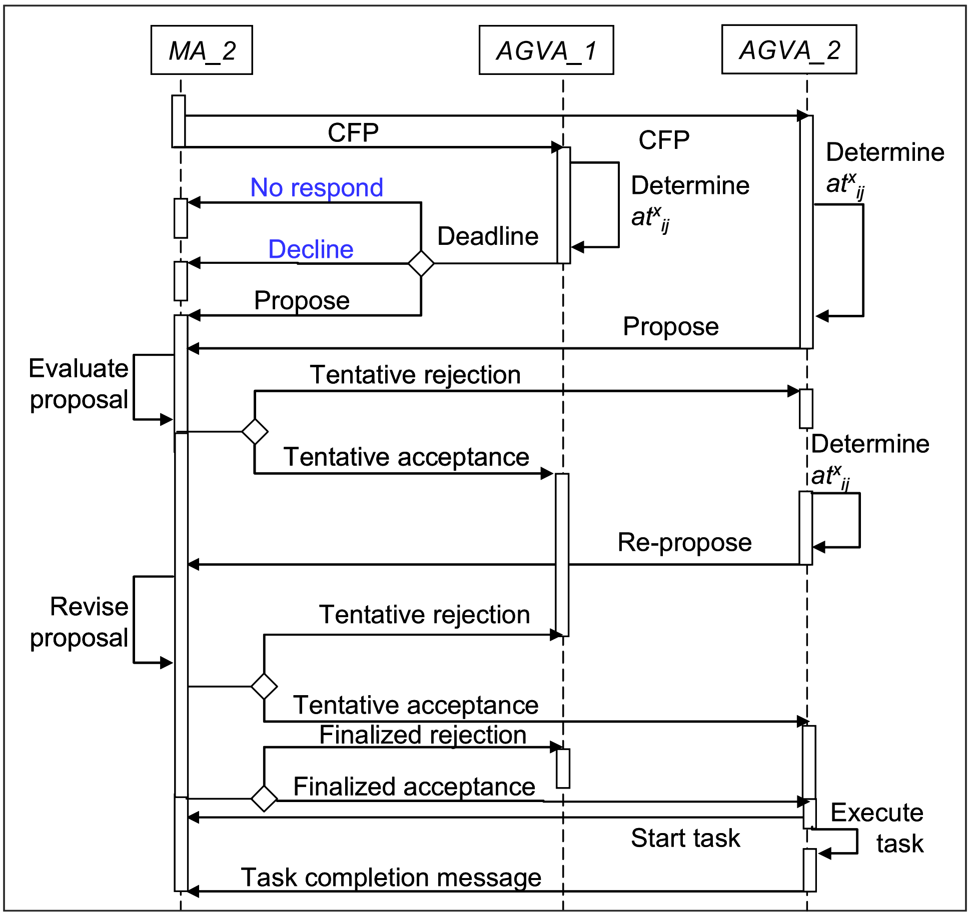

Fig. 4.4. ICNP protocol with multi-round bidding.

Upon receiving the CFP, AGVA will start to determine its earliest expected arrival time based on the following algorithm:

Step 1. Determine pickup time, tr_{ij} and delivery time, td_{ij}

Step 2. Calculate earliest AGV arrival time, at^x_{ij}

Step 3. Send bid

Step 4. End

Upon receiving bids from the AGVs, MA will evaluate them and select the best proposal. Steps of the bids processing algorithm for the first round bidding are as follows:

Step 1. Select AGVs with arrival time satisfying earliest and latest start time constraints, $te_{ij} \leq at^x_{ij} \leq tl_{ij}$.

Step 2. Calculate $wait_m$ based on each at^x_{ij}.

Step 3. Select AGV that provide Min ($wait_m$). If selected number of AGV, $Gsx > 1$, then go to Step 4. Otherwise go to Step 5.

Step 4. Select one AGV randomly.

Step 5. Assign expected loading start time, $tva_{ij} = at^x_{ij}$ and selected AGV, $SVID = AGV\text{-}x$.

Step 6. Send *TentativeAcceptance* to *AGV-x* and *TentativeReject* to others.

Step 7. End.

It will then send a *Tentative Acceptance* message to the winner while providing others with T*entative Rejection* messages. However, the initiator could still receive bids and revise the acceptance accordingly as long as it is still within the auction period. Slack time concept has been applied in establishing termination criterion for auction period. Two slack time components i) te_{ij} and ii) tl_{ij} for each delivery were calculated in order to determine the amount of time that a delivery can be delayed past its earliest start time without delaying the entire sequence operation.

As te_{ij} also marks the end of machine operation-*ij*, this research uses it as the termination criterion for auction period as defined in (Eq. 4.11) to (Eq. 4.14) where tpa^m_{ij} is the starting time of machine processing of task-*ij*. In this case, tv_{ij} need to be taken into account because the vehicle is nevertheless occupied during the process. Consequently, re-bidding for a task could be made by any vehicle until te_{ij}.

$$te_{ij} = tp^m_{ij}\alpha^m_{ij} + tpa^m_{ij}\alpha^m_{ij} - tv_{ij}\alpha^m_{ij} \quad \text{....................} \qquad (4.11)$$

$$tpa^m_{ij}\alpha^m_{ij} < tpb^m_{ij}\alpha^m_{ij} \quad \text{..} \qquad (4.12)$$

$$\sum_{i\in I}^{I}\sum_{j\in J}^{J} tpa^m_{ij}\alpha^m_{ij} + tp^m_{ij}\alpha^m_{ij} \le \sum_{i\in I}^{I}\sum_{j\in J}^{J} tpa^m_{ij+1}\alpha^m_{ij+1} \quad \text{....} \qquad (4.13)$$

$$tpa^m_{ij}\alpha^m_{ij} < tw_{ij}\alpha^m_{ij} \quad \text{...} \qquad (4.14)$$

Meanwhile, tl_{ij} value could be determined as in (Eq. 4.15) where rt_j refers to released time of job-*j*, mt_j refers to remaining time of the respective job and dt_j refers to due time of the job. Fig. 4.5 shows the conceptual time-window for auction period and the time-window constraints comply with (Eq. 4.15).

$$tl_{ij} = rt_j + dt_j - mt_j \quad \text{................................} \qquad (4.15)$$

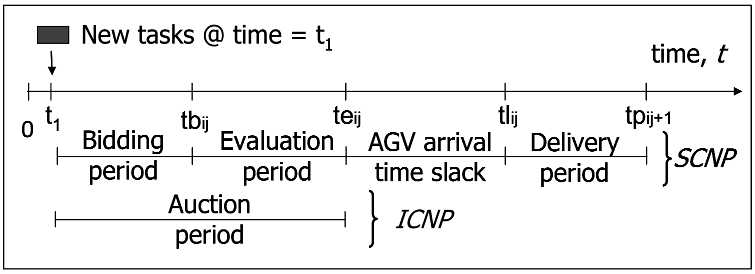

Fig. 4.5. Conceptual time-window for auction period.

The algorithm for the MA to decide the revision of the task assignment (selecting the earliest serving AGV) is as follows:

Step 1. Determine if AGV's at_x value satisfying earliest and latest start time constraints, $te_{ij} \leq at^x_{ij} \geq tl_{ij}$.

Step 2. Calculate $wait_m$ based on each at^x_{ij}.

Step 3. Compare at^x_{ij} with tva_{ij}. If $tva_{ij} > at^x_{ij}$, then go to Step 4. Otherwise go to Step 6.

Step 4. Assign $tva_{ij} = at^x_{ij}$ and selected AGV, $SVID = AGV_{x+1}$.

Step 5. Assign *TentativeAcceptance* to the AGV_{x+1} and *TentativeReject* to AGV_x. End

Step 6. Send *TentativeAcceptance* to the AGV_x and *TentativeReject* to AGV_{x+1}. End

The selected participant will send *StartTransport* message upon finishing earlier task or just before starting to transport the task. The message will trigger *CloseAuction* function where the initiator will close the respective CFP.

4.4 Worked example

4.4.1 Problem Description

This research adapted problem set from Reddy and Rao [46] as the proof of concept for the proposed protocol. In the case, AGVs are deployed as a material handling mechanism for Flexible Manufacturing System (FMS). The FMS is based on a job shop layout configuration and is depicted in Fig. 4.6.

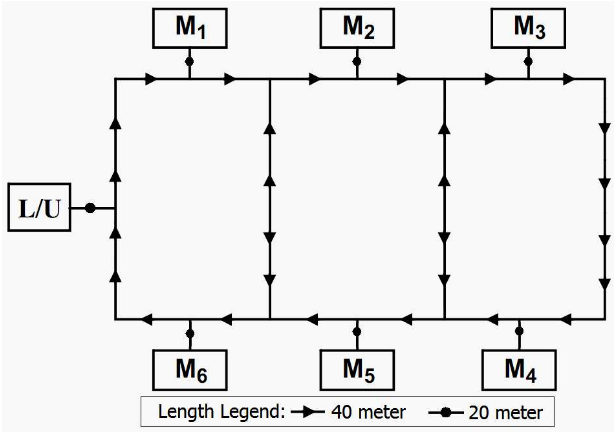

Fig. 4.6. Job shop layout configuration.

There are six non-identical computer numerical control (CNC) machines and two identical AGVs for material delivery purpose. Furthermore, this research defines:

- *job* as the product need to be produced by a manufacturing system
- *operation* as (sequence of) machine processes needed to complete a job
- *transportation task* (or *task*) as the material transfer need to be made by an AGV

The FMS system is based on certain set of assumptions. Each machine processes one operation at a time. Likewise, each AGV transports one load at a time. The speed of each vehicle is constant at 40 m/minute. Loading and unloading works consume 0.5 minute each. Transportation policy applied does not require vehicles to return to Loading/Unloading (L/U) station between operations and each station has its own parking node.

Machines processing times are normally distributed with standard deviation, σ = 0.5 minutes while jobs arrival rate comply with exponential distribution pattern. Machines are assumed to have infinite input and output buffer capacity. No part is rejected due to quality problem.

There are six job types with a sequence of six operations in every job type. Average ratio of *transportation time* to *machine processing time* = 1.38. Related data on dedicated machine (M) and processing time (PT) are shown in

Table 4.2 and the travelling distance chart (in meter unit) is shown in Table 4.3.

Table 4.2. Job sets specification.

Job Type	Operation sequence					
	1	2	3	4	5	6
	M (PT)	M (PT)	M (PT)	M (PT)	M (PT)	M (PT)
1	M2 (1)	M6 (3)	M1 (6)	M3 (7)	M5 (3)	M4 (6)
2	M1 (8)	M2 (5)	M4(10)	M5(10)	M6(10)	M3 (4)
3	M2 (5)	M3 (4)	M5 (8)	M6 (9)	M1 (1)	M4 (7)
4	M1 (5)	M6 (5)	M2 (5)	M3 (3)	M4 (8)	M5 (9)
5	M2 (9)	M1 (3)	M4 (5)	M5 (4)	M6 (3)	M3 (1)
6	M1 (3)	M3 (3)	M5 (9)	M6(10)	M4 (4)	M2 (1)

*M=Machine, PT= Processing Time (in minutes)

Table 4.3. Traveling distance chart.

Machine	**L/U**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
L/U	0	160	240	320	560	480	400
M1	400	0	120	200	440	360	280
M2	480	600	0	120	360	280	360
M3	560	680	600	0	280	360	440
M4	320	440	360	280	0	120	200
M5	240	360	280	360	600	0	120
M6	160	280	360	440	680	600	0

4.4.2 Experimental Design

This section explicitly discusses the factors of which the values were varied in the experiments. A set of experiment is designed to determine the effectiveness of the proposed vehicle control approaches. Factors that have been considered are task auction protocol and the number of vehicles utilized. The details of experimental factors are summarized in Table 4.4. Two distributed protocol have been evaluated:

- Standard CNP (*SCNP*)
- Improved CNP (*ICNP*)

Table 4.4. Experimental factors

	Factor	Range (Value)
1	Demand variation	Low to high jobs arrival rate per hour (j/h), λ (5, 10, 15, 20)
2	Fleet sizing	Low to high number of vehicles, *fs* (2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13)

In order to enable *SCNP* to use system's latest information when bidding for task, the bidding is postponed till the bid closing time. Analysis was carried out to determine the performance of agent-based AGV control system. Simulation has been carried out testing all of the combination of experimental factors over 24-hour production time based on a full factorial design. Hence, a total of 112 numbers of simulations were conducted.

4.4.3 Performance Measurement

For analysis purpose, two performance indicators (PI) - system throughput (*STH*) and percentage of loaded travel (*PLT*) have been used to measure the impact of the proposed control approaches.

STH is defined as the summation of the jobs completed by the system. It is selected as the indicator to measure the performance of the target system as a consequence of implementing the proposed protocol. Meanwhile, *PLT* is utilized to indicate the efficiency of vehicle utilization as in (Eq. 4.16).

$$PLT = \frac{\sum_{x=1}^{X} \sum_{i=1}^{I} \sum_{j=1}^{J} (td_{ij}^{x} \beta_{ij}^{x}) * 100}{TOT * fs} \quad \text{...............} \qquad (4.16)$$

Apart from both indicators, resulted *AWT* for both categories are also analyzed to give better understanding on the objective functions stated. From MAS perspective, throughput could represent the benefit gained by the auctioneer while percentage of loaded travel reflects the profit that bidders obtained through the contract awarded.

4.5 Computational experiments and analysis

4.5.1 System Development

The system application has been developed by using Eclipse 3.5.2 [47], an open-source integrated development environment (IDE) as the main tool. Meanwhile, multi agents system has been developed based on Java Agent Development Framework (JADE) control platform [48]. JADE was developed using JAVA language of Sun Microsystems. It complies with FIPA standard and is commonly used to establish multi-agent application. JADE platform provides a distributed system where it can be employed over several hosts with anyone of the host acts as a system front end.

The functions were computed using ILOG CPLEX solver [49]. OptimJ was used to integrate CPLEX solver into Eclipse IDE. OptimJ is an extension of the Java with language support for writing optimization models [50].

4.5.2 Performance analysis

In order to compare the effect of both control approaches, demand rate is fixed at 15 jobs per hour. Fig. 4.7 shows the comparison of *STH* produced by both systems under study. In general, significant improvements could be achieved when employing *ICNP* compared to *SCNP*.

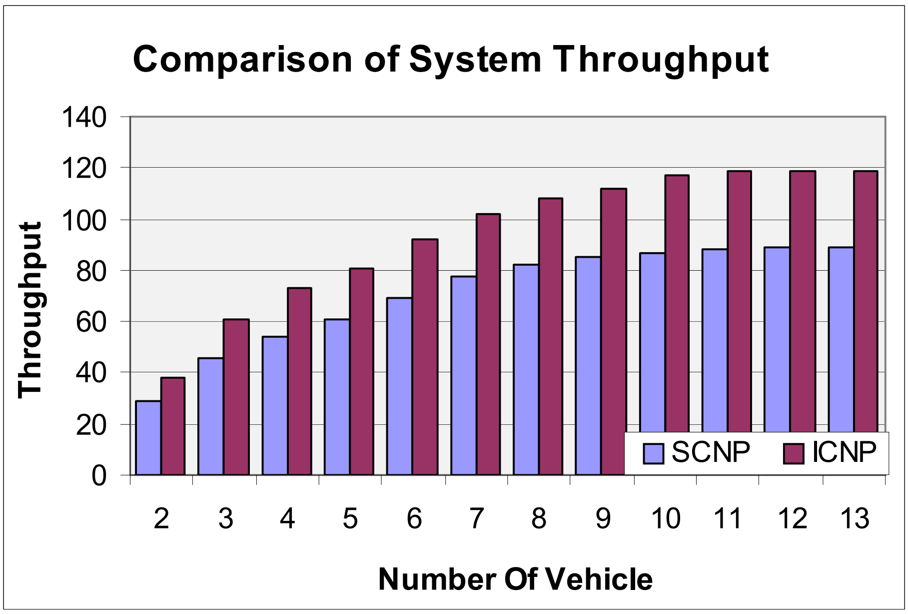

Fig. 4.7. Comparison of *STH*.

In terms of throughput improvement, an average of 33% increment could be achieved by the proposed technique. Generally, the result proved that for the specified experimental environment, the impact of transportation resource on the STH became saturated after the deployment of 11 vehicles. This can be associated to the machine bottleneck problem as the number of machines in the system is not added.

