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Three essays on the battery management of automated guided vehicles

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Three essays on the battery management of automated guided vehicles

by

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Major: Business and Technology (Supply Chain Management)

Program of Study Committee:
Yoshinori Suzuki, Major Professor
Danny Johnson
Toyin Clottey
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DEDICATION

I dedicate this dissertation to my parents for their continuous support and inspiration throughout my life.

TABLE OF CONTENTS

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CHAPTER 1: GENERAL INTRODUCTION

This dissertation explores battery management for automated guided vehicles (AGVs). AGVs are driverless vehicles that usually run on batteries. According to Le-Anh and De Koster (2006), battery management of AGVs deals with the issues like how long a particular AGV will operate before its battery is recharged or replaced, capacity of the battery stations, location of the battery stations, availability of idle time for the AGVs, etc.

Literature on AGV systems generally ignores battery management assuming that the effect of battery management is negligible. However, there have been a few studies showing that battery management can play an important role for the overall performance of an AGV system (e.g., McHaney, 1995). As the competition in the business world grows, firms need to find new and innovative ways to improve their performance. In that case, battery management has the potential to be a source of competitive advantage for a firm that uses AGVs.

There is no unique way of battery management that works well for all kinds of AGV systems. The ideal way of battery management needs to be developed assessing the conditions under which the batteries are deployed (Preuss, 2003). Consequently, practitioners using AGVs need to be aware of different factors related to battery management so that they can make the right decision in this regard. Unfortunately, it is difficult for a practitioner to make such a decision because battery management, so far, received very scant attention in the literature. Dearth of literature also makes it difficult to conduct academic research on this topic. Emphasizing the importance of battery management, Vis (2006) called for more research on the battery management of AGVs.

The main reason of selecting the battery management of AGVs as the topic of this dissertation is to help enhance the literature of this topic. To fulfill that objective, this dissertation has been designed as a three-paper model so that three different attributes of battery management can be addressed extensively. Each of the three papers represents a chapter in this dissertation (i.e., chapter 2, chapter 3, and chapter 4).

Chapter 2 (i.e., the first paper) is mainly based on literature review. The literature review has been augmented by the information gathered from practitioners. The purpose of chapter 2 is to have a better understanding of the battery management of AGVs and to explore common themes among different dimensions of battery management. Chapter 3 (i.e., the second paper) explores the possibility of increasing manufacturing flexibility through battery management of AGVs. This chapter shows how a firm can use battery management to meet an unexpected increase in demand for the short run. Chapter 4 (i.e., the third paper) compares and contrasts different routing techniques for battery management in order to investigate how such routing techniques can affect the productivity of an AGV system.

References of Chapter 1

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CHAPTER 2: POTENTIAL OF BATTERY MANAGEMENT TO ENHANCE THE PERFORMANCE OF AUTOMATED GUIDED VEHICLE SYSTEMS - A LITERATURE REVIEW

2.1 Abstract

Objective of this chapter is to explore how battery management can be used to enhance the performance of a system that uses automated guided vehicles (AGVs). To attain that objective, the chapter reviews the literature on the battery management of AGVs and synthesizes the findings. Information collected from practitioners was used to augment the literature review. Two themes were generated through this study. These themes are: improving battery management practices, and integrating battery management with other components of an AGV system. Different aspects of these themes were discussed in detail. Particular focus was given on the availability of different options with regards to the battery management of AGVs. It was observed that the literature on the second theme of integrating battery management is quite sparse. The study identified the benefits of conducting research based on the second theme and raised a few research questions that can be considered for future research.

2.2 Introduction

Automated guided vehicles (AGVs) are self-driven vehicles used for transporting materials from one location to another location without any accompanying operator (Sarker and Gurav, 2005). According to Le-Anh and De Koster (2006), a system like a manufacturing plant, warehouse, distribution center, or terminal that uses AGV-based internal transportation is commonly referred as automated guided vehicle system (AGVS). Besides having a fleet of

AGVs, an AGVS also usually has a navigation network, and software for dispatching, routing, and traffic-management (Choobineh et al., 2012). One of the important advantages of AGVs is that they can have interface with other production and storage equipment (Lacomme et al., 2013).

Most AGVs use batteries, which need to be recharged or replaced on a regular basis (Vis, 2006). To ensure proper functioning of the AGVs, it is important that the batteries are managed efficiently and effectively. Battery management refers to the functions required to ensure optimum use of the battery in a portable device (Bergveld et al., 2002). For an AGV system, important aspects of battery management include capacity of the battery stations (i.e., how many charging positions are available at a battery station), location of the battery stations, how long a particular AGV will operate before its battery is recharged or replaced, availability of idle time for the AGVs etc. (Le-Anh and De Koster, 2006).

McHaney (1995) showed that battery management should be considered when determining the required number of AGVs for busy systems (i.e., systems with little or no idle time). Also, managing the timing of battery charge helps to avoid battery deterioration that eventually helps to reduce battery related costs and improve the efficiency of AGVs (Kawakami and Takata, 2011). So, battery management is an important task that can help a firm to improve the overall performance of its AGV system. In spite of its importance, literature on battery management of AGVs is very sparse. This is testified by the fact that Vis (2006) called for research to investigate how battery management decisions affect the design and control of AGV systems.

Because of the improvement in technology, a wide variety of batteries, chargers, and other related equipment are now available in the market, which makes the decision-making process more challenging for small (or new) users of battery powered material-handling vehicles like AGVs (König, 2003). To help managers face such challenges, it is important to investigate different options available for battery management and analyze the links between battery management and other components of an AGV system.

One of the goals of this study is to put together important issues of battery management in one place so that both managers and researchers find this study valuable. The study compares and contrasts different options related to battery management so that managers can get a comprehensive picture about this topic. For example, this study not only discusses different schemes that a manager can adopt for battery charging, but also explores the pros and cons of those charging schemes. Such a comparative analysis is likely to be helpful for the managers to take a decision about battery management.

This study is also likely to be helpful for the researchers who want to explore the role of battery management within the total AGV system. That is, the study investigates the relationship between battery management and other components of an AGV system. For example, the study discusses how the location of a battery station can influence the layout design of a facility. Adding battery management constraint may make it more difficult to find a solution of such a problem; but the solution, when found, will be more practical and valuable.

Battery management of AGV systems is an under-researched but emerging issue that has the potential to help a firm improve its performance. Le-Anh and De Koster (2006), and Vis (2006) encouraged for more research on the issue of battery management for AGV systems.

Literature review is an appropriate way to tackle an emerging issue in order to contribute in developing a conceptual model in future (Webster and Watson, 2002). This study was undertaken to provide a better understanding of battery management of AGV systems so that more research can be conducted in future to explore and strengthen the links between battery management and other components of an AGV system. Consequently, literature review was deemed appropriate to conduct this study.

It may be noted that this study was conducted from the perspective of battery user, not battery manufacturer. As a result, the managerial aspects of battery use are given more importance as opposed to the technical aspects.

2.3 Methodology

As mentioned in the previous section, literature review was the main base of this study. However, industry executives were also interviewed to gain additional insight on the subject matter. Information gathered through literature search and interviews were analyzed to synthesize different dimensions of battery management and to explore how battery management is related to other components of an AGV system.

A systematic approach was taken to search the previous literature on battery management of AGV systems. Three academic databases were searched for relevant articles on the subject matter. These databases are: ABI/INFORM Global, Google Scholar, and Ebsco Academic Search Elite. Online database search was made in two stages. In the first stage, research articles were searched in reputed academic journals that regularly publish articles on AGV systems (not necessarily covering battery management). The journals used at this stage were: International Journal of Production Research, International Journal of Production Economics, European

Journal of Operational Research, and Computers & Industrial Engineering. This first stage of literature search was conducted to have a detail understanding on the design and control of AGV systems so that the role and importance of battery management can be determined more effectively.

In the second stage of literature search using the same online databases, focus was given on battery management of AGVs. An initial search revealed that the number of research articles on battery management of AGVs published in reputed academic journals is very few. Consequently, the search process was broadened to include all peer-reviewed articles (including dissertations) and articles published in practitioner journals. Also, Iowa State University library was used to obtain relevant books.