The result also shows that implementation of *ICNP* has bigger effect on larger number of vehicle when compared to the *SCNP*. This is shown by the throughput gap produced that there is a moderate increment of gap upon deployment of new vehicle. However, the increment of throughput gap stops after 10 vehicles were utilized in the MTS.

In addition, we extended the analysis by looking into the total AGV travel time for the proposed method. Generally, there is a decreasing trend of percentage of AGV travel time when NOV is increased. For instance, increasing the NOV from 2-AGV to 4-AGV resulted in reduction of travel time percentage from 93% to 79%. Furthermore, large NOV (12-AGV) resulted in under-utilized AGV of only 28%. Theoretically, it is advisable that a factory to have AGV utilization of 60% to 80% so that it could accommodate any dynamic demands (e.g.: express jobs order) or equipment failures. The result is illustrated in Fig. 4.8.

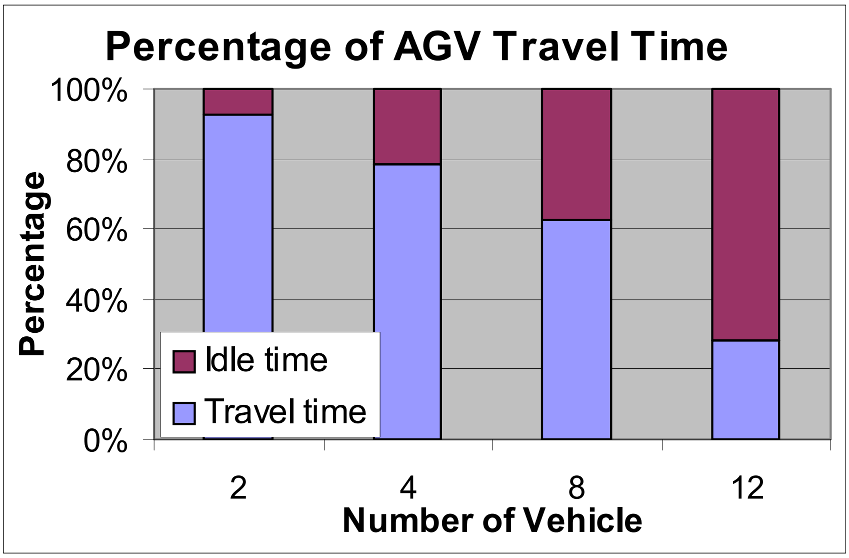

Fig. 4.8. Comparison of percentage of AGV travel time.

Additionally, there are significant differences in *PLT* between the two distributed techniques as illustrated in Fig. 4.9. This means that the improved protocol provides better vehicle utilization by minimizing empty travels. It is also found that number of vehicle factor has an impact on the percentage of loaded travel where the increment of number of vehicle leads to the decrement of loaded travel percentage. This may due to the fact that the transportation responsibilities have been fairly shared and executed by other AGV.

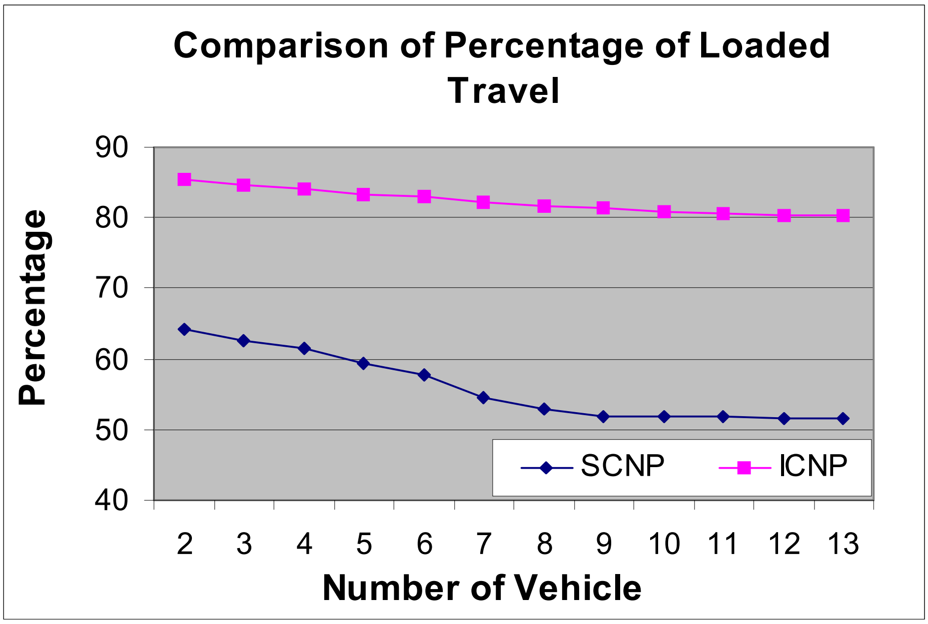

Fig. 4.9. Comparison of *PLT*.

However, the difference of loaded travel percentage between a small fleet and a bigger fleet is not critical as for the proposed technique. The difference of *PLT* between 2-AGVs and 13-AGVs is less than 5%. On the other hand, *SCNP* yielded about 12% difference between the same groups. Thus, the proposed agent control proved to be more capable in providing better performance regardless of the number of vehicle.

For analysis purpose, the *AWT* only consider the arrival within the earliest and latest pickup start time. It is due to the reason that this time-window represents the allowable AGVs' start time. Fig. 4.10 depicts *AWT* comparison between *SCNP* and *ICNP* (time unit: second). We found that applying the proposed technique directly reduced the pickup waiting time.

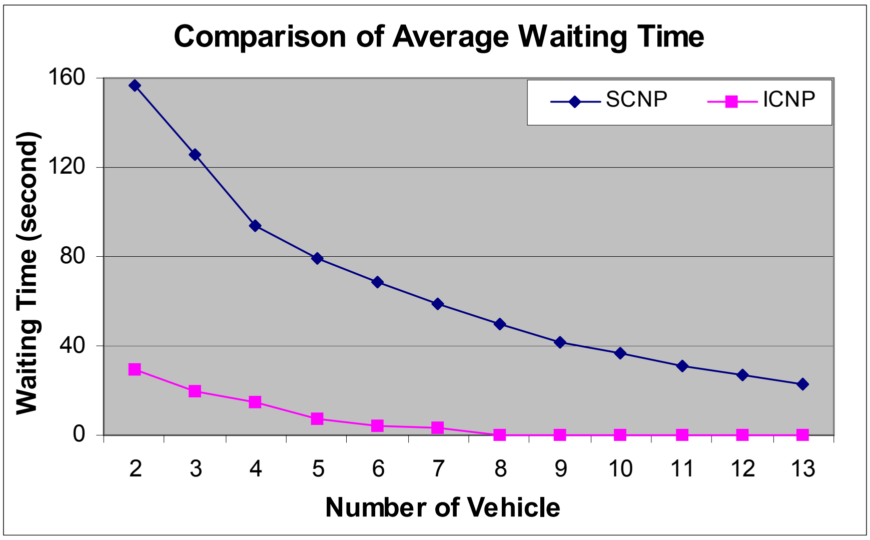

Fig. 4.10. Comparison of *AWT*.

Additionally, experiment was also conducted to determine the effect of the protocol under different environment. Number of vehicle deployed has been varied and four different job arrival rates have been used. The result is depicted in Fig. 4.11. Generally, all categories possess the same trend where there are throughput increments until reaching specific saturated points. A maximum of 12 vehicles would fully satisfy jobs demand at 20 jobs per hour rate while 11 vehicles are needed for the other demand categories. In addition, both 15 j/h and 20 j/h categories yielded small difference in term of throughput outcomes.

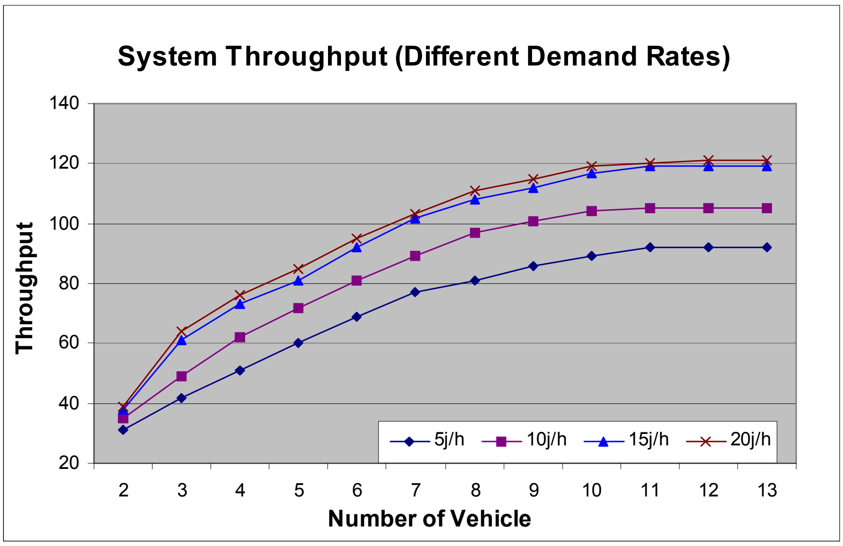

Fig. 4.11. Comparison of *STH* (different demand rates).

Meanwhile, *PLT* resulted from different job arrival rates were increased when more jobs were inputted into the system. Another observable trend is increasing the vehicle number of AGV has resulted in the decreasing of *PLT*. One of the possible causes is that when bigger fleet is employed, the chance of any specific vehicle to be assigned is get smaller.

This leads to a situation where after completed a delivery, an empty travel is needed to pick a new transportation request. Consequently, the *PLT* is reduced. This is shown in Fig. 4.12.

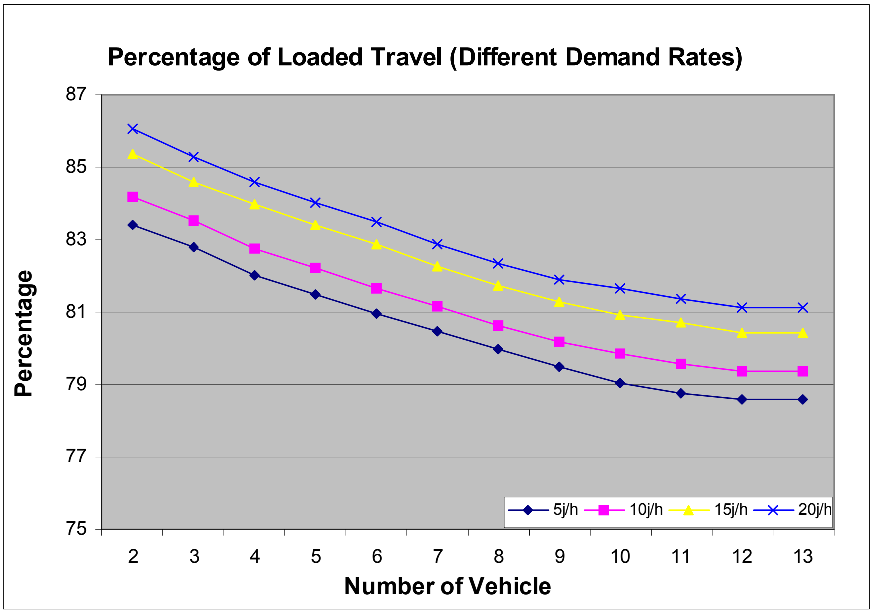

Fig. 4.12. Comparison of *PLT* (different demand rates).

4.5.3 Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) has been carried out by using Minitab software to further investigate the performance of proposed approach. Statistical tests were executed for $\alpha = 0.05$ significance level. Table 4.5 presents the effect of experimental factors on performance indicators.

Based on the result obtained, it can be indicated that number of vehicle has an important influence on both PI as the P-values are below the significance level for both factors.

Table 4.5. Main effects of design variables on PI.

Design variables	PI	*Sum of Square*	*df*	*Mean square*	*F-value*	*P-value*
Number of vehicle	*STH*	52941.888	1	52941.888	99.641	0.0000
	PLT	145.170	1	145.170	38.247	0.0001
	AWT	93.0477	1	93.0477	2873.676	0.0000
Job arrival rate	*STH*	8.715	1	8.715	0.046	0.8347
	PLT	0.796	1	0.796	0.416	0.5333
	AWT	0.356436	1	0.356	8.879	0.0138

4.5.4 Computational Requirement

Another worthy point of discussion is regarding the computational time requirement of the proposed method. Combinatorial complexity rises dramatically when number of resources and tasks pool size increase. Considering the requirement of a large scale system, we can theoretically compare the computational complexity of a centralized and distributed method. Consider a manufacturing facility where 50 AGVs are used to transport materials for 100 machines. Given total transportation tasks for 24 hours-operation is 12000 tasks (5 tasks/ machine*hour), and assume each AGV put a single bid on each task, total assignment combination are:

- Centralized control method: $n^m = 50^{12000}$
- Proposed method: n*m*k = 50*12000*50

where n = number of AGV, m = number of tasks and k = average number of bidding rounds per task. As the complexity for centralized control method would be very large, it is reasonable to say that it is not feasible for it to be computed on real-time basis. Meanwhile, the complexity for the proposed method is still within acceptable range. This proves that distributed control approach greatly reduce the computational requirement.

4.6 Summary

The chapter has successfully resolved AGVs task assignment shortcomings by extending the contract net protocol based on multi-agent architecture. Dedicated MAS configuration has been proposed as well. Dedicated functions for multi-pass proposal acceptance under limited communication range have been discussed in detail. Consequently, performance of material handling system was improved considerably.

Experiment variables were varied in order to demonstrate the flexibility of the proposed method to suit different scenarios. Based on the result, it is found that the proposed approach is able to provide better outcomes compared to the SCNP approach. Quantitatively, performance comparison between ICNP and SCNP (case: 10-AGV) are:

- STH: Improved by 34%
- PLT: Improved by 56%
- STH: Reduction of almost 100%

The result also shows that further enhancement of agent-based system could potentially be a better alternative over a centralized system.

Chapter 5

Distributed Transportation Scheduling for AGV with Multiple-Loading Capacity

5.1 Introduction

5.1.1 Overview

Recently, distributed system concept has been implemented in numerous industrial and research applications. One of the research applications that have attracted worldwide attention is the distributed manufacturing system. There are many factors that need to be considered in establishing a distributed manufacturing system. Among others are the system architecture, entities specification and conflict resolution procedure. Specific functions and decision making capability has to be equipped into each of the system components. In realizing AGV system for material transportation purpose, appropriate task assignment method need to be devised in order to enhance vehicle utilization to increase system performance. One of the increasingly prominent key research topics in distributed manufacturing system domain is regarding task assignment/ sharing problem [51], [52], [53].

Although significant improvement has been achieved as a result of numerous researches conducted on distributed AGV task assignment problem, it is obvious that the problem is still far from convincing in order to completely replace centralized AGV system in controlling industrial system, particularly from performance point of view. Therefore, there is an important need to address this issue.

Most of the researches on auction-based multi-load AGV assignment still employed conventional approach of assigning single-task per auction. In addition, [54] and [55] established task-pickup, delivery-dispatching and load selection rules to utilize multi-load vehicles. Meanwhile, [56] utilized fuzzy dispatching rules to decide between retrieve/ delivery action execution. Moreover, [34] also utilized conventional method in distributing tasks for multi-load AGV system.

The following research aims are addressed in this chapter: i) to establish a decentralized task assignment procedure for multi capacity AGV, ii) to concurrently conduct multi-tasks assignment per single auction to increase system performance and efficiency and iii) to investigate system performance when different vehicle's loading capacity is varied. We employed combinatorial auction method to solve task assignment problem for multi-load AGV. Several recent studies justify that combinatorial auction could provide good outcomes particularly to solve task assignment problem [57], [35].

5.1.2 Problem Statements

As discussed earlier, the problem of assigning transportation tasks to a fleet of vehicles inherits the Vehicle Routing Problem (VRP) set of attributes. However, in a condition where pickup and delivery requests are made in real-time mode, the requirements of the problem vary. Some of the researchers regard it as on-demand transportation [58], [59], [60] or dial-a-ride [61], [62] problems.

One of the industrial applications that inherit the problem's set of attributes is Automated Guided Vehicle (AGV). Recently, AGV is utilized to serve wide variety of industries ranging from manufacturing plant, warehouses, container terminals and even hospitals. From material handling perspective, AGV system has several advantages over other transportation system in that it is flexible and highly scalable. This is important particularly to address highly fluctuating market needs that the industry is facing. It makes the demand for AGV system to increase significantly.