Key sources of information that were used for this study can be broadly divided into two categories. One category refers to research oriented sources such as PhD dissertation, and articles published in academic journals and conference proceedings. The other category refers to practice oriented sources such as books, book chapters, and practitioner journals. Upon analyzing both the categories of sources, two themes emerged: (i) improving battery management practices, and (ii) integrating battery management with other system components. Key sources of information used to develop these themes are summarized in the appendix. Details of these themes are discussed in the following sections to give a holistic view on the battery management of AGV systems and to develop a research agenda on this topic.

2.4 Theme 1 - Improving Battery Management Practices

Improving battery management practices is a theme that emerged through literature review conducted for this study. This theme has a narrow focus of improving battery management without considering other components of an AGV system. That is, the relationship between battery management and other components of an AGV system or how one may affect the other is not a part of this theme. Important features of this theme are discussed below.

2.4.1 Battery types for AGVs

Batteries used for industrial trucks like AGVs and forklifts are known as traction battery or motive power battery (Crompton, 1990). These batteries come into two broad categories: lead acid battery, and nickel cadmium battery (Preuss, 2003). Besides battery, an AGV can also use inductive power transfer to get energy. For inductive power transfer, a constantly energized wire (i.e., primary conductor) placed in the floor generates magnetic field above the floor and a secondary winding on a ferromagnetic core placed at the AGV’s lower surface inductively “picks up” the energy (Schulze and Wüllner, 2006.) However, because of the complexity of installing and operating inductive power transfer, battery is still the preferred source of energy for AGVs. This is testified by the fact that only 8% of all the AGVs put into operation in 2006 by European vendors used inductive power transfer (Schulze et al., 2008).

Between lead acid battery and nickel cadmium battery, the former is less expensive. Consequently, lead acid battery is more commonly used for AGVs (Kawakami and Takata, 2011). However, if proper care is not taken, lead acid batteries may not last long. Average lifespan of lead acid batteries is 5.5 to 6 years; but factors like overcharging, undercharging, using defective charging equipment, and using batteries at high temperature can reduce the lifetime of such batteries (Kiehne, 2003). So, the users of AGVs need to have proper maintenance system for long life and proper functioning of the batteries (the next section has a detail discussion on battery maintenance).

Nickel cadmium batteries, though more expensive than lead acid batteries, can be charged faster and last longer (Van der Heijden et al., 2002). Consequently, a firm should go for lead acid battery or nickel cadmium battery depending on its preference for low cost or low charging time (i.e., more productive time for the AGVs).

Besides the cost or speed of charging, a firm should also consider the amount of energy that the battery needs to deliver to an AGV. If an AGV is supposed to have a demanding workload (e.g., loading heavy pallets, travelling in an upward slope), then a more powerful battery should be selected. Sometimes, a firm may not be sure if the initial plan of workload for an AGV will continue for a long time. In such cases, it makes good economic sense to fit the largest (i.e., most powerful) battery possible so that the AGV becomes flexible enough to be switched to a more demanding duty than what the original intended application was (Crompton, 1990).

2.4.2 Battery maintenance

A battery with poor health not only needs to be replaced earlier, such a battery may also stop functioning suddenly causing an AGV to stop in the middle of a busy work schedule. Consequently, a firm not only loses the productivity from that particular AGV, but also additional congestion is created for other AGVs. So, using a battery management system to maintain the health of the batteries is very important to reduce the operational cost of a system.

A battery management system monitors and controls a battery’s charging and discharging process in order to ensure that the energy inside the battery of the portable product is used in an optimum way and the risk of damaging the battery is minimized (Bergveld et al., 2002). Using a battery management system helps a firm not only to avoid premature battery failure and underperformance of the batteries, but also helps to reduce the number of batteries for industrial trucks (like AGVs and forklifts) by up to 50% (Williams, 2010).

According to Kiehne (2003), proper maintenance of the batteries of electrically powered trucks (like AGVs) can be ensured by adopting some simple practices like keeping the battery clean and dry, not discharging the battery more than 80%, recharging the battery immediately after discharging, not overcharging the battery, and not letting the temperature of a battery go over 55°C. Without adequate maintenance (e.g., putting right quantity of water at the right time), batteries often underperform and eventually get discarded before their typical life expectancy (Bond, 2013). By ensuring good health of the batteries, a firm can reduce the number of batteries to be bought for its AGVs. That way, the firm will save a significant amount of money. Also, risk of battery failure will reduce if batteries are taken care of regularly.

2.4.3 Cost

Now-a-days, the users of AGV systems have a wide variety of options to select the type of battery that they need. However, to procure the right kind of battery, a firm should look into the life-cycle cost of the battery. That is, besides the initial purchase cost of batteries, a firm should also consider other costs like the cost of associated technologies (e.g., cost of charging system), and the cost of lost production due to battery failure (Technical Marketing Staff of Gates Energy Products, 1992).

Cost of a battery is quite small in comparison to the cost of an AGV. However, since an AGV uses multiple batteries throughout its lifetime, the total cost of all the batteries used during the lifetime of an AGV is not negligible (König, 2003). So, it is important to manage the batteries well so that they last longer and the overall cost for the batteries gets reduced. Battery management can help to reduce the cost of batteries in different ways. For example, by charging the batteries at an optimum level (i.e., not overcharging or undercharging), a firm can increase the lifetime of the batteries used for AGVs.

A firm should have a battery management system that will ensure the health of the battery by monitoring the charging and discharging process. The money invested for an effective battery management system can be recovered in as little as nine months through the money saved by increased efficiency of operations, decreased maintenance costs, and decreased charging costs (Williams, 2010).

Besides buying batteries, a user of AGVs can also consider leasing the batteries. Leasing batteries, coupled with full service from the vendor, is quite prevalent now-a-days (König, 2003). If a firm does not have adequate financial or technical resources to manage the batteries, it is better for that firm to lease the batteries with full service.

2.4.4 Battery charging schemes

Battery charging schemes can be divided into two broad categories: battery swapping and automatic charging (see for example: McHaney, 1995; Ebben, 2001; and Savant Automation, 2015). In case of battery swapping, an AGV goes to a battery station when it needs to replace its depleted battery with a fully charged one; and in case of automatic charging, an AGV runs until its battery is depleted to a threshold level and then the AGV moves to a charging station where it remains until the battery is recharged to an acceptable level (McHaney, 1995).

Both battery swapping and automatic charging can be done as and when an AGV needs its battery to be swapped or recharged. However, to save productive time, an AGV can also swap or recharge its battery whenever it has idle time. Such use of idle time for battery management is known as opportunity charging. In case of opportunity charging with battery inside the AGV (i.e., automatic charging), the AGV does not wait until its battery is fully charged again. Rather, an AGV charges its battery using only the idle time it has. The pros and cons of battery swapping and automatic charging are discussed in the following paragraphs of this section.

Advantage of battery swapping in comparison to automatic charging is that battery swapping allows a system to have more productive hours from the AGVs (for automatic charging, an AGV is unavailable for a long time since the battery remains inside the AGV while the charging process takes place). Consequently, battery swapping should be preferred when there is not enough idle time to conduct automatic charging. However, automatic charging also has some advantages in comparison to battery swapping.

The major advantage of automatic charging is that it is safer and less complex in comparison to battery swapping. If a facility has enough idle time, then it makes sense to go for automatic charging. Battery stations required to conduct the battery swapping process needs to have special safety features like acid-proof floors (Ebben, 2001). Consequently, a firm needs to spend a substantial amount of money to construct a battery station for battery swapping. On the contrary, charging points can be installed near the workstations and storage rooms for automatic charging. That is, automatic charging reduces the fixed cost of battery management because no investment is needed to construct battery stations with special safety features (König, 2003).

Probability of making a mistake is higher for battery swapping than that for automatic charging. This is because battery swapping involves more steps and more complicated process in comparison to automatic charging. So, it is important to employ highly skilled workers to manage or conduct battery swapping. It may be noted that mistakes committed to swap a battery can reduce the operational efficiency of a facility. Also, for battery swapping, there is always a risk of accident or environmental hazard while a depleted battery is replaced with a fully charged battery (König, 2003). So, from occupational and environmental standpoint, automatic charging would be preferable to battery swapping.