Currently, there are growing interests to apply distributed control system in manufacturing industry. This is due to some advantages that could be gained when applying distributed control architecture. Among them include higher system reliability by eliminating single-node system failure, better system flexibility and scalability as well as speedier information processing where multiple entities share computational burden [63], [64]. AGV system also received worldwide attention in which various research papers [65], [66], [44] discussed on employing distributed control architecture for AGV system. In addition, task-pickup and delivery-dispatching rules to utilize multi-load vehicles has been established [67]. Besides, fuzzy dispatching rules were also tested to decide between retrieve/ delivery action execution [56]. Besides, integrated scheduling of machines and multiple-load AGV have also been devised using single scheduler approach [17].

However, despite all of the advancement achieved, there are still certain task assignment aspects that are yet to be improved. Based on our survey, there is still no paper that specifically addresses the task assignment method for multiple-load AGV based on decentralized architecture. Moreover, most of the researches on auction-based multi-load AGV assignment still employed conventional approach of assigning single-task per auction. Therefore, this chapter aims to bridge this gap.

There are some difficulties in addressing the problem. The main challenge is due to the reason that multiple-capacity vehicle possesses combinatorial resource allocation problem especially when dealing with load selection issue. Another problem is regarding the information sharing approach in a distributed environment where conflict-resolution approach needs to be established. In addressing both challenges, each entity within the operational environment needs to be equipped with specific intelligence to plan their own resource allocation aspect.

5.2 Highlights of the Chapter

This chapter proposes a contemporary approach to solve decentralized transportation assignment problem by utilizing both engineering and non-engineering approaches. In establishing a decentralized multiple tasks assignment mechanism, this chapter aims to bridge the shortcoming of the following technical requirements for a distributed AGV system to be efficiently implemented:

R1. As far as the survey is concern, all of the researches on distributed AGV task allocation depended on single-task per auction even when dealing with multi-capacity AGV. This hinders the entire assignments from being fully optimized where bidders could not evaluate the complementary or substitutability attributes among transportation requests.

R2. In order to realize a distributed transportation control architecture, there is a need to accommodate multiple-auctioneer multiple-bidder communication protocol. Conventional auction only permits single-auctioneer to multiple-bidders protocol. Thus, there is a need to improve the basic combinatorial auctions (CA).

Two strategies have been devised to overcome the identified shortcomings:

S1. Introduce task assignment procedure based on CA method. This enables the bidders to concurrently determine appropriate combination of tasks that they should transport by evaluating the interdependent of those tasks. This could reduce the risks of obtaining only a subset of tasks that are not as profitable as the entire set. Furthermore, it would also be possible for a bidder to submit multiple packages each consisting of one or more distinct tasks.

S2. A conventional CA method corresponds to trading situations of single auctioneer and multiple bidders, whereas extended framework is needed to accommodate operational requirements of a distributed automated manufacturing system. Therefore, we propose multi-lateral CA to enable multiple-auctioneers and multiple-bidders communication take place.

The proposed method to address S1 and S2 is discussed in Section III. Equally important, it is significant to clarify that the main focus of this chapter is to establish an agent-based CA method to solve AGV task assignment problem.

In order to establish an auction-based task assignment method for multiple loading AGV operation, it is essential to clarify the scope and system components. Fig. 5.1 summarizes the proposed system architecture to realize combinatorial auction mechanism. This research uses intelligent agent architecture to realize the auction mechanism. In addressing the conflict-free AGV navigation, algorithm specification from Singh and Tiwari [22] has been adopted.

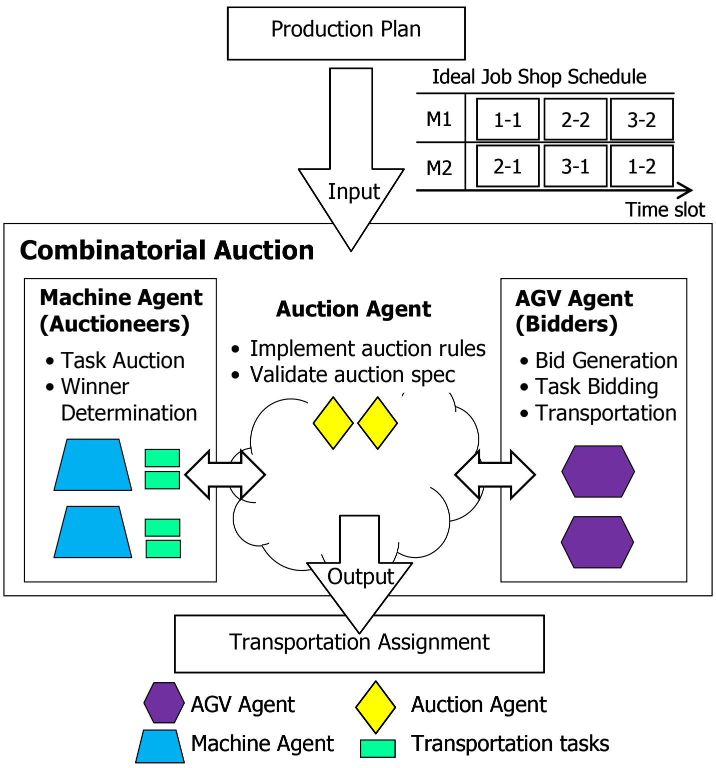

Fig. 5.1. Proposed system architecture.

5.3 Formalizing AGV Capacity Utilization using Knapsack Problem Model

Allocating transportation tasks to an AGV with multi loading capacity could be categorized as resource allocation problem. In dealing with the problem, this research used knapsack problem (KP) to model the load selection mechanism. KP that is NP-hard are formulated as in Eq. 5.1 to Eq. 5.3 where j is an item within a set of n items. Each item has its own cost, c_j and integer weight w_{ij} attributes.

Minimize $$\sum_{j=1}^{n} c_j y_j \quad (5.1)$$

$$\sum_{j=1}^{n} w_j y_j < c \quad (5.2)$$

$$y_j \in \{0,1\} \quad \forall j \in \{1,...,n\} \quad (5.3)$$

AGV has the objectives to minimize its expected arrival time and the cost to transport the loads it is taking as in Eq. 5.4. Since AGV does not deal directly with monetary profit or cost as in the conventional MKP, there is a need for this research to consider the mapping of c_j component of the objective function as in Eq. 5.5 and Eq. 5.6. Thus the complete objective function is formulated as in Eq. 5.7.

$$at_{ij}^{x} \cdot \beta_{ij}^{x} + \sum_{i=1}^{I} \sum_{j=1}^{J} c_{ij} y_{ij} \quad (5.4)$$

$$c_{ij} = \sum_{i=1}^{I} \sum_{j=1}^{J} ct \cdot sd_{ij}^{x} \cdot \beta_{ij}^{x} \quad (5.5)$$

$$y_{ij}^{x} \in \{0,1,...,n\} \quad (5.6)$$

$$w_{ij}^{x} \in \{0,1,...,Cp_x\} \quad (5.7)$$

5.4 Enabling multiple tasks assignment per auction using Combinatorial Auctions method

5.4.1 Bid Generation Problem

In bidding for transportation tasks, the main goal for vehicle is to provide the best service while minimizing its respective cost. This could be achieved by identifying and exploiting the inter-dependencies of the transportation tasks to optimize specific objective function. Consequently, AGV will bid for combination of multiple tasks simultaneously. This process is known as bid generation. It defines how and what bidder should bid based on its objectives and constraints.

Each AGVA is equipped with this function and thus enables each of them to plan their schedule and route. The function possesses components from vehicle routing model and knapsack optimization model thus making it as NP-hard problem. Discussion on how the model adapted knapsack problem has been explained earlier [69]. Moreover, y^x_{ij} refers to the quantity of a homogenous transportation request in an indivisible package. This research considers divisible package condition where each tasks does not necessarily be transported in a prespecified package. As such, $y^x_{ij} = 1$. BGP that is adopted to determine the optimal task assignment is based on the integer programming formulation as in the following:

Minimize $$at^x_{ij} \cdot \beta^x_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} ct \cdot sd^x_{ij} \cdot \beta^x_{ij} \tag{5.8}$$

Subject to

$$at^x_{ij} = tr^x_{ij} + ct_x \tag{5.9}$$

$$ct_x = \sum_{i=1}^{I}\sum_{j=1}^{J}\left[\left(tta^x_{ij} + (tr^x_{ij} + td_{ij}) + (tv_{ij} + tw_{ij})\right)\beta^x_{ij}\right] \tag{5.10}$$

$$\beta^x_{ij} = 1 \tag{5.11}$$

$$cc^x_m < cp_x \tag{5.12}$$

$$cc^x_m \geq 0 \tag{5.13}$$

$$cc^x_m + cl^x_m \leq \sum_{m \in S}^{S} \delta^x_m \cdot cp_x \tag{5.14}$$

$$ce^x_m = 1 \Rightarrow cc^x_m + cl^x_m = cc^x_n \tag{5.15}$$

$$\sum_{mn \in L}^{L} \delta^x_{mn} - \sum_{no \in L}^{L} \delta^x_{no} = 0 \tag{5.16}$$

$$\sum_{p_{ij}m \in L}^{L} \delta^x_{p_{ij}m} - \sum_{ne_{ij} \in L}^{L} \delta^x_{ne_{ij}} = 0 \tag{5.17}$$

$$\sum_{p_{ij}m \in L}^{L} \delta^x_{p_{ij}m} = 1 \tag{5.18}$$

$$\sum_{ne_{ij} \in L}^{L} \delta^x_{ne_{ij}} = 1 \tag{5.19}$$

$$\sum_{mn \in L}^{L} \delta_{mn}^{x} = 1 \qquad (5.20)$$

$$\sum_{mn \in L} \delta_{mn}^{x} + \sum_{mn \in L} \delta_{nm}^{x} \leq 1 \qquad (5.21)$$

$$sd^{x} = \sum_{i \in I}^{I} \sum_{j \in J}^{J} \sum_{mn \in L}^{L} d_{ij}^{x} \delta_{ij}^{x} \qquad (5.22)$$

$$\sum_{b \in B_x}^{B_x} \xi_{b}^{x} \geq 1 \qquad (5.23)$$

AGVA has the objective to minimize both expected arrival time and its respective transportation cost that complies to (5.8). Equation (5.9) calculates the earliest predicted arrival time for the AGV could start the pickup. Eq. (5.10) defines the expected completion time for assigned tasks. Eq. (5.11) ensures only assigned tasks are taken into consideration when estimating vehicle expected arrival time. Eq. (5.12) ensures that the number of tasks on-board is less than the full capacity the vehicle can carry. Eq. (5.13) reflects that loading capacity only takes non-negative values. Eq. (5.14) ensures loading and unloading activities are conducted within the capacity limitation. Eq. (5.15) is the binary decision variable represents the vehicle capacity.

AGV routing (Eq. 5.16 to Eq. 5.21) are based on conflict-free vehicle routing with pickup and delivery principle [17], [70]. Eq. (5.16) represents AGV routing continuity when visiting a particular machine. Any time when an AGV travels to a station through its incoming lane, the constraint ensures that the vehicle leaves through the outgoing lane. Eq. (5.17) obligates a vehicle to deliver each picked up load to the final destination. Eqs. (5.18) and (5.19) define the starting and destination nodes that an AGV needs to obligate. In addition, Eq. (5.20) ensures that at any time, each AGV is located at a unique position and Eq. (5.21) represents collision avoidance constraint. The AGV's bid generation model consist of a non-linear integer programming, which demands long computation time. Eq. (5.22) calculates the resulted traveling distance for the AGV. Eq. (5.23) necessitates the agent to involve in the auction.

5.4.2 Winner Determination Problem

In an auction procedure, an auctioneer determines the winners—that is, decides which bid is winning and which are losing based on the auctioneer's profitable gain. For single-task auction, such decision making is relatively easy as it could be carried out by selecting the highest bid for each item independently. However, WDP in combinatorial auctions is hard particularly it deals with large instances with combinatorial behavior. Thus, there is an important need to have an efficient computational system to address the problem.

Let IJ represents the set of transportation tasks to be auctioned where any AGVA can place a bid, $b_x(ij) > 0$, for any combination $ij \in IJ$. Number of tasks in the bid define the upper limit of a bid length itself. Bid with the best offer will be selected while others will be discarded. In this research bids attributes are define as the following:

- the best bid for a package is define as $b_x(ij) = \min b_x(ij)$, $x \in X$, $ij \in IJ$.
- if an agent does not bid for a task, $b_x(ij) = 0$ is assigned for the bidder.

Specific WDP function has been constructed as a mixed integer programming model. Auctioneer utilizes the function to evaluate bids received in an auction. The function should be able to single-out buyer with the best bid hence awarding the contract/ good to the buyer. In this research, MA takes the role as the auctioneer thus is equipped with the WDP module. The function is designed to find the vehicle that could provide closest at_x compared to the te_{ij}.

Minimize $$\sum_{i \in I}^{I} \sum_{j \in J}^{J} ad_{ij}^{x} \cdot \xi_{b}^{x}(ij) \tag{5.24}$$

Subject to

$$ad_{ij}^{x} = \left| te_{ij} - at_{ij}^{x} \right| \tag{5.25}$$

$$te_{ij} \le at_{ij}^{x} \le tl_{ij} \tag{5.26}$$

$$tl_{ij} = rt_j + dt_j - mt_j \tag{5.27}$$

$$te_{ij} = tp_{ij}\alpha_{ij}^m + tpa_{ij}\alpha_{ij}^m \tag{5.28}$$

$$tpa_{ij}^m \geq \left(tpa_{ij-1}^m + tp_{ij-1}^m + tv_{ij-1}\right)\alpha_{ij-1}^m + tw_{ij} \cdot \alpha_{ij}^m \tag{5.29}$$

The MA's objective function is to minimize the difference between vehicle expected arrival time and earliest task pickup time as in (5.24). Eq. (5.25) calculates the difference of earliest pickup start time and AGV expected arrival time. Eq. (5.26) ensures that expected arrival time neither start before the earliest task pickup time nor exceed the latest start time. Eq. (5.27) defines the latest start time for operation-*ij* and Eq. (5.28) suggests the definition of earliest start time. Eq. (5.29) ensures that machine operations should comply with the precedence sequence for operations belong to the same job.

5.4.3 Design of Auction Coordination

Equipping the bidding agent with ability to analyze the tasks interdependence means that it could judge the complementary attributes. However, the mechanism still does not explicitly allow the agent to express bidding substitutability. To do so, this research uses Exclusive OR (XOR) as the bidding language so that bidders could indicate their interest in two mutually exclusive bundles. The XOR auction rule used in this research is based on these assumptions:

- Each and all of the tasks can be transported by any vehicle within the system. Task is not required to be carried by a specific AGV.
- Each and all of the tasks are divisible for transportation purpose. No tasks need to be transported in specific group.
- The auction rule allows a bidder to express bidding substitutability as long as the bidder fulfills all of the bidding constraints
- A bidder may submit more than one bid package.
- At the end of an auction, a bidder can win at most one of its bids.

The research introduces Auction Agent (AA) that is responsible to implement the auction rules and coordinate the procedure. There is no specific objective function need to be computed but in implementing the rules, the agent is bound to:

- authenticates all bids submitted comply with XOR bidding rules where:

  $B_x = \{(b_1)\ xor\ (b_2)\ xor\ (b_3)\}$ and $b_1 = (<IJ,\ at_{ij}^{x}>)$ (5.30)

- validates each task is awarded at most once (Eq. 5.31).

  $$tpa_{ij}^{m} \geq \left(tpa_{ij-1}^{m} + tp_{ij-1}^{m} + tv_{ij-1}\right)\alpha_{ij-1}^{m} + tw_{ij} \cdot \alpha_{ij}^{m} \qquad (5.31)$$

- validates that the number of awards made do not exceed the number of available tasks as in Eq. (5.32). This constraint is important for conducting auction of multiple tasks.

  $$\sum_{i \in I}^{I} \sum_{j \in J}^{J} IJ_m \cdot \beta_{ij}^{x} \leq IJ_m \qquad (5.32)$$

- Validate each AGV can only win at most one of its bids. The constraint for a specific AGV complies with Eq. (5.33). This constraint is a mandatory to fulfill the XOR constraint implementation.

  $$\xi_b^x = 1 \Rightarrow \sum_{b \in B_x}^{B_x} \xi_b^x \leq 1 \qquad (5.33)$$

While the first three rules are necessary to determine either stopping criteria for the task assignment have been met, the forth rule: validation of AGV winning requires specific protocol to be achieved.