As discussed above, both battery swapping and automatic charging have advantages and disadvantages. A firm needs to select a charging scheme (i.e., battery swapping or automatic charging) depending on the availability of space, money, skilled workforce, and the nature of its operations (i.e., availability of idle time).

2.4.5 Occupational safety

As discussed above, in comparison to automatic charging, there are more scopes of error for battery swapping as it involves more steps to replace the depleted battery of an AGV. That is, there is always a risk of accident while swapping a battery (König, 2003). So, removing the depleted battery and mounting a fully charged battery should be done with strict adherence to the guidelines of battery manufacturers. According to Technical Marketing Staff of Gates Energy Products (1992), employees operating batteries should not only be careful about the toxic materials of a battery (e.g., sulfuric acid, lead etc.), but also about the potential accidents like short circuits that may be caused by the battery (short circuit current of these batteries can cause severe burns to an operator). So, a firm needs to spend more money on training its employees if it uses battery swapping (particularly if the battery swapping is done manually).

To maintain a safe working place for the employees, there are specific regulations about the construction and operation of battery rooms (i.e., battery stations) where batteries are swapped. For example, it is strictly required that a minimum distance is always maintained between the battery cells and any electric spark-generating source at a battery room (König, 2003). A firm should always follow such regulations and guidelines when constructing a battery room (i.e., battery stations). It is also important to ensure that the employees assigned to work at a battery station have adequate skill and experience to work there.

2.4.6 Environmental safety

Improper disposal of batteries containing lead, mercury, cadmium and other hazardous materials have serious environmental impacts (Technical Marketing Staff of Gates Energy Products, 1992). That is why most of the countries (particularly in Europe) have strict rules regarding the proper disposal of batteries.

According to König (2003), battery users earlier could expect to get reimbursed by the smelters in exchange of their old batteries; but such reimbursement hardly exists now because recycling costs for smelters have increased (smelters now have to take many expensive measures against pollution). But lack of reimbursement or additional cost for disposing batteries should not discourage the users of AGV systems to dispose the batteries properly.

A user of AGVs will face very steep penalty if batteries of the AGVs create any environmental hazard due to the negligence of the user. So, users should make sure that the spent batteries at their AGV systems are disposed in compliance with all the relevant rules and regulations. Besides the disposal of batteries, a firm also needs to make sure that the use of batteries at its facility does not affect the environment adversely. For example, the battery swapping operation must not be done at a place where there is a possibility that any spillage from the battery can eventually get mixed with the source of natural water through the drainage system (König, 2003). Use of battery swapping also requires a firm to construct battery stations with safety features like acid-proof floors (Ebben, 2001).

2.5 Theme 2 - Integrating Battery Management with Other System Components

It is important to integrate battery management with other components of an AGV system to harness the total organizational potential. This is the second theme that emerged through this study. In contrast with the first theme, this theme has a wider focus. That is, the relationship between battery management and other components of an AGV system is the focal point for this theme. This theme is important because different design and operational aspects of an AGV system can affect battery management and vice versa. Important features of this theme are discussed below.

2.5.1 Location of battery stations

There have been many scholarly studies on the layout design for AGV systems (e.g., Gaskins and Tanchoco, 1987; Kim and Chung, 2007; Ho and Liao, 2009). However, the location of battery stations has hardly got any attention in the literature. The only study that was found to deal with the location of battery stations for AGVs is Ebben (2001). But location of battery stations should be given more consideration in the layout design because the AGVs should have easy access to the battery stations and there is a greater likelihood of congestion around a battery station (so more space is need for a battery station).

Ebben (2001) recommended that traffic flow should be a major consideration while deciding about the location of a battery station. In other words, the heavier the traffic flow, the more suitable a place is as the location of a battery station. However, an area with heavy traffic flow may get congested if a battery station is located there because the battery station is likely to increase the traffic further. So, careful thought should be given to balance the benefit of easy access to a battery station and the potential increase in congestion around the battery station.

Ebben (2001) also suggested that cost and available space be considered before deciding about the location of a battery station. By talking with the industry executives, it was learned that another important factor for the location of battery stations is the availability of power lines. That is, battery stations are often located near the place where power lines enter into the facility (usually towards the back of the building).

All the factors discussed above make the layout design for AGV systems more challenging. However, incorporating battery management constraints would make a layout design more realistic and acceptable. Also, considering battery management issues at the beginning (i.e., at the design phase) will be much less expensive for a firm than making any change in the layout later.

2.5.2 AGV fleet size

There have been a good number of scholarly works on the determination of AGV fleet size (e.g., Mahadevan and Narendran, 1993; Rajotia et al., 1998; Ji and Xia, 2010). Some of the factors considered in the literature for determining AGV fleet size are: topology of the guide path through which AGVs travel, locations of the pick-up and drop-off stations, and dispatching policy for the AGVs (Choobineh et al., 2012). However, the issue of how battery management can affect the AGV fleet size has received very scant attention in the literature.

McHaney (1995) showed through simulation experiments that more AGVs are needed for busy systems when battery management is considered. In other words, systems with enough idle time can ignore battery management while determining AGV fleet size; but busy systems that do not have enough idle time should consider battery management to decide about AGV fleet size. However, a firm should be careful about adding more AGVs in its facility because the price of an AGV is quite high. According to Van der Heijden et al. (2002), price of an AGV is about $75,000. Besides being expensive, additional AGVs may create congestion, increase maintenance costs, and create unnecessary complexity in the system. All these factors may greatly reduce the marginal utility of an additional AGV.

Sometimes firms may decide not to deploy all the AGVs at once. Rather, the AGVs are added gradually with the gradual expansion of the system. If a scope of adding more AGVs in future is kept in the system (e.g., keeping empty space for the AGVs), such a scope should also consider additional resources that will be needed for battery management (e.g., additional or bigger battery station, additional chargers etc.). Otherwise, battery management can create a bottleneck in the system when more AGVs are added.

2.5.3 Productivity

For industrial trucks (like forklift trucks and AGVs), firms often try for more service or less cost on a per-vehicle basis, but firms often overlook similar opportunities on a per-battery basis (Bond, 2015). Battery management can help a firm to increase the productivity of its AGVs in multiple ways. For example, a firm can add 30 minutes or more of productive work per lift truck each day by changing (i.e., swapping) batteries at the proper time rather than at peak periods (Williams, 2010).

Chapter 3 of this dissertation discusses how battery management can help a firm to meet sudden increase of demand for the short term. Also, chapter 4 of this dissertation shows that productivity can be increased by more effectively routing the AGVs for battery management. These studies show that there are ways to improve the productivity of a system through battery management.

2.5.4 Dispatching of AGVs

Dispatching refers to a rule for executing a task of transportation (Vis, 2006). For example, if multiple AGVs are available to do a pick-up task, the AGV that is located nearest to the pick-up point can be selected to do the pick-up task. In this case, the dispatching strategy of shortest travel distance is used to select an AGV. According to Egbelu and Tanchoco (1984), dispatching at an AGV system can be work-center initiated (when an AGV needs to be selected from multiple idle AGVs) or vehicle initiated (when an AGV needs to accept a transportation request from multiple transportation requests).

There are a good number of scholarly works on dispatching of AGVs (e.g., Kim and Hwang, 1999, Kim et al. 1999); but very few of them incorporated battery management in the dispatching decision for the AGVs. Bian et al. (2015) incorporated battery capacity in the dispatching decision for an AGV so that an AGV with insufficient power (i.e., low charge) is not considered for any transportation job until that AGV gets recharged. Incorporating battery management constraint in the dispatching decision of an AGV system can help scholars to develop novel and more realistic dispatching rules.

2.5.5 Routing of AGVs

Routing of an AGV refers to the selection of the route that the AGV will take and the sequence of jobs to be performed by that AGV (Le-Anh and De Koster, 2006). Besides selecting the jobs to perform, an AGV also may need to decide which battery station to go to in order to swap its depleted battery with a fully charged battery. So, routing for battery management is important when a facility uses battery swapping and it has multiple battery stations to conduct the swapping operation. For automatic charging, routing for battery management is less important because the charging points are usually available near a pick-up point or drop-off point.

There are many research studies on the routing of AGVs (e.g., Soylu et al., 2000; Qiu et al., 2002; Nishi et al., 2009). Research on the routing of AGVs usually focus on ensuring conflict-free routing for the AGVs. Oboth et al. (1999) suggested that battery charging can be implicitly modeled like other job requests. However, to get a more accurate picture of an AGV system, it is important to explicitly model battery charging because there is a greater likelihood of congestion around a battery station in comparison to that of a pick-up point or a drop-off point. Also, until a low-charge AGV is recharged or gets its depleted battery replaced, it cannot be routed for a task of pick-up or drop-off (i.e., effective fleet size of the system is reduced).

The only study that was found to provide a detail discussion on routing of AGVs for battery management is Ebben (2001), who suggested four heuristics to decide how to route an AGV to a battery station. These four heuristics are: selecting the nearest battery station, selecting a battery station that will cause minimum delay considering both travel time and waiting time in a queue, selecting the first battery station on the current route, and selecting the farthest reachable battery station on the current route.

From the industry executives, it was learned that the common preference of routing an AGV for battery management is to send it to the nearest battery station. However, as chapter 4 of this dissertation shows, sending an AGV to the nearest battery station may not be a good practice for the productivity of the system. Rather, a firm should consider the total travel distance and potential delay while routing an AGV to a battery station. So, before adopting a routing technique for the battery management of its AGVs, a firm should analyze the potential effect of the routing technique in its facility. Also, researchers should consider how battery management can affect the routing techniques they develop.

2.6 Conclusion and Future Work

This study is mostly based on literature review. It was a challenging task to find the relevant literature because literature on battery management of AGVs is very sparse. A wide range of sources like academic journals, conference proceedings, PhD dissertations, books, book chapters, and practitioner journals were analyzed to conduct this study.

This study developed and discussed two themes related to battery management of an AGV system. The first theme focuses on the improvement of battery management practices (e.g., selection of batteries, maintenance of batteries etc.), and the second theme explores how battery management can be integrated with other components of an AGV system (e.g., effect of battery management on AGV fleet size). Also, the study discussed both long-term aspects like facility layout as well as short-term aspects like operational cost. The discussions were made from managerial perspective as opposed to technical perspective; though it was sometimes difficult to clearly differentiate the two perspectives.

It was found through this study that the first theme mentioned above is more resourceful in terms of the availability of literature. This is because there are a good number of technology handbooks that discuss battery management practices for industrial trucks like forklifts and AGVs. On the contrary, literature on the second theme is very sparse. There are two possible reasons for this dearth of literature on the second theme. First, battery management is generally ignored in the study of AGV systems assuming that effect of battery management would be negligible. This assumption is usually correct for situations where the AGVs have enough idle time to spend for battery management. But there could be many situations with little or no idle time. In those situations, battery management should be considered. Secondly, conducting research integrating battery management with other system components can be quite complicated and challenging (particularly because of the dearth of literature).

To move the body of knowledge related to AGV systems further, it is important that battery management is integrated with other aspects of AGV systems. Journal editors and reviewers can take a proactive step in this regard by encouraging such studies. Also, researchers can take the dearth of literature as a scope to find new and innovative solutions for AGV systems that integrate battery management with other components of AGV systems. Such a research is likely to be more realistic and interesting. Consequently, practitioners would find the results of such a research more valuable.

Some of the potential research questions related to the second theme of integrating battery management are mentioned below. It may be mentioned that the first two questions have been addressed in the next two chapters of this dissertation.

(i) Is it possible to get more output from a facility by changing the charging duration of the AGVs when that facility uses automatic charging?

(ii) Can the productivity of a facility be improved by changing the way the AGVs are routed to battery stations to swap their depleted batteries?

(iii) How can a facility using battery swapping schedule battery charging to minimize the total number of batteries required?

(iv) What would be the optimum way of designing the guide-path of an AGV system in presence of battery management constraints?

(v) How can an efficient battery management process help to reduce the AGV fleet size?

(vi) How can battery management be used to develop a novel and more realistic dispatching strategy for an AGV system?

Issues discussed in this study are expected to encourage new research studies to be conducted on battery management of AGV systems. This study discussed how different components of design and operation of an AGV system can be integrated with battery management. It is expected that this study, by highlighting battery management of AGVs, would contribute in making the analysis of an AGV system more relevant and holistic. That way, the study will be able to make both scholarly and practical contributions in the area of material handling systems in general and AGV systems in particular.

Appendix 2A: Key sources for theme 1 - Improving battery management practices

Authors	**Year**	**Source Type**	**Summary**
Crompton	1990	Book	Provides information on almost all types of batteries that are commercially produced. Discusses the selection criteria for traction batteries like the ones used in AGVs.
Technical Marketing Staff of Gates Energy Products Inc.	1992	Book	Provides information on design and application of sealed lead acid battery and sealed nickel-cadmium battery. Offers practical explanations of battery behavior.
Bergveld, Kruijt, and Notten	2002	Book	Defines battery management and battery management systems. Discusses the design of battery management systems with the aid of simulation.
Kiehne	2003	Book chapter	Discusses different topics related to the batteries of electrically powered industrial trucks like AGVs. Topics discussed include market demand for batteries, service life and economy, charging techniques, and maintenance.
König	2003	Book chapter	Discusses battery management from user’s perspective. Topics include battery maintenance, safety of operation, selection criteria of batteries, charging techniques, charging operation, and maintenance.
Preuss	2003	Book chapter	Provides overview on the power supply concepts for driverless industrial trucks. Topics discussed include the types of batteries, effect of temperature, and selection of a battery.
Williams	2010	Practitioner journal	Discusses how battery management systems can increase efficiency and reduce costs.
Bond	2013	Practitioner journal	Discusses about the wastage of resources for battery management and how to reduce such wastage.
Bond	2015	Practitioner journal	Discusses how battery management can be turned into a source of efficiency at a facility.

Appendix 2B: Key sources for theme 2 - Integrating battery management with other system components

Authors	**Year**	**Source Type**	**Summary**
McHaney	1995	Journal	Provides a comprehensive overview on battery management including different technologies (e.g., battery types, charging mechanisms). Explains how to incorporate battery management into the simulation studies of AGV systems.
Oboth	1999	Journal	Suggests that routing for battery charging can be done like other routing processes.
Ebben	2001	PhD dissertation	Provides a comprehensive analysis on the battery management of an underground transportation system. Discusses different topics like methods of battery charging, dispatching of AGVs to battery stations, location of battery stations, effect of battery management on the logistics performance of the system, and cost for different options of battery management.
Van der Heijden, Van Harten, and Ebben	2002	Journal	Uses simulation to analyze battery management and other aspects of a real-life AGV-based underground transportation system.
Le-Anh and De Koster	2006	Journal	Reviews the literature related to design and control of AGV systems (including battery management). Points out that battery management is usually omitted in research though it can affect the performance of a system (particularly where AGVs need to travel long distances).
Vis	2006	Journal	Reviews the literature related to design and control of AGV systems (including battery management). Called for more research on battery management of AGV systems.
Schulze and Wüllner	2006	Conference proceedings	Provides an overview of AGV systems including discussions on technological developments, operating costs, and requirements planning.
Schulze, Behling, and Buhrs	2008	Conference proceedings	Explains how an AGV system works. Discusses technological developments, applications, and operating costs. Also provides statistics on AGV usage.
Kawakami and Takata	2011	Conference proceedings	Develops a simulation model for an AGV system to evaluate battery related costs and to design battery management strategy.
Bian, Yang, Mi, W., and Mi, C.	2015	Journal	A dispatching rule for AGVs is proposed that considers battery management (i.e., a low-charge AGV is not dispatched until that AGV is recharged).

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CHAPTER 3: INCREASING MANUFACTURING FLEXIBILITY THROUGH BATTERY MANAGEMENT OF AUTOMATED GUIDED VEHICLES

3.1 Abstract

This paper investigates how the duration of battery charging for automated guided vehicles (AGVs) can be varied to increase flexibility of a manufacturing system. The key concept is that a lead acid battery, the most widely used battery type for AGVs, receives most of its charge during the initial phase (time) of charging (as opposed to the later phase), so that more productive hours can be obtained from the AGVs by reducing the duration of each charging occurrence (i.e., by recharging the batteries to less than full capacity). In this approach, an AGV needs to be recharged more frequently, but the total productive hours available from the AGVs can increase. Simulation models were developed to investigate the effect of this approach. Results show that productivity of a manufacturing system increases significantly. This approach can be quite helpful for a firm if AGVs are the bottleneck in its manufacturing plant and the firm needs to have a significant improvement of its productivity in the short-run.