In order to carry out the assignment validation, AA is equipped with *Validate Assignment* function. The logic for the function is summarized as the following while the conflict resolution protocol involved is illustrated in Fig 5.2:

If [ξ_b^1] <= 1

Then Propagate Message to $AGVA_1$

Else If $MA_1\_ad^{x}_{ij} < MA_2\_ad^{x}_{ij}$

Then Request Revise Assignment to MA_2

Propagate MA_1_Assignment to $AGVA_1$

Else If $MA_2\_ad^x_{ij} < MA_1\_ad^x_{ij}$

Then Request Revise Assignment to MA_1

Propagate MA_2_Assignment to $AGVA_1$

Finish

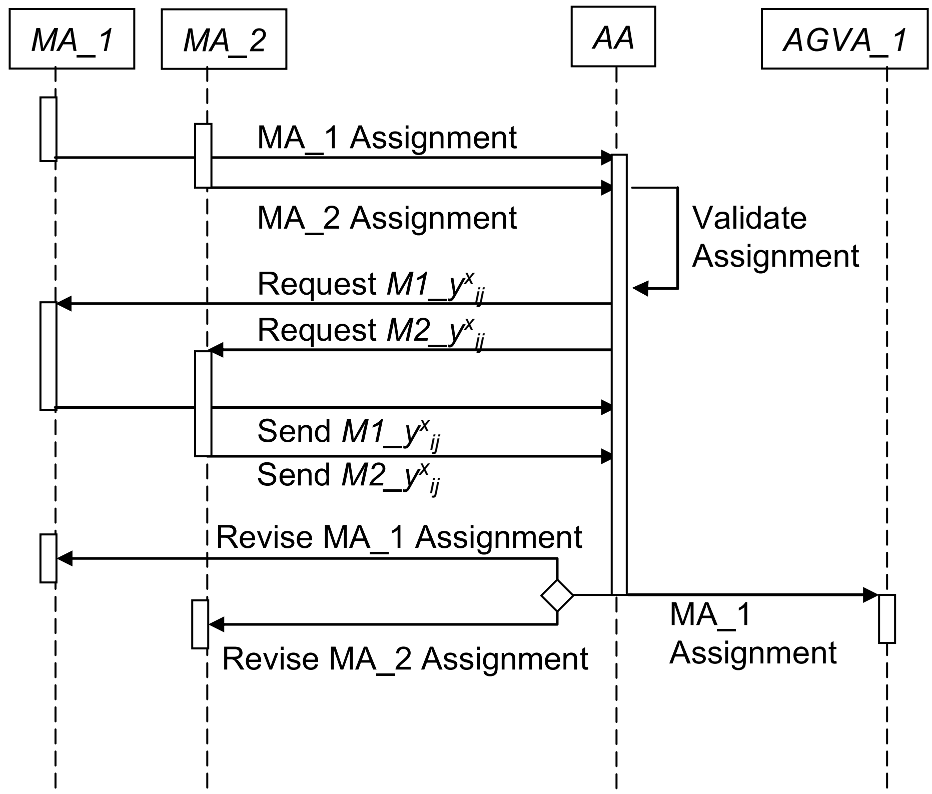

Fig. 5.2. Sequence diagram for assignments conflict resolution.

5.5 Worked example

5.5.1 Problem Description

This section tests the effectiveness of the proposed auction-based task assignment approach and compares them with other control methods. Environment setting typically employed in a manufacturing plant is studied.

Eclipse IDE [47] has been used as the main tool for system development. Simulation of the combinatorial auctions has been developed based on Recursive Porous Agent Simulation Toolkit (Repast) platform [71]. Repast is an open-source agent-based simulation package that enables systemic study of complex system behaviors through controlled and replicable computational experiments. Meanwhile, agent communication complies to Agent Communication Language (ACL) standard provided by JADE. ILOG CPLEX solver [49] was used to compute the functions for both the BGP and WDP. Meanwhile, OptimJ [50] was used to integrate CPLEX solver into Eclipse IDE. It is an extension of the Java with language support for writing optimization models.

The shop floor configuration consists of a Flexible Manufacturing System (FMS) as illustrated in Fig. 5.3. The path layout has been divided into several path segments for route analysis purpose (numbers start with prefix "A', e.g: A1).

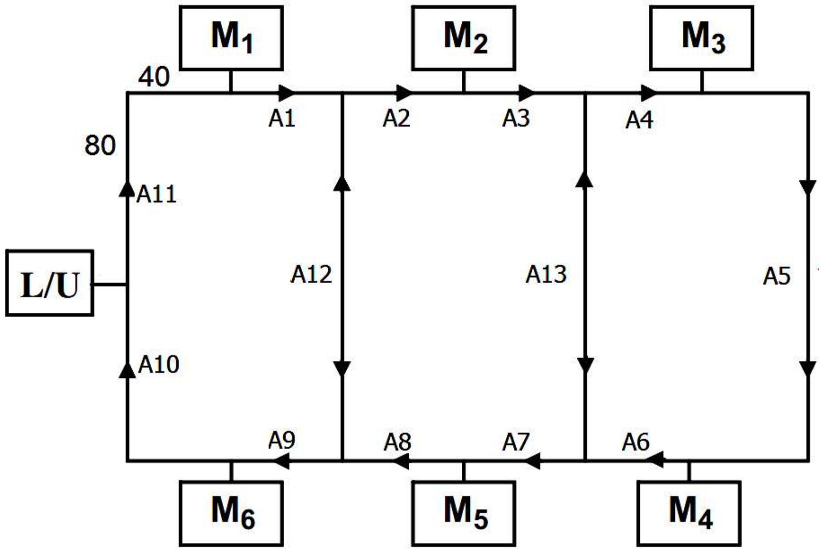

Fig. 5.3. Layout of an FMS.

The machine-to-machine distance for the shop floor is shown in Table 5.1 (in meter unit). Additionally, two job shop data set have been used independently to evaluate the effectiveness of the proposed approach as the following:

- Example 1.
- Example 2.

Table 5.1. Machine-to-machine distance chart.

Machine	L/U	M1	M2	M3	M4	M5	M6
L/U	0	160	240	320	560	480	400
M1	400	0	120	200	440	360	280
M2	480	600	0	120	360	280	360
M3	560	680	600	0	280	360	440
M4	320	440	360	280	0	120	200
M5	240	360	280	360	600	0	120
M6	160	280	360	440	680	600	0

System specification is as the following:

- The FMS consists of six CNC machines and two AGVs.
- Due time, dt_j for each job is 35 minutes which also serves as the maximum flow time for each job.
- Loading and unloading times are fixed at 0.5 min each.
- There are 6 job sets with each possessing six different operations sequence, dedicated machine, M and processing time, PT. The machine operations are given in M(PT) format, e.g.: M3(4) means the operation by machine M3 takes 4 minutes to complete. Details are given in Table 5.2 (Example 1) and Table 5.3 (Example 2).
- Vehicles constantly travel at 40 m/min.
- AGV does not need to return to Loading/ Unloading (L/U) station in between transportation job.
- All resources are assumed to have 100% efficiency.
- Machines processing times are normally distributed with standard deviation, $\sigma = 0.5$ minutes.
- Jobs arrival rate with mean, E = 20 minutes according to an exponential distribution.
- First Come First Serve (FCFS) dispatching rule is employed in managing L/U outgoing queue.

Table 5.2. Job set details (Example 1).

Job Set	Operation sequence					
	1	2	3	4	5	6
1	M2 (1)	M6 (3)	M1 (6)	M3 (7)	M5 (3)	M4 (6)
2	M1 (8)	M2 (5)	M4(10)	M5(10)	M6(10)	M3 (4)
3	M2 (5)	M3 (4)	M5 (8)	M6 (9)	M1 (1)	M4 (7)
4	M1 (5)	M6 (5)	M2 (5)	M3 (3)	M4 (8)	M5 (9)
5	M2 (9)	M1 (3)	M4 (5)	M5 (4)	M6 (3)	M3 (1)
6	M1 (3)	M3 (3)	M5 (9)	M6(10)	M4 (4)	M2 (1)

Table 5.3. Job set details (Example 2).

Job Set	Operation sequence					
	1	2	3	4	5	6
1	M3(1)	M1(3)	M2(6)	M4(7)	M6(3)	M5(6)
2	M2(8)	M3(5)	M5(10)	M6(10)	M1(10)	M4(4)
3	M3(5)	M4(4)	M6(8)	M1(9)	M2(1)	M5(7)
4	M2(5)	M1(5)	M3(5)	M4(3)	M5(8)	M6(9)
5	M3(9)	M2(3)	M5(5)	M6(4)	M1(3)	M4(1)
6	M2(3)	M4(3)	M6(9)	M1(10)	M5(4)	M3(1)

5.5.2 Experimental Work

To exemplify the solution methodology, this section implements the combinatorial auction model into the specified FMS problem configuration. Data communication involves during the auction are as the following:

- Data structure of the tasks announcement made by MA:

  $<IJ, p_{ij}, e_{ij}, te_i, tl_{ij}>$.

- Upon determining its suitability to transport the auctioned tasks, AGVA will send set of bids attempting to acquire the tasks. Bidding data submitted are:

$B_x = \{(b_1) \text{ xor } (b_2) \text{ xor } (b_t)\}$ where $b_1 = (\langle IJ, at^x_{ij} \rangle)$.

- Auctioneer will find the best offer and award the task to the winner. The award data structure is $\langle IJ, AGV_x \rangle$.

Example 1

The first instance takes tasks assignment condition for 2 vehicles with 3-loading capacity each. Table 5.4 shows an example of six independent tasks that need to be transported. The information in the table refers to the information of the transportation request made by MA.

Table 5.4. List of transportation requests.

Operation ID	Request ID	p_{ij}	e_{ij}	te_{ij}	tl_{ij}
ON6.2	L11	M3	M5	10:33	10:45
ON5.2	L12	M1	M4	10:32	10:40
ON0.1	L15	L/U	M2	10:28	10:36
ON2.3	L16	M4	M5	10:43	10:54
ON5.1	L19	M2	M1	10:30	10:40
ON6.1	L20	M1	M3	10:35	10:45
ON3.4	L21	M6	M1	10:52	10:57
ON0.2	L24	L/U	M1	10:55	11:02
ON4.3	L26	M2	M3	10:42	10:50

Upon starting the machine processing of operation-*ij*, MA computes the expected finish time for the machine operation. The expected finish time also serves as the earliest task pickup time, teij. Both te_{ij} and latest task pickup time, tl_{ij} were computed based on Eq. 18 and Eq. 19. Both te_{ij} and tl_{ij} are the timestamps and format of 'hour:minute' are used. Data on the pickup station, p_{ij} and delivery station, e_{ij} could be extracted based on operation sequence information in Table 5.2.

A standard naming convention is used as an identifier for all of the operations. Operation is named based on its respective "job.operation sequence" information format with "ON" prefix, e.g. the third operation of Job 6 will be identified as ON6.3. Furthermore, in identifying transportation requests, all of the requests are also labeled based on the chronological order.

Request names start with prefix “L”, e.g. L10.

Each bidder calculates the best transport combination it could offer and submits the bid to the auctioneer. In this case each AGV would attempt to minimize its traveling distance subject to a set of constraints. Shortest path for AGV-x, d^x_{ij} to transport load-ij from pickup node, p_{ij} to destination node, e_{ij} is derived from the distance matrix.

Participant will then submit arbitrary number of bids as XOR bidding rule is employed. Table 5.5 depicts partial bid specification generated and subsequently submitted to auctioneers based on the auctioned tasks as in Table 5.4.

Table 5.5. Partial generated bid specification.

AGV	Bid ID	Bid Details (Request ID, at_x)
AGV$_1$	B1-1	(<L12,10.32>)
	B1-2	(<L12,10.32>, <L16, 10.43>)
	B1-3	(<L15, 10.28>, <L12,10.32>, <L20, 10.35>)
	B1-4	(<L15, 10.28>, <L12,10.32>, <L20, 10.35>, <L26, 10.42>)
AGV$_2$	B2-1	(<L19, 10.30>, <L11,10.34>)
	B2-2	(<L19, 10.30>, <L11,10.34>, <L16, 10.42>)
	B2-3	(<L19, 10.30>, <L11,10.34>, <L16, 10.42>, <L21, 10.51>, <L24, 10.56>)

Transportation assignments are made based on the AGV that is capable to provide the best pickup time compared to the earliest pickup start time. In term of the AGV movement, a reasonably good vehicle routing could be obtained based on the routing decision made. The awarded tasks are listed Table 5.6.

Meanwhile, Fig. 5.4 depicts the traveling route for both vehicles and their respective total traveling distances based on the awarded tasks (B1-4 and B2-3 respectively). Supplementary to the route, Fig. 5.5 exhibits the travel time window of both vehicles as well as the stops made for pickup and delivery.

Table 5.6. Awarded tasks for each AGV.

AGV	Awarded Tasks (respective at_x sequence)
AGV_1	L15, L12, L20, L26 (10.28, 10.32, 10.35, 10.42)
AGV_2	L19, L11, L16, L21, L24 (10.30, 10.33, 10.43, 10.52, 10.56)

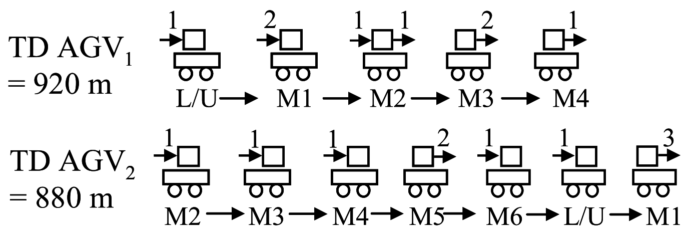

Fig. 5.4. Vehicle routing based on the awarded tasks.

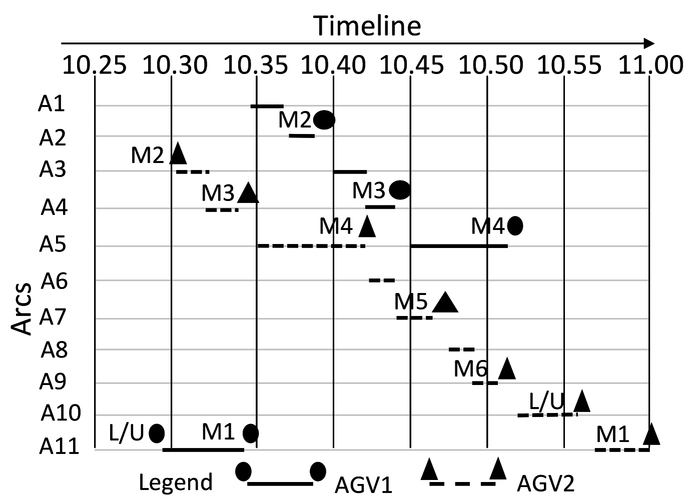

Fig. 5.5. Travel timeline of both vehicle.

Example 2

In addition to the first example, another case was also used to evaluate the proposed method (the job set detail is given in Table 5.3). The instance for list of the transportation requests for is provided in Table 5.7. AGV fleet of 4-vehicle with 2-loading capacity were deployed for material transportation purpose.

Table 5.7. List of transportation requests (Example 2)

Operation ID	Request ID	mp_{ij}	md_{ij}	te_{ij}	tl_{ij}
ON2.2	L112	M3	M5	4:10	4:15
ON3.5	L114	M2	M5	4:15	4:21
ON6.3	L115	M6	M1	4:15	4:26
ON5.5	L116	M1	M4	4:18	4:22
ON1.4	L117	M4	M6	4:18	4:26
ON0.5	L118	L/U	M3	4:20	4:45
ON4.3	L120	M5	M3	4:25	4:38

Consequently, the tasks assignment for each of the vehicle is summarized in Table 5.8.

Table 5.8. Awarded tasks for each AGV.