3.2 Introduction

Automated guided vehicles (AGVs) are unmanned vehicles that are often used for transporting loads from one location to another (Gaskins and Tanchoco, 1987). These vehicles can automatically travel through a guided path that is usually made up of embedded wire or tape in the floor (Kim and Hwang, 1999). AGVs are widely used for material handling because of their dexterity, efficiency, and flexibility (Oboth et al., 1999). Another important advantage of AGVs is that they can be interfaced to other equipment and easily controlled through an intelligent computer system (Lacomme et al., 2013). Traditionally, AGVs were used at manufacturing facilities; but today AGVs are also regularly used for repeating transportation tasks in areas like warehouses, container terminals, and external transportation systems (Vis, 2006). AGVs are also being introduced in new areas of application (e.g., healthcare). This study focuses on the use of AGVs in a manufacturing facility.

Sometimes business firms may need to increase their manufacturing capacity within a short time. Such a need may arise due to situations like underestimated forecast for a new product or disruption in a competitor's supply chain. Underestimation of market demand is particularly probable for products such as electronics, for which the life cycle is short and demand is volatile (Weng, 1999). Disruption in the supply chain of a competitor can also create the need for a firm to increase its production within a short time. For example, when Ericsson had to scale down its production after its supplier in New Mexico was burned down in 2000 (Lee, 2004), some of its competitors that were capable of increasing production capacity quickly were able to successfully increase market shares by taking away the market share of Ericsson.

However, it is usually not possible to install a new manufacturing facility within a short time to meet unexpected increase in demand. Besides, it is not rational to make a large investment for a new facility because of a sudden increase in demand. Rather, a firm facing a sudden increase in demand should investigate if the increased demand is going to sustain in the long run before deciding to make a large investment to install new manufacturing facility.

To fulfill a sudden, short-term increase in demand, business firms can go for outsourcing (i.e., asking outside firms to supply the required product). But sometimes it may be difficult to find a competent supplier who can do the outsourced job satisfactorily. Besides, the outsourcing firm (the firm offering the job) may face the risk of opportunism, when the supplier firm can act with guile, as well as out of self-interest (McIvor, 2009). The stakes for opportunism are particularly high when the outsourcing firm has proprietary technology or other trade secrets that may have to be compromised if the firm outsources the manufacturing job. In such a case, it may be desirable for the outsourcing firm to have a solution that can help increase its own production capacity within a short time.

For manufacturing facilities using AGVs, one of the potential bottlenecks to increase production capacity is the number of productive hours available from a fleet of AGVs. AGVs create such a challenge because simply adding more AGVs may not help increase the material movement capacity of a manufacturing facility. Adding more AGVs can cause the system to have more congestion, which may, in turn, decrease the productivity. In such a case, changing the duration of battery charging may be a helpful solution to meet a sudden increase in demand. This is the basic premise of this study.

This study focuses on studying how the duration of battery charging of AGVs can be varied to increase the output of a manufacturing system without increasing the number of AGVs. In other words, the study investigates how the flexibility of a manufacturing system can be enhanced with respect to the system capacity by means of adjusting AGV operations. Through simulation experiments, this study shows that the production output of a manufacturing system can be increased significantly by altering the charging duration of the AGVs.

3.3 Study Scope and Related Literature

Key elements of design and control process of an AGV system include guide-path design, determining the number of vehicles required, vehicle scheduling, idle-vehicle positioning, vehicle routing, deadlock resolution, traffic management, load transfer, and system management (Le-Anh and De Koster, 2006; Martínez-Barberá and Herrero-Pérez, 2010). Also, close monitoring and effective control strategies are essential to ensure the proper functioning of an AGV system (Krishnamurthy et al., 1993).

One of the important aspects of an AGV system is battery management because most of the AGVs (as well as other material handling vehicles) are run through batteries. Effective battery management has the potential to help a firm using battery driven vehicles to improve its performance. For example, a firm can add 30 minutes or more of productive work per lift truck each day by changing batteries at the proper time rather than at peak periods (Williams, 2010).

Valve-regulated lead acid (VRLA) batteries are most common in AGVs because these batteries have high reliability and low cost in comparison to other types of batteries (Kawakami and Takata, 2011). Although effort is currently underway to develop effective system of inductive power transfer that can replace the batteries of AGVs, only a small portion of AGVs currently use inductive power transfer, making battery the most widely used source of power for the AGVs. In fact, only 8% of all the AGVs put into operation from European producers in 2006 used inductive power transfer (Schulze et al., 2008). Because of the dominant presence of VRLA batteries as a source of energy for AGVs, this study will focus on the effect of VRLA batteries on the performance of an AGV system.

Important factors related to the battery management of AGVs include the location of battery charging stations, capacity of the battery charging stations (how many charging positions are available in a charging station), how long will a particular AGV can operate before it needs to be recharged, availability of idle time for the AGVs etc. (Le-Anh and De Koster, 2006). In spite of the important role of battery management in determining the performance of an AGV system, there has not been sufficient research in this area. This is evidenced by the fact that Vis (2006) called for research to explore how battery management decisions affect the design and control of AGV systems.

McHaney (1995), one of the early studies conducted on battery management of AGVs, showed through simulation experiments that battery management should be considered when determining the required number of AGVs for busy systems (i.e., systems with little or no idle time). Ebben (2001) used simulation to determine the effect of battery management on an underground freight transportation system that uses AGVs. Kawakami and Takata (2011) used simulation for evaluating battery related costs and designing battery management strategies. Berenz et al. (2012) proposed a method of using probability density function for evaluating the risk of battery depletion for mobile robots. However, as far as the author knows, there has been no study, thus far, that explored how the duration of battery charging can be varied to increase the production volume without increasing the fleet size of AGVs. This study will try to address this research gap.

There are certain instances where the effects of battery management can be ignored because of the limited impact of battery management on the performance of an AGV system. Such instances include systems with naturally occurring breaks coinciding with battery charging, systems with significant amount of idle time, and systems where battery charging can be controlled without affecting the system operations (McHaney, 1995). The AGV system considered in this study will not have such characteristics. Rather, the focus will be on AGV systems that run continuously without any idle time.

The most common charging schemes for AGV batteries are battery swapping and automatic charging (see for example: McHaney, 1995; Ebben, 2001; and Savant Automation, 2015). In case of battery swapping, an AGV goes to a battery station (also known as battery room) when its battery reaches a low level of charge and then the battery is replaced by a fully charged battery. In case of automatic charging, an AGV runs until its battery is depleted to a threshold level, which signals that the AGV needs to move to a charging station where it will remain until the battery is recharged to an acceptable level (McHaney, 1995).

The advantage of automatic charging is that no additional battery is required. However, the disadvantage of automatic charging is that the AGVs are not available for work during the time of charging. With battery swapping, a facility will lose minimum amount of productive time for battery charging (the lost time will be mainly due to the time required to replace a discharged battery with a fully charged battery). However, the disadvantage of battery swapping is that special battery stations are required to execute the swap operation; and these battery stations need additional features like acid-proof floors (Ebben, 2001). Creating special battery stations for battery swapping not only increases the cost, but also additional space is required to build such stations. Besides, there is always a risk of accident or environmental hazard while swapping a battery (König, 2003).

This paper considers a manufacturing facility that already has a system of automatic charging scheme for its AGVs, and needs to have a short-term solution to increase the production volume. In such a situation, changing the duration of battery charging may help the firm overcome that problem.

3.4 Research Idea

3.4.1. Basic concept

For a lead acid battery, the acceptable charge current at the beginning of a charging period can be very high; but the charge current decreases as the battery gets more and more charge (Glaize and Genies, 2012). Because of gradually reducing current fed into a lead acid battery, the incremental (i.e., marginal) charge accumulated in the battery diminishes significantly with time. That is, a battery receives most of its charge during the initial phase (i.e., time) of charging as opposed to the later phase. This phenomenon is shown in figure 3.1, where ampere-hour is considered as the unit of charge.

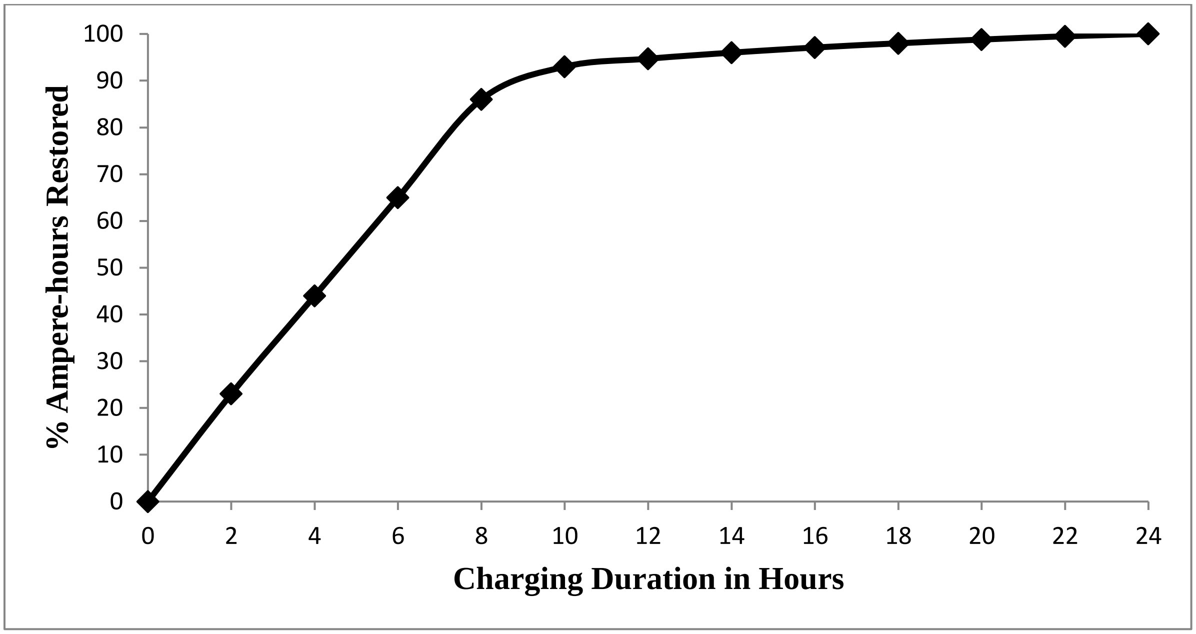


Figure 3.1: Typical charging profile of a valve regulated lead acid battery (Modified from Figure 2 of C&D Technologies, 2012a)

As indicated in figure 3.1, there is a potential for increasing the productive time of AGVs by reducing the duration of charging time because the level of charge that a battery receives is not proportional to the time it gets charged. By reducing the duration of each charging occurrence, one may need to charge an AGV more frequently; but the total time spent by an AGV in the charging stations per day is likely to be reduced. The net result may be that an AGV will spend more time in serving the system as opposed to getting charged. Consequently, the system would have the possibility of providing more outputs with the same number of AGVs (i.e., flexibility of the system is likely to increase). This is the main idea of this paper.

3.4.2. Modeling charging duration

Time required for recharging a battery heavily depends on its depth of discharge (DOD), which refers to how much (%) ampere-hours a battery lost in comparison to its full capacity (C&D Technologies 2012b). (It may be noted that ampere is the unit of current and ampere-hour is the unit of charge.) If a battery has a full capacity of 200 ampere-hours and it loses 120 ampere-hours, then its DOD will be 60%.

Another important concept regarding the charging time for a battery is the state of charge (SOC), which refers to the amount (%) of ampere-hours remaining in a battery in comparison to its full capacity (C&D Technologies 2012b). That is, SOC = 100% – DOD (e.g., in the example above SOC = 100% – 60% = 40%). According to Kiehne (2003), batteries of material handling vehicles should not have less than 20% SOC (i.e., batteries should not have more than 80% DOD).

Giving a battery less than full charge (i.e., targeting an SOC of less than 100%) is not desirable because such undercharging deteriorates the health of a battery in the long run (C&D Technologies, 2012c). In the short run, however, one can target to recharge a battery to a lower level of SOC in order to save time. For example: as shown in figure 3.2, a VRLA battery needs to be recharged for nearly over 3,000 minutes (i.e., nearly 52 hours) if it has lost all its charge (i.e., DOD = 100%) and if it needs to be fully recharged (i.e., target SOC = 100%). However, the same battery (with 100% DOD) needs to be recharged for only 1,550 minutes (i.e., approximately 26 hours) if the target SOC is 95%.

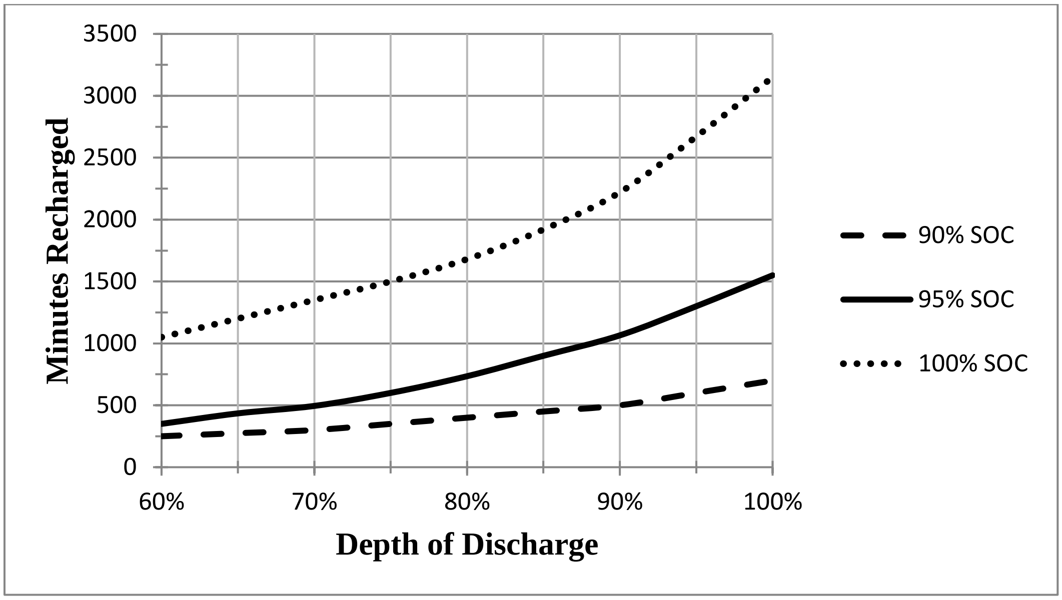


Figure 3.2: Recharge time vs. depth of discharge for a valve regulated lead acid battery with 2.3 volts/cell and a rating of 0.1C (Modified from Figure 1 of C&D Technologies, 2012a)

To find the relationship between recharging time (in minutes) and DOD, relevant data were obtained from figure 3.2. Regression technique was then used to fit equations to the obtained data. The fitted equations are given below, where x is DOD and y is recharge time in minutes. Equations (1), (2), and (3) below represent the regression formulas for 90% SOC, 95% SOC, and 100% SOC respectively.

$$y = 51.115e^{2.5773x} \qquad (1)$$

$$y = 37.442e^{3.7248x} \qquad (2)$$

$$y = 205.29e^{2.6785x} \qquad (3)$$

R^2 for each of these three equations was found to be more than 0.99, which indicates a very good fit. This means that the fitted regression equations can be used to estimate the required recharge time for AGVs reasonably well. This study uses these regression equations to investigate the impact, if any, of adjusting the charging duration of AGVs on the short-run efficiency of a manufacturing system.

In the paragraphs that follow, this study performs a series of simulation experiments that operate an AGV system under a variety of settings and charging durations to investigate the impact that the charging duration can have on system outputs. Such experiments should provide important normative implications to both researchers and practitioners regarding how long an AGV should be charged under many conditions to maximize the system output.