AGV	Awarded Tasks (respective at_x sequence)
AGV_1	L112, L117 (4:10, 4:17)
AGV_2	L115, L118 (4:15, 4:19)
AGV_3	L116 (4:15)
AGV_4	L114, L120 (4:15, 4:22)

The corresponding vehicle routing and the traveling timeline are shown in Fig. 5.6 and Fig. 5.7. Based on Fig. 5.7, it is visible that there are sufficient time gap among all of the AGVs when traveling along a path segment.

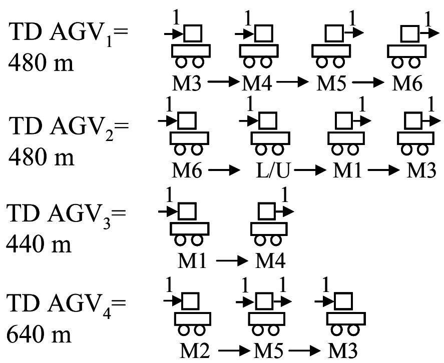

Fig. 5.6. Vehicle routing (Example 2)

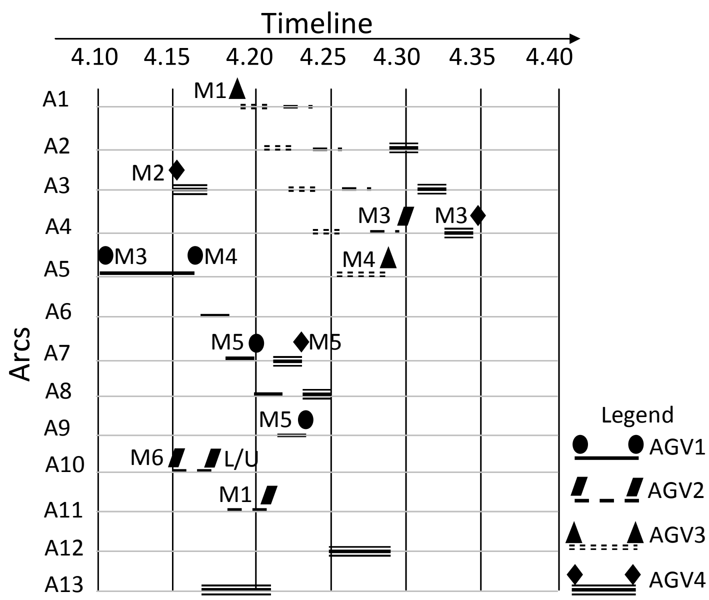

Fig. 5.7. Travel timeline (Example 2)

5.6 Performance Measurement

This research decided to use the performance measurement of three different aspects of the auction mechanism by using three performance indicators (PI). The CA aspects and their respective PIs are as the following:

- System performance.

  Throughput (*STH*) is selected as an indicator to measure the performance of the system because it could reflects the system efficiency as a consequence of implementing the proposed method. Throughput is defined as the summation of the jobs completed by the system.

- Bidders performance.

  Percentage of fully loaded travel (*FLT*) is an important measure to indicate the direct impact of the proposed method on the bidders' own operation. Percentage of fully loaded travel is defined as the percentage of time duration the vehicles are fully loaded in comparison to the entire operation time. Fully loaded travel distance is computed by using Eq. (5.34) while the average fully loaded travel is measured by Eq. (5.35).

$$loaded_x = \sum_{i\in I}^{I}\sum_{j\in J}^{J}\sum_{mn\in L}^{L}|Ce_{ax} - 1|(\beta_{ij}^{x})(td_{ij}) \quad (5.34)$$

$$FLT = \sum_{x\in X}^{X}\left(\frac{loaded_x}{totalTime \cdot |X|}\right) \quad (5.35)$$

- Auctioneers performance.

  In this case, auctioneers also act as the customers as winning bidders will serve respective auctioneers. In order to measure the impact of proposed method on the customer, average waiting time is used as the indicator. In this case waiting time is defined as the actual arrival time with regards to the earliest start time. Total waiting time (in seconds) for each machine is defined as in Eq. (5.36) and the average waiting time (*PWT*) is calculated as in Eq. (5.37).

$$wait_m = \sum_{i=1}^{I}\sum_{j=1}^{J}(tva_{ij} - te_{ij})\alpha_{ij}^{m} \quad (5.36)$$

$$PWT = \sum_{m=1}^{M}\left(\frac{wait_m}{J_m}\right) \quad (5.37)$$

5.7 Result and analysis

Analysis has been conducted with the intention to demonstrate the performance of auction-based task assignment technique for multi-load AGV. Using Example 1, experiments have been carried out to investigate system performance over a 24-hour production time. Experimental factors have been varied as listed in Table 5.9 while the Design of Experiment (DOE) was based on a full factorial design. Hence a total of 24 sets of simulation were conducted.

Table 5.9. Experimental factors.

	Factor	Range (Value)
1	Loading capacity	Low to high loading capacity (1, 3, 5, 7)
2	Fleet sizing	Low to high number of vehicles (2, 4, 6, 8, 10, 12)

5.7.1 Performance Analysis

The resulted performances are as the following:

- *STH* analysis – Deployment of different number of vehicle evoked different *STH* outcomes. The result shown in Fig. 5.8 ascertains that single-loading AGV is not capable to achieve the throughput obtained by fleet of multi-load AGV. Additionally, the deployment of vehicle with bigger loading capacity would directly contribute to increase system throughput when compared to the same number of vehicle with lower capacity. Vehicle with 5- and 7-capacity reached maximum throughput with 6-AGV. Meanwhile 3-capacity AGV only managed to reach the saturation points with 8-AGV.

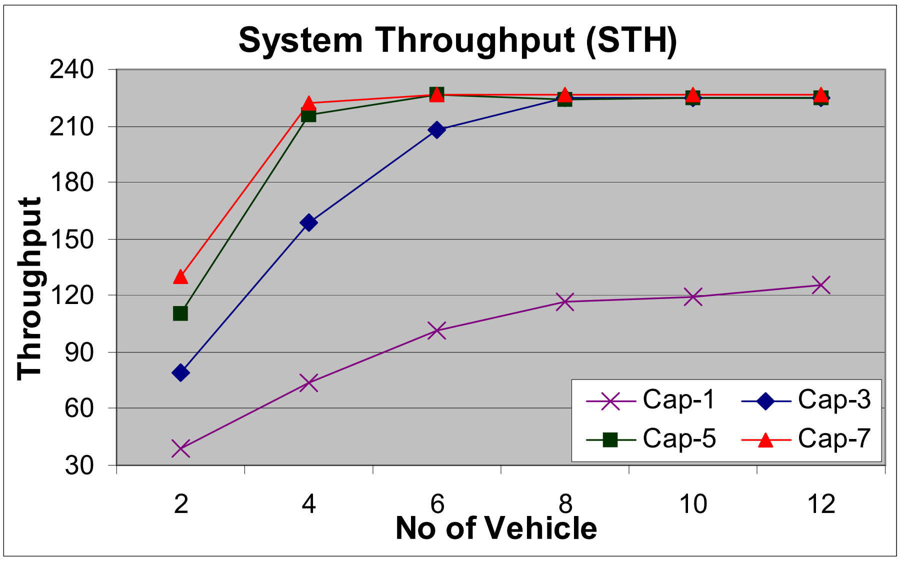

Fig. 5.8. Comparison of *STH*

- *PWT* analysis – Fig. 5.9 depicts *PWT* comparison for all of the capacity groups. We find that increasing the capacity would result in lowering the pickup waiting time. The differences are bigger when the NOV are smaller (2- and 4- AGV groups). It is worth to mention that optimization function should not feature maximizing the load quantity as an objective as it may directly increase *PWT*.

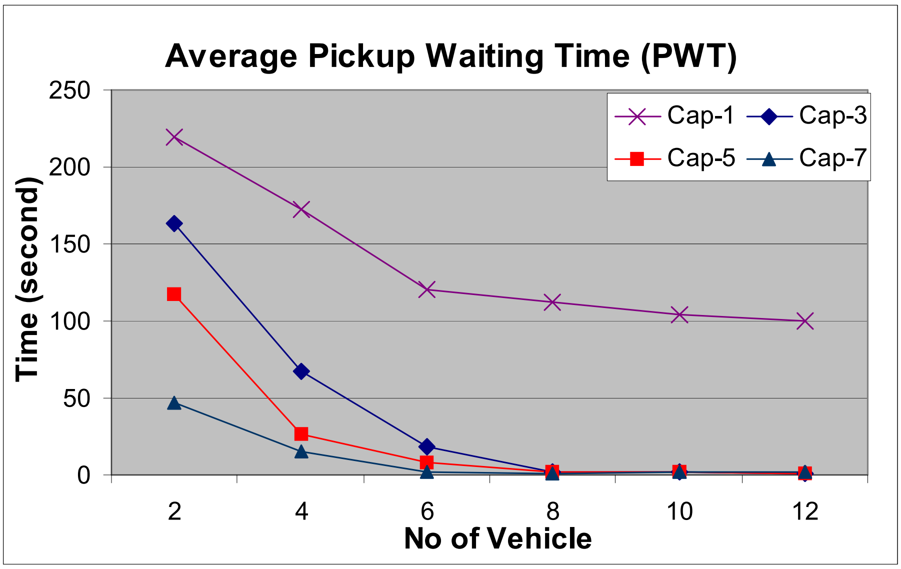

Fig. 5.9. Comparison of *PWT*

- *FLT* analysis – Fig. 5.10 illustrates the resulted capacity utilization for the selected loading capacity. There are different characteristics between single-load and multi-load categories. Single-load AGV didn't have huge impact on the characteristic of *FLT* when number of vehicle is increased. On the contrary, the *FLT* were reduced significantly when the NOV of multi-load AGV were increased. In solving the specified FMS problem, 3-capacity AGV proved to have the best performance in term of capacity utilization particularly for NOV: 2-AGV and 4-AGV.

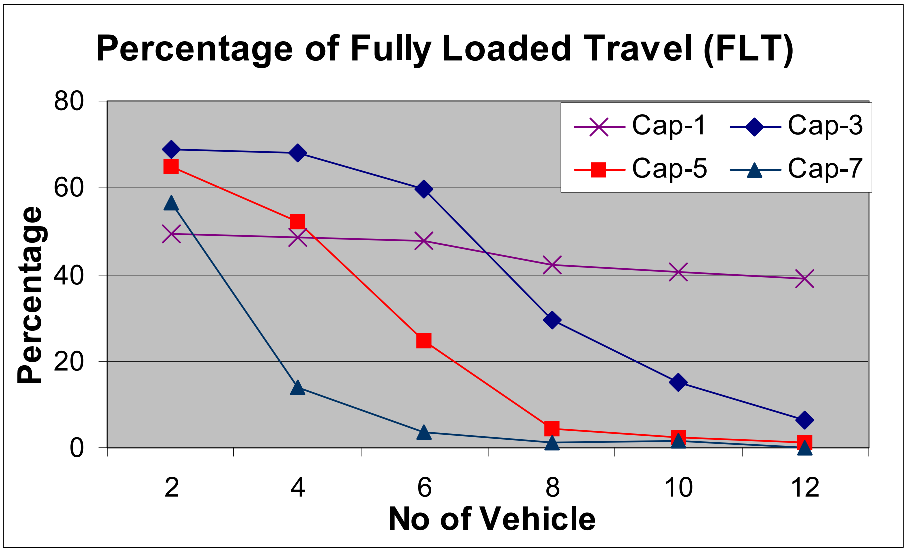

Fig. 5.10. Comparison of *FLT*

Additionally, understanding the resultant of *FLT* would provide fundamental knowledge on how vehicle capacities can be utilized. For instance, if a warehouse or production plant intents to expand their material handling capacity, they will be able to take into account the utilization aspect.

Based on the analyzed results (in Fig. 5.8 to Fig. 5.10), it can be summarized that utilizing multi-load AGV could reduce the NOV required in achieving specific performance targets. Comparison on the achievement of system performance between single-load (case: 8-AGV with 1-CAP) and multi-load AGV (case: 2-AGV with 5-CAP) are as the following:

- Efficient energy utilization.

  Analyzing the FLT achievement, single-load AGV resulted in FLT of 45% while multi-load AGV resulted in FLT of 52%. This shows that utilization of multi-load AGV could result in better energy utilization by obtaining higher percentage of fully loaded travel.

- Reduced NOV is required in achieving specific level of production performance.

  Single-load AGV is able to produce STH of 117 jobs. Alternatively, utilizing multi-load AGV shows that multi-load AGV could produce STH of 114 jobs; that is approximately the same level of STH. Looking into performance of PWT, single-load AGV resulted in PWT of 112 seconds while multi-load AGV resulted in PWT of 116 seconds.

5.7.2 Sensitivity Analysis for Single Variable

In order to get the insight of how STH performance is affected by the increment of CAP compared to the increment of NOV independently, the analysis was extended by comparing the achievement of STH level for both categories. Values for vehicle capacity and number of vehicle have been varied. The corresponding STH are shown in Table 5.10.

Table 5.10. STH resulted from variation of design variable.

		CAP Variation		
		2-Cap	4-Cap	6-Cap
NOV Variation	2-AGV	51	94	129
	4-AGV	108	-	-
	6-AGV	148	-	-

Comparison between 2-AGV with 2- and 6-capacities demonstrates that STH could be improved by 153%. Meanwhile, comparison between 2- and 6-AGV with 2-capacity each resulted in throughput improvement of 190%. This proves that NOV has greater effect on STH compared to CAP. The comparison is depicted in Fig. 5.11.

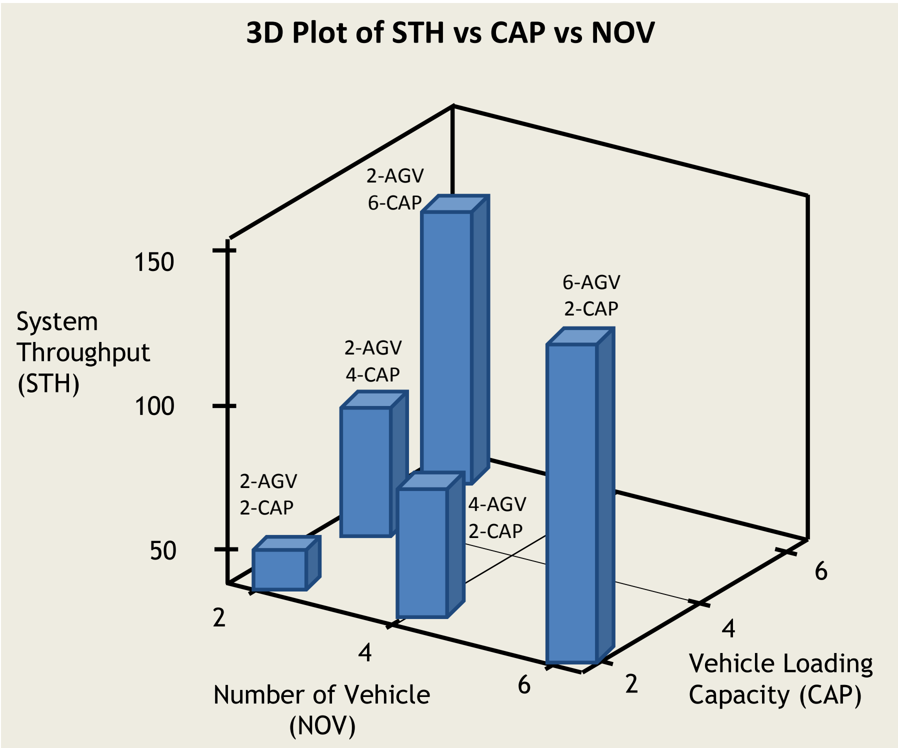

Fig. 5.11. Comparison of *STH* (design variable analysis)

5.7.3 Benchmark Study against Centralized Optimization Method

In order to determine the performance of the proposed method relative to the conventional centralized optimization methods, we have conducted benchmark study to compare the *STH* performance for case: 4-AGV with 3-capacity. Fixed input has been used in order to provide equal requirement for job arrival. Analysis for computational requirement considers the monitoring period of 20 minutes involving the assignment of 12 transportation tasks.

In a conventional transportation task assignment approach, AGV doesn't need to bid for any transportation task. A centralized scheduler is equipped with the necessary functions to allocate all of the tasks to the entire fleet. For the Centralized Method, i) the optimization equations (Eq. 5.8 and Eq 5.24) have been aggregated and ii) respective constraints (Eq. 5.9 to Eq. 5.23 and Eq. 5.25 to Eq. 5.29) been directly coded based on centralized scheduler architecture. Mathematical model for Centralized Method is directly coded and solved by using ILOG CPLEX software.