3.5 Experimental Design

A discrete event simulation model was developed to test the research idea of this study. It is a common approach to use simulation in a research on AGV systems. McHaney (1995) and Ebben (2001), two early studies on the battery management of AGVs, used simulation as the methodology. There are many other scholarly works in which simulation was used to study different aspects of AGV systems. Examples of such scholarly works include Mahadevan and Narendran (1994), Rajotia et al. (1998), Ji and Xia (2010), and Kawakami and Takata (2011).

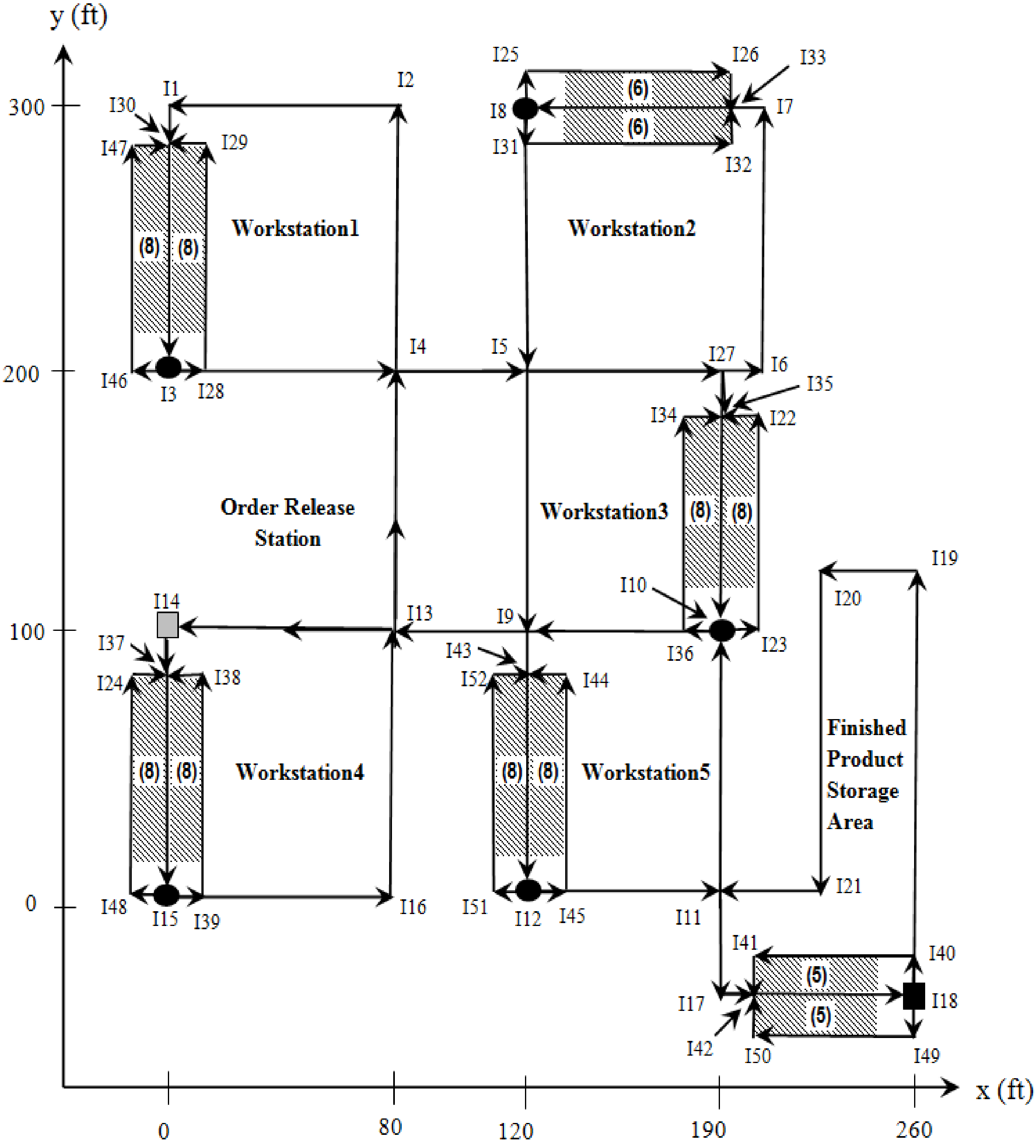
Arena software (version 14.7) was used to develop the simulation model. The model was run in a notebook computer with 3.00 GHz Intel Core i7 processor and 8 GB of RAM. Most of the data used for this study were taken from secondary sources (using secondary data for simulation is quite common; see, e.g., Kesen and Baykoç, 2007). However, some other data were obtained from the interviews that were conducted with selected vendors of battery and AGV systems.

3.6 Experimental Setting

3.6.1 Facility layout

Basic layout of the manufacturing facility, as shown in figure 3.3, is adapted from Egbelu (1987). Guide-path of the facility is unidirectional and the shaded areas in the layout represent charging areas. Each intersection in the guide-path network has been given a name that starts with I (e.g., I1, I2 etc.).

It is to be noted, however, that the layout shown in figure 3.3 differs in three ways from that of Egbelu (1987). First, charging area is added in figure 3.3 near all the stations except the order release station (Egbelu [1987] did not address the charging of AGVs because the AGVs considered in that study ran for 8 hours a day; i.e., there were enough idle time to charge the AGVs). Order release station of figure 3.3 does not have a charging area because after picking up a part, an AGV, even if its charge goes below the threshold level, needs to drop-off that part to the designated point before going for charging. Equal number of charging points, as shown in figure 3.3, is available in both sides of a pick-up/drop-off point to reduce the possibility of blockage.



● = Pick-up and drop-off points at the workstations

▨ = Pick-up point at order release station

■ = drop-off point at finished product storage area

(n) = Number of charging points available in the shaded area

Figure 3.3: Layout of the manufacturing facility (adapted from Egbelu 1987)

The second way that the layout of figure 3.3 differs from that of Egbelu (1987) is the location of pick-up points and drop-off points. In Egbelu (1987), most of the work-centers have their pick-up points and drop-off points located at different places. In figure 3.3, however, it is assumed that each of the 5 workstations has their pick-up point and drop-off point located at the same place. In other words, each workstation has a single point from where both pick-up and drop-off take place. Keeping the location of pick-up point and drop-off point at the same place is in line with the example of Kelton et al. (2015), from where the data for shop processing and AGV routing are taken (details are given in section 3.6.2), as well as with Gaskins and Tanchoco (1987).

Third, the layout of Egbelu (1987) had 8 stations (i.e., 8 work-centers), but the layout used in this paper has 7 stations. The number of stations has been decreased from 8 to 7 in order to allocate space for charging the AGVs near each station. Among the 7 stations, the first station is order release station where the parts first arrive and then get released to different workstations; the next five stations represent workstations where parts are processed; and the last station is the finished product storage area where the finished parts are stored after being processed. AGVs come to the order release station only to pick-up the parts (but no drop-off). On the contrary, the AGVs go to the finished product storage area only to drop-off the parts (no pick-up). Both pick-up and drop-off take place in each of the five workstations. In spite of the presence of a good number of charging points around the pickup/drop-off points, blockage can be created by a low-charge AGV. The following paragraphs, with the example of workstation-2, clarify how such a blockage can be created.

Let’s assume an AGV needs to go for charging after dropping-off a load at intersection I8 (i.e., workstation-2). If no other AGV is getting charged around workstation 2, the low-charge

AGV travels along link I31-I32 and goes to the charging point nearest to I32. If a second AGV comes for charging while the first AGV is still getting charged, then the second AGV will travel along link I31-I32 and go to the charging point second-nearest to I32 (the nearest charging point to I32 is being occupied by the first AGV). If a third AGV comes for charging while the second AGV is still getting charged, the third AGV will travel along link I31-I32 and go to the charging point third-nearest to I32. It may be noted that by the time the third AGV entered I31-I32, first AGV may have left (after getting charged) making the nearest charging point to I32 empty. Still, the third AGV will not be able to access that nearest charging point to I32 because the second AGV is blocking the path leading to that charging point (the second AGV is still getting charged at the second-nearest point to I32). Consequently, the third AGV will go to the third-nearest charging point to I32.