Yielded *STH* values and the computational requirements have been analyzed as the following:

- *STH* comparison – Fig. 5.12 shows the STH achievement by both Proposed and Centralized methods for different NOV. On average the proposed method could achieved 82% of the STH produced by the centralized system.

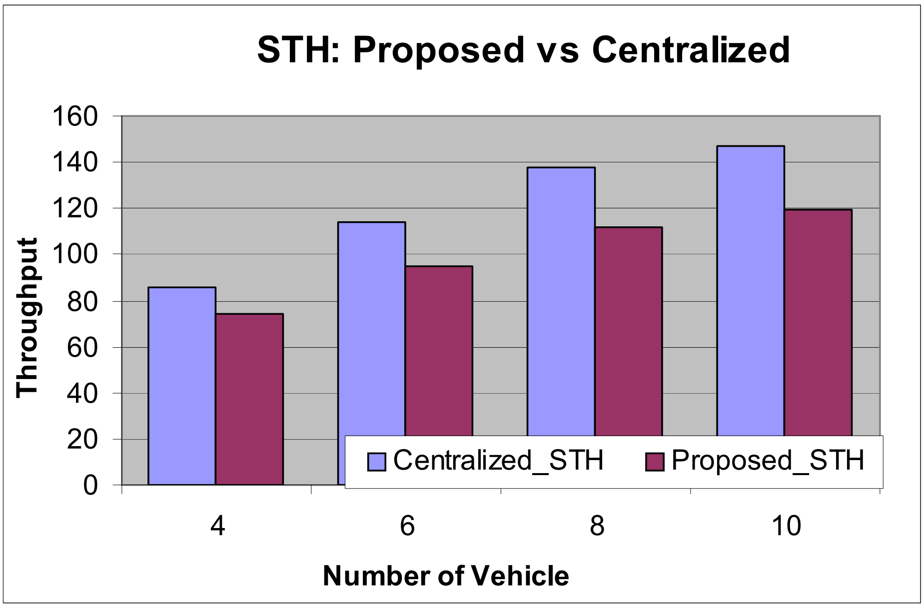

Fig. 5.12. Optimality Analysis (Comparison of STH)

- In term of the computational requirement, there are large gaps for the time needed between both of the approaches as shown in Fig. 5.13. The reason on why distributed approach needed far less time are due to the fact the optimization model has been decomposed into sub-models where each agent solves the model that suits its own interest. This enables parallel computing to be conducted within the system as well as adheres to the principle of divide-and-conquer algorithm in solving complex problem.

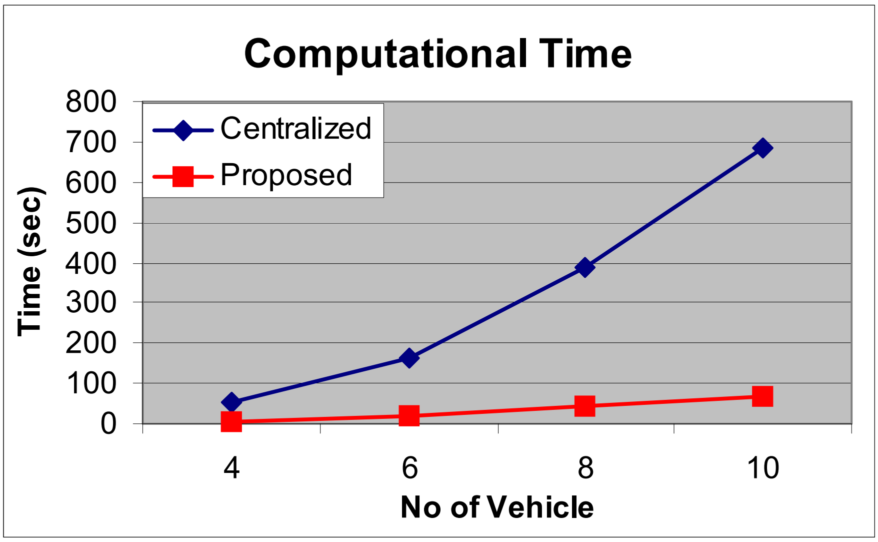

Fig. 5.13. Optimality Analysis (Comparison of computational time)

5.8 Summary

This study has proposed a combinatorial auction with XOR auction rule approach to solve distributed task assignment problem for multiple loading capacity AGV. Analysis has been carried out and performance indicators shown that multi-load AGV could outperform single-load AGV significantly. The chapter summarizes that:

- Even though centralized-approach may provide better solution, it can't provide it in a timely manner especially when the problem size increases. This raises the feasibility issue particularly in responding to various dynamic factors.
- There is a need to further investigate the interaction effects of both design variables on multiple objective functions. This is important particularly when large scale AGV system need to be designed. As such, the chapter follows will discuss on the matter.

Chapter 6

Multi Objective Design Procedure for AGV System and Its Case Study

6.1 Introduction

This dissertation has presented the improved methods to establish an efficient scheduling for autonomous AGV with multiple-loading capacity in both Chapters 4 and 5. Another important perspective need to be studied when considering the implementation of AGV system is the system design.

With regards to the operational design domain, among the important aspect of AGV system design is vehicle requirement analysis. This research refers vehicle requirement analysis as the process of defining the best combination of design variables, which include the number of vehicle to deliver specific amount of transportation requests and to obtain desired level of performances.

Looking at the recent trend where AGVs have been deployed in various other industrial sectors which include container terminals, hospital and warehouses [72], [73], [74], providing an efficient system design method is critical to ensure the actual implementations and investments will be profitable.

This chapter focuses on addressing the issue by providing an effective design tool to decide design parameter of MAS-based AGV system for multi-objective problem. Two main approaches have been taken to establish the simulation-approach of MAS-based AGV system design: i) development of integrated simulation tool for MAS-based AGV system; ii) utilize RSM method for optimizing design parameters' values using dominance-based multi-objective optimization approach.

6.2 Design Procedure of MAS-based AGV System

There are some stages needed in order to carry out the system design. The stages utilized in this research include:

i) Model specification – acquisition of production system specification.

ii) Model simulation – development of simulation model based on the acquired specification.

iii) RSM analysis – analysis of simulation result to determine best combination of design parameters.

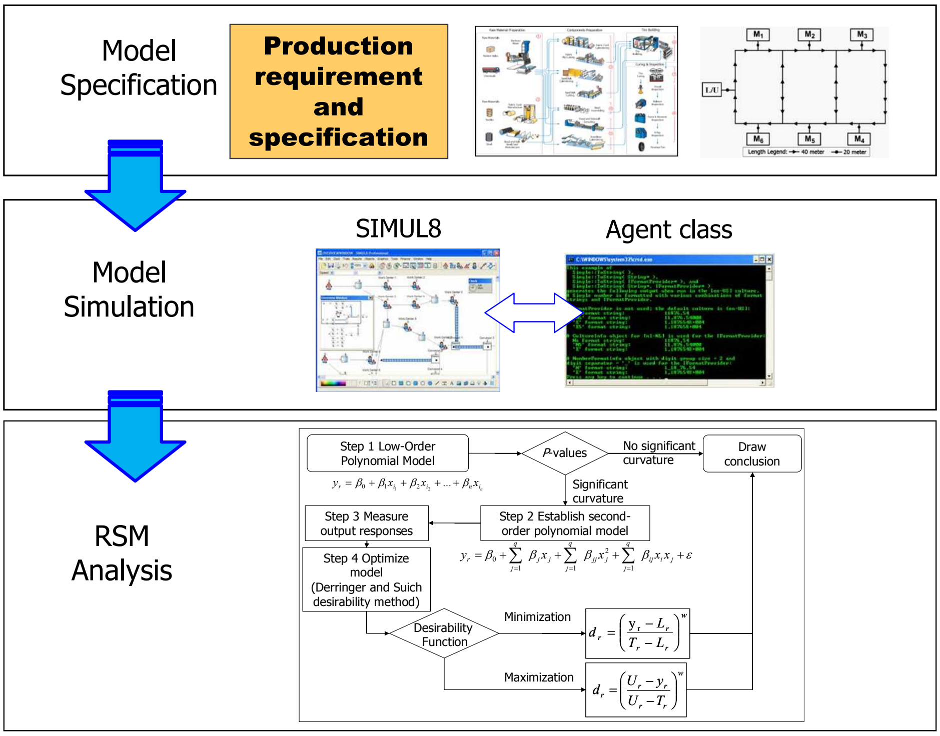

Fig. 6.1. Stages of AGV system design.

6.3 Configuration of the Proposed Design Tool

There are some components needed in order to carry out the system design. The components are:

- *Agent class* is the collection of classes containing agents' functions. It is necessary to conduct agent-based AGV system design. Three types of agent developed are AGV Agent, Machine Agent and Monitor and Coordinate Agent.
- *RSM Tool* is necessary to carry out result analysis based on Response Surface Method. RSM Tool uses input data from Simul8.
- *Data Visualization Tool* is necessary to provide graphical interactivity of the RSM result. System designer will be able to use it in making decision on the combination of design variables.
- *Component Object Model (COM)* is necessary to integrate agent object into SIMUL8 program.
- *Simul8* is necessary as the simulation tool.
- *Windows* as the computer Operating System used.

The proposed tool configuration is depicted in Fig. 6.2.

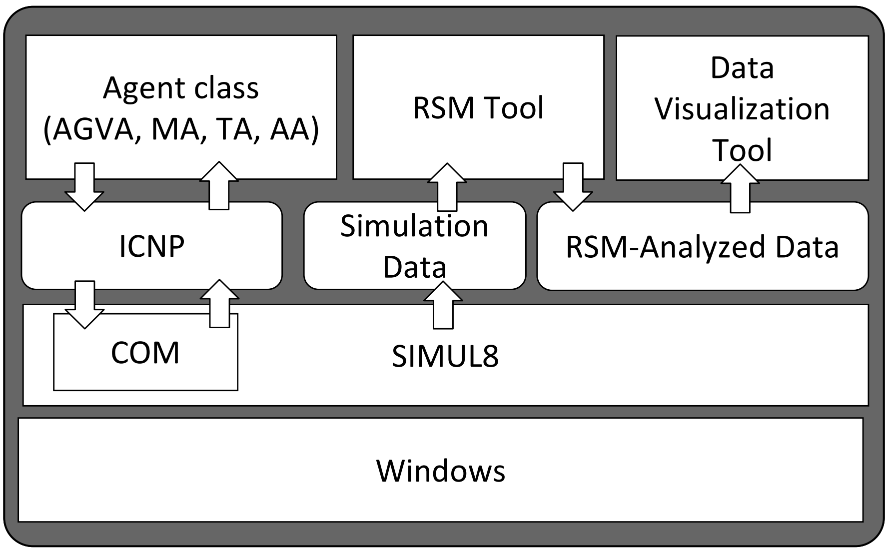

Fig. 6.2. Tool configuration for AGV system design.

6.4 Case Study: Tire Manufacturing Factory

6.4.1 Material Transportation System

There are several factors need to be decided in implementing an AGV system for tire manufacturing factory. Among the important perspectives is to optimize the number of vehicle needed for material transportation purpose. This is critical due to several reasons. Under-estimated number of vehicle simply means insufficient medium of transportation that might affect the schedule of the entire shop floor. Meanwhile, over-estimated number of vehicle requires bigger capital investment will result to under-utilized vehicles while increasing operational-related cost. This highlights the importance to determine minimum number of vehicles required.

Basically, vehicle requirement can be determined by two main approaches – analytical and simulation methods. Analytical methods employ mathematical models and heuristic algorithms. Nevertheless, realistic material transportation planning is a very complicated process and typically involves various combinatorial problems. For instance, the decision on the best design variables combination should consider various design parameters as well as dynamic operation parameters which include randomness in job arrivals, traffic congestion, alternate vehicle routing and failure. This makes the system to have high nonlinearity where the impact of each factor and their interactions are difficult to be analyzed and verified using analytical method especially when large scale transportation system is considered. This justifies the importance of applying simulation method to analyze vehicle requirements.

In this chapter, simulation approach is utilized to model a multi-load AGV operation. Based on the result, the interactions of design parameters and the resulted system performance were investigated. Based on the outcomes, required minimum number of AGVs could be forecasted with respect to specific performance targets. The study used tire manufacturing factory as a target example.

6.4.2 Tires Manufacturing Process

Pneumatic tires (in short: tires) are produced using relatively standardized series of processes. Traditionally, tires-making processes illustrated in Fig. 6.3 could be divided into four major stages as the following:

- Raw Material Preparation (RMP)
- Components Preparation (CP)
- Tire Building (TB)
- Curing and Inspection (CI)

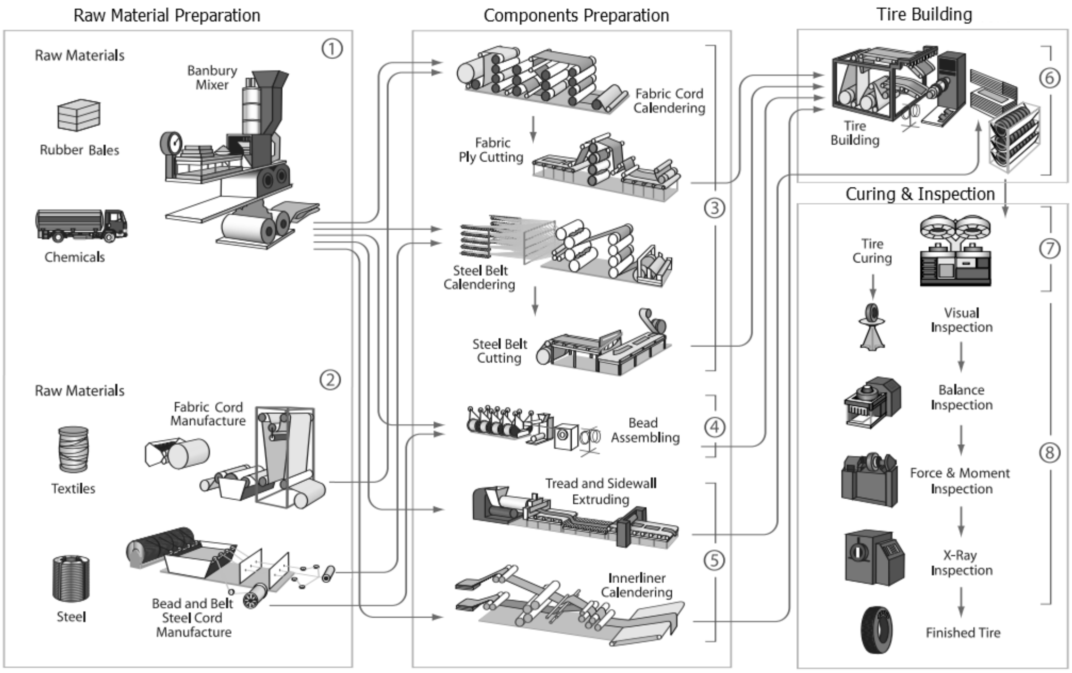

Fig. 6.3. Tire making processes [75].

RMP consists of compounding and cords fabrication. Compounding generally refers to the preparation of rubber compound that will be used as the main tire components. The operation starts with combining all of the substances required to mix a batch of rubber compound based on specific composition. The ingredient is then blended together typically by using Banbury mixer to obtain a homogenous compound. The compound is then dropped into an extrusion or milling machine to produce a thick rubber sheet called ‘slap’. The slap will be moved to the various CP processes.

Apart from the slap, there are also two other materials need to be prepared for CP: i) fabric cord and ii) bead and belt steel cord that are prepared independently. CP provides the components required to build a tire. Generally, the components could be classified based on their respective needed production processes: calendaring, extrusion and bead building. Components fall into three classes based on manufacturing process: calendaring, extrusion, and bead building. Extrusions are used to produce tire thread, sidewall profiles and inner liners. Calendaring process consists of fabric calendar; steel belt calendar; and innerliner calendar that are needed to produce body plies and belts (fabric and steel). Additionally, tire bead are also assembled using Bead Building Machine.

All of the components produced are then transferred to a Tire Building Machine (TBM). Conventional TB comprises of two-stage operation where firstly- inner liner, body plies and sidewalls are wrapped around a drum. Then, beads are attached to the assembly before sidewalls are pressed onto both sides of the tire. In the second stage, the belt package, nylon cap and thread are applied to complete the building of a '*green tire*'. It is then inflated and ready to be cured.

Curing is an operation of applying high-temperature and high-pressure to a green tire in a curing mold. By doing so, a series of chemical reactions take place and these change the properties of the tire. The exterior shape of the tire corresponds to the respective shape of the mold cavity used. A series of tests and inspections are carried out to ensure the quality of the tire produced.

6.4.3 Simulation Model

The simulation model is based on tire manufacturing factory. Part of the entire shop floor with process-based layout has been modeled with the intention of studying the vehicle-based material transportation process. The model possesses certain technical specifications and assumptions as the following:

i) System specification

Plant layout used in the manufacturing system is based on process layout. There are 19 process centers in the system where each process has a set of machines as shown in Fig. 6.4. 'IN' refers to the station for incoming raw material while ‘OUT’ refers to the station for outgoing finished goods.

There are 5 job sets with each possessing specific number of operation sequences. The detail of the job sets are described in Table 6.1. In order to acquire stable data on the production flow, the warm up period are fixed for 2 hours. Thus, data for analysis purpose are only collected after the warm up period. Jobs arrival rates of 80 jobs/ hour with mean, E follows a Poisson distribution.

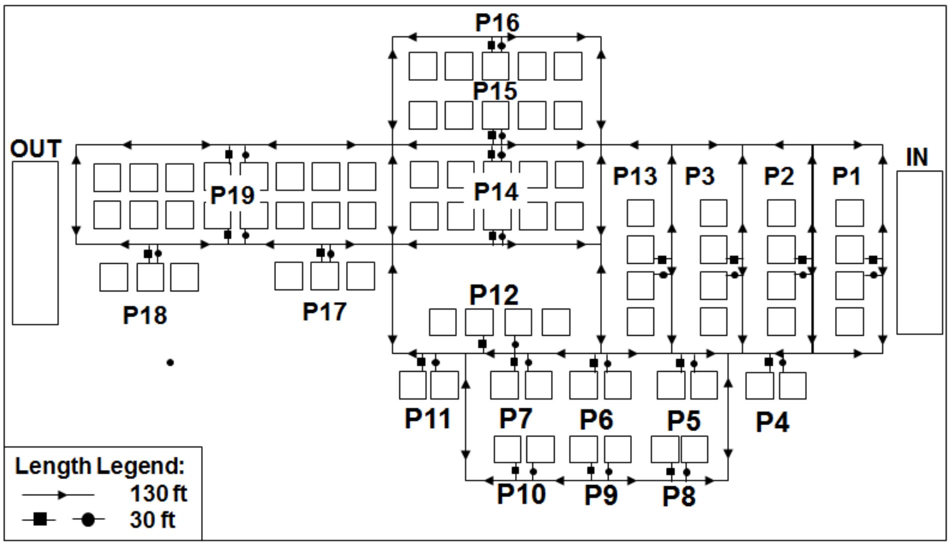

Fig. 6.4. Factory layout.

Table 6.1. Job data set.

Job No	Volume Mix (%)	Machine sequence (processing time in minutes)
1	25	P 1 (4) - P 2 (8) - P 3 (3) - P 14 (4) - P 17 (1) - P19 (12) - P 20 (1)
2	25	P 1 (4) - P 2 (8) - P 3 (3) - P 6 (3) - P 7 (1) - P 14 (4) - P 17 (1)- P 19 (12)- P 20 (1)
3	20	P 5 (2) - P 6 (3) - P 7 (1) - P 15 (5) - P 17 (1) - P 19 (15) - P 20 (1)
4	15	P 1 (4) - P 2 (8) - P 3 (3) - P 4 (4) – P 13 (3) - P 14 (4) - P 17 (1) - P 19 (15) - P 20 (1)
5	15	P 8 (3) - P 9 (5) - P 10 (1) - P 11 (8) - P 12 (4) - P 16 (6) - P 17 (1) - P 19 (22)- P 20 (1)

ii) Machine specification

Number of machines, m in the system is fixed. Machine's processing times are normally distributed with standard deviation, σ = 0.5 minutes. In allocating specific operation to a machine within a process group, rounded uniform distribution function were used. Task loading and unloading times are fixed at 0.5 minute each. Finite numbers of input and output machine buffers are used. First In First Out (FIFO) dispatching rule is employed for the input and output buffers in prioritizing tasks in queue waiting for a) processing on a machine and b) transportation.

iii) AGV specification

Multiple loading capacity AGVs are deployed for material handling purpose. For standardization purpose, loading capacity is based on the number of pallets regardless of the actual unit size of a material. The number of AGVs, v in the system is known. Vehicle's velocity, vel_x are constant at 130 ft/min. The travel paths connecting the processing machines are bidirectional. There is no other material handling medium used. All machines and AGVs are assumed to operate at 100% efficiency.

6.5 Proposed Method to Estimate Vehicle Requirement

6.5.1 Discrete-Event Simulation as a Decision Support Tool

Discrete event simulation (DES) refers to simulation that employs mathematical and logical models of a physical system to represent state changes at precise points in simulated time [76]. Taking advantages of the computing advancement, DES has been intensively developed for modeling, simulating, and analyzing dynamic and complex systems. This is meant to enable research on advanced industrial system to be conducted.

In this research, Simul8 simulation software [77] is used to model material transportation operation within a manufacturing workplace. There are several advantages of Simul8 software particularly in its ability to accommodate mathematical and logical procedure with relative ease through Visual Logic. Furthermore, it is also possible to integrate codes developed using Visual Basic into Simul8 simulation framework. Based on the features, we chose Simul8 as the tool to model proposed vehicle-based transportation system in a tire manufacturing plant.

6.5.2 Response Surface Methodology

Response Surface Methodologies (RSM) is a combination of statistical methods that are used to study the relationships between several explanatory factors and the resulted response variables. RSM is a simple yet effective method to optimize the responses when input factors are fixed, hence the name response surface optimization. As such, it could be used to determine optimal input factors when desired response variables are provided [79], [80].

RSM analysis starts with the approximation of a functional relationship between explanatory variables and response variables. This is carried out by a low-order polynomial modeling of the independent variables. Simple linear regression model is assumed to sufficiently model the relationship as in Eq. (6.1):

$$y_r = \beta_0 + \beta_1 x_{i_1} + \beta_2 x_{i_2} + \ldots + \beta_n x_{i_n} \qquad (6.1)$$

where y_r are the output variables, β_j are the unknown coefficients and x_i are coded units of the independent variables. The values for β_s are determined using the least square analysis method based on the simulation results.

Based on the results of variance analysis, if the developed models show that obtained *P*-values are less than their respective significant levels, then significant curvature of the relationship exists. This requires a second-order polynomial model with two-factor interaction to be established according to Eq. (6.2):

$$y_r = \beta_0 + \sum_{j=1}^{q} \beta_j x_j + \sum_{j=1}^{q} \beta_{jj} x_j^2 + \sum_{j=1}^{q} \beta_{ij} x_i x_j + \varepsilon \qquad (6.2)$$

The output responses are measured for all of the simulation experiments. Subsequently, the problem will be optimized based on Derringer and Suich desirability method [81] where each response will be modeled based on Eq. (6.3) for maximization and Eq. (6.4) for minimization functions.

Parameters needed to determine desirability function, d_r are lower limit, L_r; target value, T_r and upper limit, U_r.

$$d_r = \left(\frac{y_r - L_r}{T_r - L_r}\right)^w, \quad L_r \le y_r \le T_r \tag{6.3}$$

$$d_r = \left(\frac{U_r - y_r}{U_r - T_r}\right)^w, \quad T_r \le y_r \le U_r \tag{6.4}$$

The proposed flow for tuning of design variables is illustrated in Fig. 6.5.

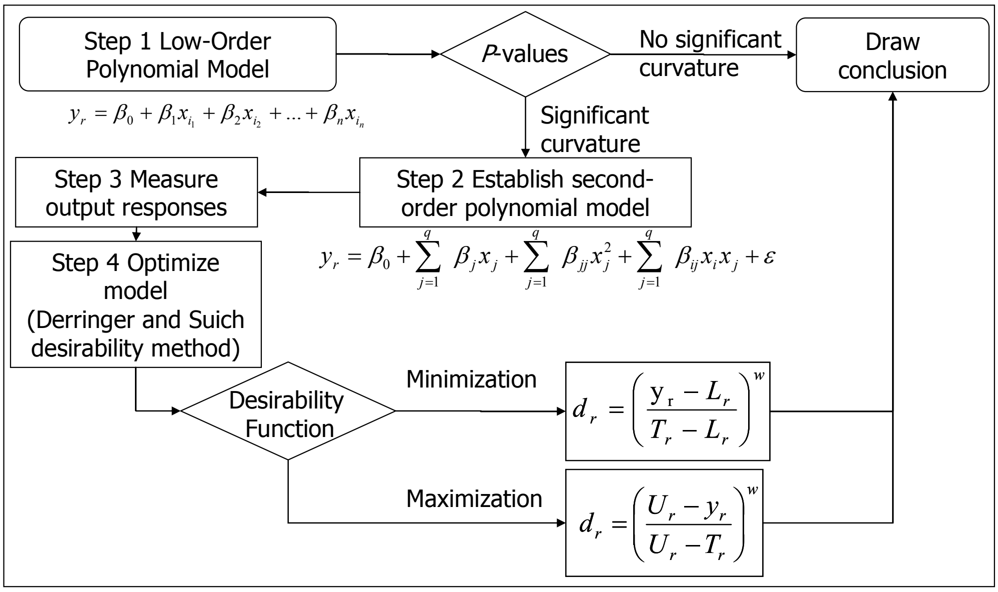

Fig. 6.5. Proposed flow for tuning of design variables.

6.6 Experimental Design

The experiments conducted were designed to achieve several perspectives of the AGV operation. The experiment plans are classified based on the following aspects:

- Design Variable (DV)

  DV refers to the controllable input factors that are contemplated during the development of an AGV system. The study starts with experimenting two critical factors: i) number of vehicle (*NOV*) and ii) AGV loading capacity (*CAP*).

- Performance Variable (PV)

  PV are uncontrollable factors resulted when a set of input factors are utilized. Some of the important output factors used in this research includes:

  - System Throughput (*STH*) – *STH* is the amount of finished goods produced by a system over a period of time. It is used to measure the system-wide performance.

    $$STH = \sum_{i=1}^{I} F_i \tag{6.5}$$

    $$F_i = \sum_{i=1}^{I}\sum_{j=1}^{J} fo_{ij} \tag{6.6}$$

    $$fo_{ij} = fu_{ij}\theta_{m,ij} * fp_{m,ij}\theta_{m,ij} * ft_{x,ij}\beta_{x,ij} \tag{6.7}$$

  - Mean Flow Time (*MFT*) – flow time, F_i refers to the time duration required for a job to be completed. Parameters needed to compute F_i include operation time, O_{ij}; machine processing time, tp_{ij}; transport time, tt_{ij}; loading/unloading time, tu_{ij}; queuing time, tq_{ij}; job release time, R_i and total number of job processed, n. MFT complies with Eqs. (6.8) to (6.11).

    $$O_{ij} = tp_{ij} + tt_{ij} + tu_{ij} + tq_{ij} \tag{6.8}$$

    $$C_i = \sum_{i=1}^{n} O_{ij} \tag{6.9}$$

    $$F_i = C_i - R_i \tag{6.10}$$

    $$MFT = \frac{1}{n}\sum_{i=1}^{n} F_i \tag{6.11}$$

  - Effective Total Distance Traveled (*ETDT*) - this research used *ETDT* as an indicator to measure effectiveness of material transportation. *ETDT* is defined as the ratio of total distance traveled to *STH* produced. *ETDT* computation is defined in Eq. (6.12). *ETDT* was selected because it could represent the vehicle traveling efficiency with regards to the system throughput.

$$ETDT = \frac{\sum_{x=1}^{v}(ta_x * pt_x * vel_x)}{STH} \quad (6.12)$$

Initial experiments are conducted based on a two-level full factorial design. Details of the design variables are summarized in Table 6.2.

Table 6.2. Input factors data.

	Design variable	Low level (coded value: -1)	High level (coded value: +1)
1	*NOV*	10	30
2	*CAP*	5	15

6.7 Simulation Analysis and Optimization

6.7.1 Simulation Analysis

Simulation has been carried out testing all of the combination of experimental factors over 8-hour production time. Analysis had been carried out with the intention to determine the performance of multi-load AGV. The outcomes of the performance indicators are analyzed.

Deployment of different vehicle loading capacity resulted in different *STH* outcomes. The result in Fig. 6.6 shows that deployment of vehicle with different loading capacity resulted in significant throughput outcomes particularly for smaller NOV category. On the other hand, the differences are less when 20-AGVs are deployed. There is also a decreasing trend of throughput specifically when the number of vehicles deployed is too high.

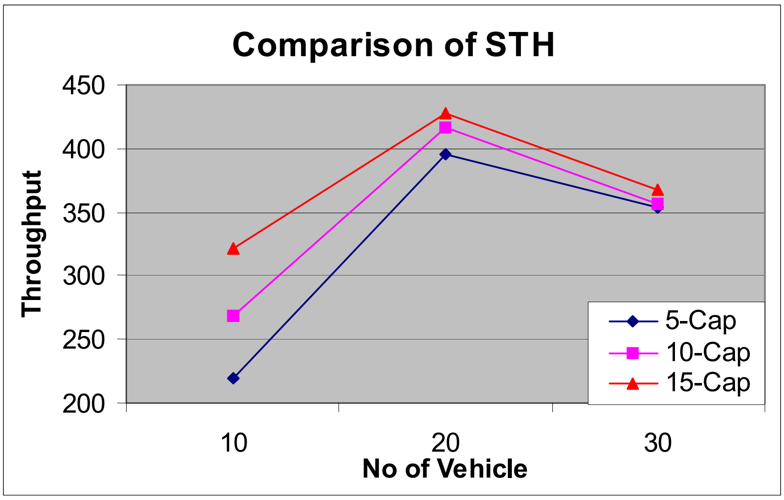

Fig. 6.6. Comparison of STH.

In addition, we also analyze the *ETDT* data for each vehicle. Generally, *ETDT* values drop when the numbers of AGVs are increased. Besides, there is also significant improvement of *ETDT* particularly when AGVs with higher loading capacity are utilized. The result depicts that AGV categories with 10- and 15-capacities consistently have better *ETDT* compared to AGV with 5-capacity. The result is depicted in Fig. 6.7.

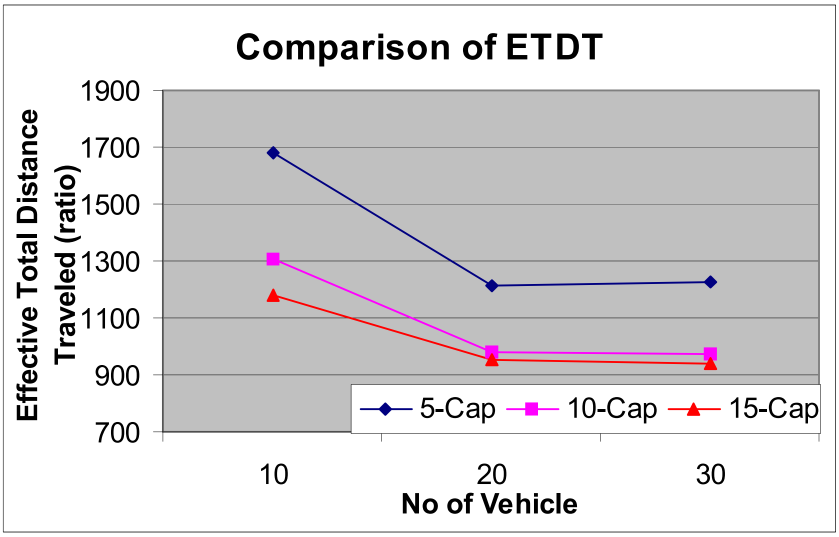

Fig. 6.7. Comparison of ETDT.

Moreover, *MFT* of the work-in-process materials has also been studied. The result illustrated in Fig. 6.8 shows that generally, the *MFT* decreases when the NOV increases up to a certain number of vehicles. Then, *MFT* starts to increase back. This simply highlights the need to identify optimal design variables when MTS is to be established. The result also shown that utilizing vehicle with higher loading capacity could improve *MFT* outcome compared to AGV with lower loading capacity.

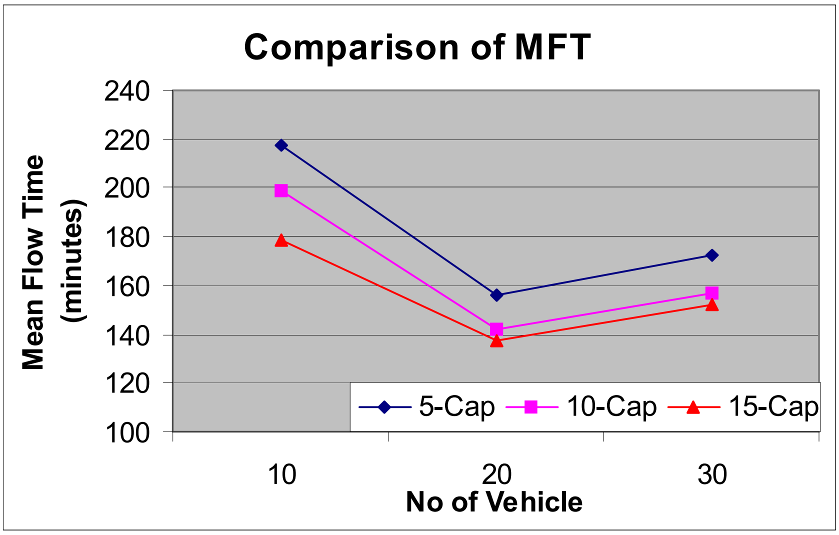

Fig. 6.8. Comparison of MFT.

To support the discussion, we also carried out variance analysis (ANOVA) on the simulation data obtained. The result is depicted in Table 6.3. Based on the ANOVA conducted with a significance level of 5%, the main effects and corresponding curvature were proved to be significant on various PVs. This implies that the operational behavior cannot be explained by the low-order model. Therefore, in order to optimize the problem's solution, second-order polynomial model is determined. Furthermore, the analysis provided only consider single factor at a time.

Table 6.3. ANOVA Result.

DP	PV	DF	SS	MS	F	P
NOV	*STH*	2	31358	15679	16.03	0.004
NOV	*MFT*	2	4529	2265	11.66	0.009
NOV	*ETDT*	2	166117	83059	1.23	0.356
CAP	*STH*	2	3692	1846	0.33	0.531
CAP	*MFT*	2	1020	510	0.65	0.553
CAP	*ETDT*	2	376349	188175	5.82	0.039

6.7.2 Optimization of Design Variables

In this study, RSM is used to address the shortcomings and to search for the optimal design variables setup in achieving specific system performance considering multiple-input and multiple-output simultaneously. The variables optimization to achieve the required level of performance is realized using Response Surface Methodologies (RSM) based on a Central Composite Design (CCD) concept.

Face-Centered CCD (FCD) was utilized to design the RSM analysis in approximating the quadratic polynomial models. 27 sets of simulation were carried out based on the experimental design summarized in Table 6.4. As such, the impact of these three independent input factors on the output factors could be studied. Selection of appropriate values for low and high levels is based on the generic manufacturing and material transportation requirements.

Table 6.4. Response surface design summary.

Input Factors	Low level (coded value: -1)	Central level (coded value: 0)	High level (coded value: +1)
1 *NOV*	10	20	30
2 *CAP*	5	10	15

The final fitted polynomial models obtained for system throughput, $\hat{y}_{\mathrm{STH}}$; mean flow time, $\hat{y}_{\mathrm{MFT}}$; and effective total distance traveled, $\hat{y}_{\mathrm{ETDT}}$ where $\{x_i\}$ are the coded units of $\{X_i\}$ are:

$$\hat{y}_{\mathrm{STH}} = 398.151 + 52.216*NOV + 25.398*CAP - 71.477*NOV*NOV - 4.173*CAP*CAP - 22.896*NOV*CAP \quad (6.13)$$

$$\hat{y}_{\mathrm{MFT}} = 144.849 - 18.76*NOV - 14.603*CAP + 31.681*NOV*NOV + 2.835*CAP*CAP + 6.409*NOV*CAP \quad (6.14)$$

$$\hat{y}_{\text{ETDT}} = 945.113 - 136.884*NOV - 149.564*CAP + 219.802*NOV*NOV + 104.390*CAP*CAP + 71.453*NOV*CAP \quad (6.15)$$

Analysis was extended in order to determine optimal combination of DPs for the case problem. Derringer - Suich desirability approach was utilized to explore input variable settings with a higher composite desirability. Basically, each response is given an individual desirability function, di from which are used to identify each response independently.

The respective values are based on the simulation results obtained. Based on Eq. (6.3) and Eq. (6.4), the desirability functions for the output responses are governed by Eq. (6.16) to Eq. (6.18) respectively:

$$d_{STH} = \left(\frac{\text{y}_{\text{STH}} - 217}{506} \right)^{w_{STH}}, \; 217 \le y_{STH} \le 506 \quad (6.16)$$

$$d_{MFT} = \left(\frac{218 - y_{MFT}}{115} \right)^{w_{MFT}}, \; 115 \le y_{MFT} \le 218 \quad (6.17)$$

$$d_{ETDT} = \left(\frac{1634 - y_{ETDT}}{716} \right)^{w_{ETDT}}, \; 918 \le y_{ETDT} \le 1634 \quad (6.18)$$

This research utilizes equal weightage of desirability functions, i.e.: $w_{STH} = w_{MFT} = w_{ETDT}$. The RSM analysis has been conducted using Minitab 15 Statistical Software [82]. Independent results for each of the performance objective are shown in Fig. 6.9.

Resulted achievements of the objective functions are summarized using 3-dimensional response surface chart illustrated in Fig. 6.10. This will enable system designer to evaluate all of the candidate solutions in providing the best combination of DPs for the system.

Additionally, the information on optimum DP values and the corresponding predicted responses are listed in Table 6.5.

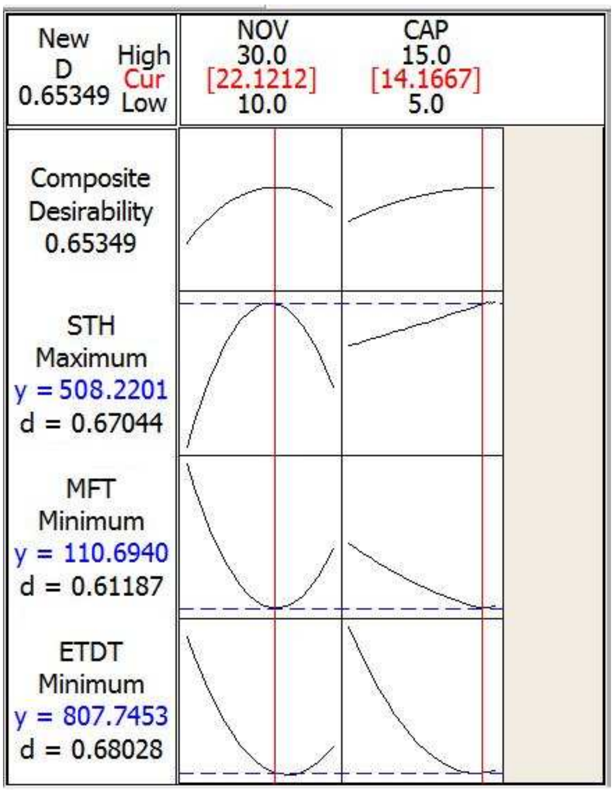

Fig. 6.9. Result for each of the objective.

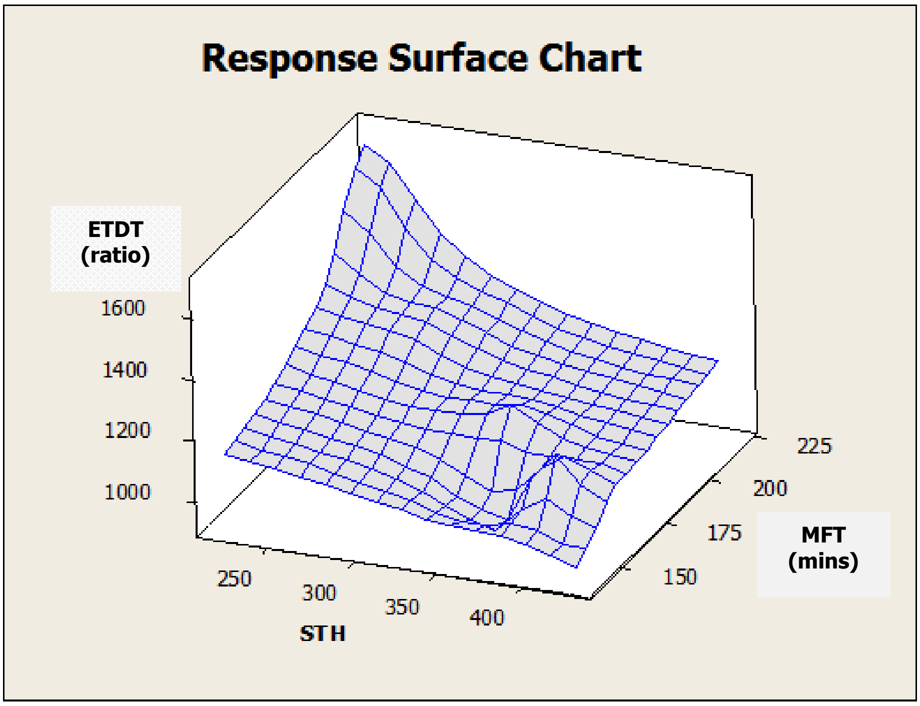

Fig. 6.10. Response surface chart for AGV system design.

Table 6.5. Response surface predicted result.

Proposed Inputs		Predicted Responses	
NOV	22	*STH*	508
CAP	14	*MFT*	110
		ETDT	807

6.8 Summary

The chapter has successfully achieved its aims to optimize design variables for vehicle-based material transportation problem in a tire-manufacturing factory. Optimization has been conducted using combined DES and RSM methods. Based on specified objectives and performance levels, optimal values for design parameters could be obtained thus enabling management to make informed decision.

Chapter 7

Conclusions and Future Works

7.1 Conclusions

The dissertation focuses on the development of an efficient scheduling method for dynamic and autonomous AGV system based on MAS architecture. Three critical problems as the following have been addressed:

i) Existing task sharing protocol does not envisage dynamism of AGV operation thus leads to system underperformance.

ii) Existing scheduling methods on distributed-controlled AGV does not provide appropriate solution for AGV with multiple-loading capacity.

iii) The research models for AGV system design either do not contemplate multiple-loading capacity factor or were based on simplified working example for evaluation purpose. In order to design a realistic AGV system, it is necessary to analyse a realistic production environment.

Therefore, this dissertation proposed appropriate methods to solve abovementioned problems categorically. The work outcomes can be summarized as the following:

i) Specific protocol has been developed to manage two important dynamic factors in AGVs operation which are dynamic status of vehicle availability and the positioning advantage of certain vehicles in handling a particular transportation request have been exploited. ICNP mechanism has been proposed that enable task to be re-assigned to a later bidder (AGVA) with better solution. Furthermore, a location-aware algorithm was introduced to distinguish vehicles within strategic distance to the pickup station.

In order to demonstrate the effectiveness of the proposed protocol, experiments have been carried out where three important transportation–related performance indicators were measured. Different values for NOV are used and the result proves that the ICNP outperformed SCNP method significantly where *STH* is improved by 25%, *PLT* of 80% is achievable and *AWT* is consistently reduced (81% decrease for 4-AGV case) could be achieved by applying ICNP method compared to SCNP.

ii) A market-based method is adapted to schedule autonomous AGV fleet consisting of vehicle with multiple-loading capacity. This successfully overcomes the weakness of conventional auction where only one job is allocated in a single auction. Meanwhile, combinatorial auctions (CA) mechanism was used in order to realize the task assignment protocol for the multi-load AGV scheduling. The functions have been divided into three components: bid generation, winner determination and auction coordination. Mixed Integer Programming (MIP) is used to obtain the solution. Meanwhile, Knapsack problem model was utilized to formalize AGV's capacity utilization.

Comparison on the achievement of system performance between single-load (case: 8-AGV with 1-CAP) and multi-load AGV (case: 2-AGV with 5-CAP) are as the following:

- Efficient energy utilization.

  Analyzing the FLT achievement, single-load AGV resulted in FLT of 45% while multi-load AGV resulted in FLT of

52%. This shows that utilization of multi-load AGV could result in better energy utilization by obtaining higher percentage of fully loaded travel.

- Reduced NOV required in achieving specific level of production performance.

  Single-load AGV is able to produce STH of 117 jobs. Alternatively, utilizing multi-load AGV shows that multi-load AGV could produce STH of 114 jobs; that is approximately the same level of STH. Looking into performance of PWT, single-load AGV resulted in PWT of 112 seconds while multi-load AGV resulted in PWT of 116 seconds.

Furthermore, the proposed method could reduce computational effort by 90% relative to the centralized-approach optimization.

iii) Combination of DES and RSM has been utilized to estimate the appropriate number of vehicle needed to achieve specific performance objectives. Vehicle requirement estimation is needed to design an AGV system. The problem is defined as to determine the best combination of AGV design variables (number of vehicle and its loading capacity) in delivering transportation requests to achieve desired target performance. The experiment case is based on data of a tire manufacturing factory involving multiple transportation objectives: i) mean flow time; ii) average pickup waiting time; and iii) total distance travelled.

Discrete Event Simulation and Response Surface Methodology (RSM) were employed to obtain the best combination of design variables. The result shows that determining proper variables combination is critical to acquire desired level of performance particularly when plural conflicting objectives were involved. Deliverable of this chapter includes the fleet-sizing decision support mechanism to design an AGV system. With regards to the case study, the numerical results are:

- Proposed DP: 22-AGV with 14-CAP
- Predicted Responses: STH: 508 jobs (average: 4115 transportation tasks); MFT: 110 minutes; ETDT:807 (average: 5.7 kilometers/ AGV)

7.2 Future Works

There are a number of interesting topics that could be studied in extending this research. In ensuring research continuity, two topics within HMS domain have been selected as possible future research directions:

- Autonomous MTS holon considering special feature

  In order to guarantee that an autonomous MTS could operate efficiently, there are several special features need to be addressed particularly for real-time applications. Those include:

  - Breakdown and dynamic fault-tolerant strategy.
  - Group of vehicles with heterogeneous vehicle attributes and capabilities.
  - AGV scalability accommodating incoming or outgoing vehicle.
  - Autonomous MTS with multiple types of equipment.

- Integration of HMS-inspired AGV-centric manufacturing system.

  We have demonstrated the importance of having an efficient an MTS in improving the performance of a manufacturing system. As such, we deem that it is a worthy effort to integrate the functional components of an HMS with MTS as the central point. Therefore AGV-centric HMS may provide an interesting future research direction.

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- Muhammad Hafidz Fazli bin Md Fauadi, Saifudin Hafiz Yahaya and Tomohiro Murata. "Intelligent Combinatorial Auction of Decentralized Task Assignment for AGV with Multiple Loading Capacity". IEEJ Transactions on Electrical and Electronic Engineering, Vol.8, No.4, 2013. Accepted.
- Muhammad Hafidz Fazli bin Md Fauadi, Hao Wen Lin and Tomohiro Murata. "Dynamic Task Assignment of Autonomous Distributed AGV in an Intelligent FMS Environment". IEEJ Transactions on Electronics, Information and Systems, Vol.132, No.5, Pp. 697-705. 2012.

Referred international conferences

- Muhammad Hafidz Fazli bin Md Fauadi, Wan-Ling Li, Tomohiro Murata and.Anton Satria Prabuwono. "Vehicle Requirement Analysis of an AGV System using Discrete-Event Simulation and Data Envelopment Analysis". Proceedings of IEEE International Conference on Computing Technology and Information Management (ICCM 2012). Pp. 819-823. Seoul, Korea. April 24-26, 2012.
- Muhammad Hafidz Fazli bin Md Fauadi, Wan-Ling Li and Tomohiro Murata. "Combinatorial Auction Method for Decentralized Task Assignment of Multiple-Loading Capacity AGV based on Intelligent Agent Architecture". Proceedings of IEEE International Conference on Innovations in Bio-inspired Computing and Applications (IBICA 2011). Pp. 207 – 211. Shenzhen, December 16-18, 2011.

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