At a certain point, it may happen that out of six charging points available along link I31-I32, only the sixth-nearest charging point to I32 (i.e., nearest charging point to I31) is occupied while the remaining five charging points along that link are empty (i.e., AGVs that earlier occupied those points have left after getting charged). Yet, the seventh AGV needing charge after dropping off at I8 will not be able to access any of the five empty charging points along I31-I32 because the path is being blocked by the sixth AGV, which is still getting charged. In such a case, the seventh AGV will travel along link I25-I26 (i.e., the other side) and go to the charging point nearest to I26. The six charging points along I25-I26 will continue to get occupied until the sixth AGV leaves link I31-I32 making all the charging points of link I31-I32 accessible again.

Sometimes the sixth-nearest charging point to I32 (i.e., nearest charging point to I31) and sixth-nearest charging point to I26 (i.e., nearest charging point to I25) may be occupied at the same time (this may happen particularly with a target SOC of 100%, which requires a long time for charging). In such a case, if an AGV needs to get charged after dropping off at I8, it will not be able to access any nearby charging point located along link I31-I32 or link I25-I26. Consequently, that low-charge AGV will wait at I8 until a charging point along link I31-I32 or link I25-I26 becomes accessible. Because of the presence of that low-charge AGV at I8, no pick-up or drop-off will take place at that location (i.e., workstation 2). This will create congestion in the system.

3.6.2 Part routing and processing time

Though the layout of the manufacturing facility is adapted from Egbelu (1987), the production parameters were not taken from the same paper because Egbelu (1987) considered the production process to be deterministic. Data related to the production process have been adapted from Kelton et al. (2015). The facility used in this study produces three different parts: part 1, part 2, and part 3. The inter-arrival times between successive part arrivals, considering all part types together, are exponentially distributed with a mean of 13 minutes. The first part arrives at time zero. The break-down of different parts arriving to the system (probability that the next arrival is a given part) are: 26% for part 1, 48% for part 2, and 26% for part 3. Arrival rate for the parts is quite high in comparison to the rate of processing the parts. This is to ensure that AGVs remain busy most of the time.

Slight modifications were made to the routing and process-time specifications of Kelton et al. (2015) to better fit the need of this study. Table 3.1 shows the routing and process times for the three parts produced at the manufacturing facility considered for this study (order release station and finished product storage area are not shown in the table because they are always the first station and last station respectively). Each process time has triangular distribution as shown in Table 3.1 and each workstation has one machine.

Each part type follows the sequence shown in table 3.1. For example, part 3 is first routed from order release station to workstation2. After getting processed at workstation2, part 3 is routed from workstation2 to workstation1 (as shown in table 3.1). Similar routing process continues for part 3 until it gets processed at workstation4 and routed from there to the finished product storage area (workstation4 is the last workstation for part 3 to get processed). Other parts also follow their respective routing sequence as given in table 3.1. All process times are in minutes and they have triangular distributions as shown in table 3.1. For example: at workstation4, part 3 has a process time distribution of 8 minutes (minimum), 11 minutes (mode), and 13 minutes (maximum). Each workstation has one machine to process the parts.

Table 3.1: Part routing and process time distributions (in minutes) with 5 workstations (adapted from Kelton et al., 2015)

Part Type	Workstation (Process Time Distr.)	Workstation (Process Time Distr.)	Workstation (Process Time Distr.)	Workstation (Process Time Distr.)	Workstation (Process Time Distr.)
1	Workstation1 (6, 8, 10)	Workstation2 (5, 8, 10)	Workstation3 (12, 16, 20)	Workstation4 (8, 12, 16)	Workstation5 (4, 7, 9)
2	Workstation1 (11, 13, 15)	Workstation2 (4, 6, 8)	Workstation4 (15, 18, 21)	Workstation3 (24, 27, 31)	Workstation5 (6, 9, 13)
3	Workstation2 (7, 9, 11)	Workstation1 (7, 10, 13)	Workstation3 (15, 19, 23)	Workstation5 (6, 9, 12)	Workstation4 (8, 11, 13)

3.6.3 AGV movement

Basically, each time an AGV arrives at a station, its charge status is checked and if the charge status is below the threshold level, the AGV goes to the nearest charging area from that station. The logic of movement by an empty AGV differs from that by a loaded AGV. Figure 3.4 shows the flowchart (logic) of an empty AGV for a pick-up task and figure 3.5 shows that of a loaded AGV for a drop-off task.

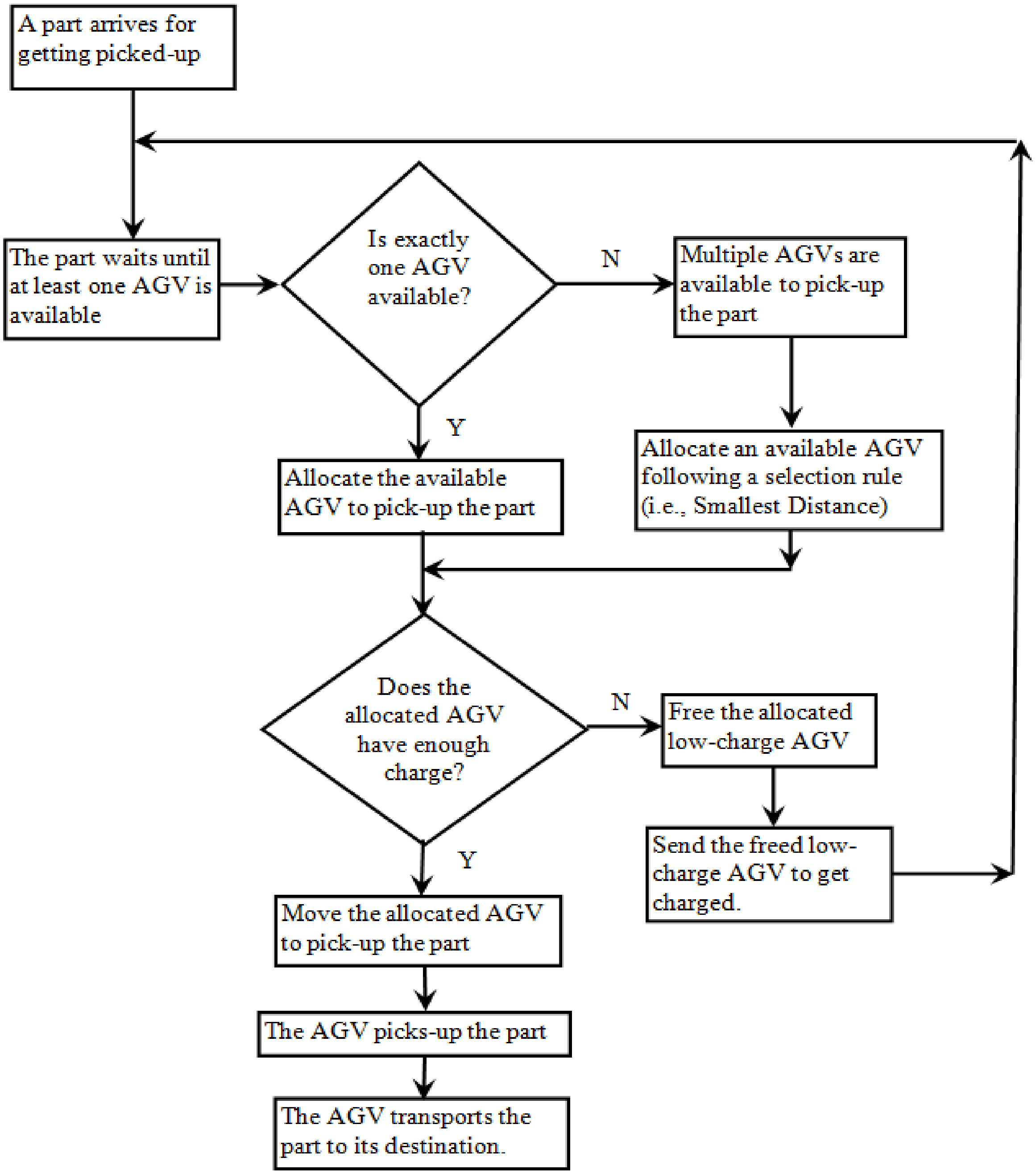


Figure 3.4: Allocation flowchart for empty AGVs

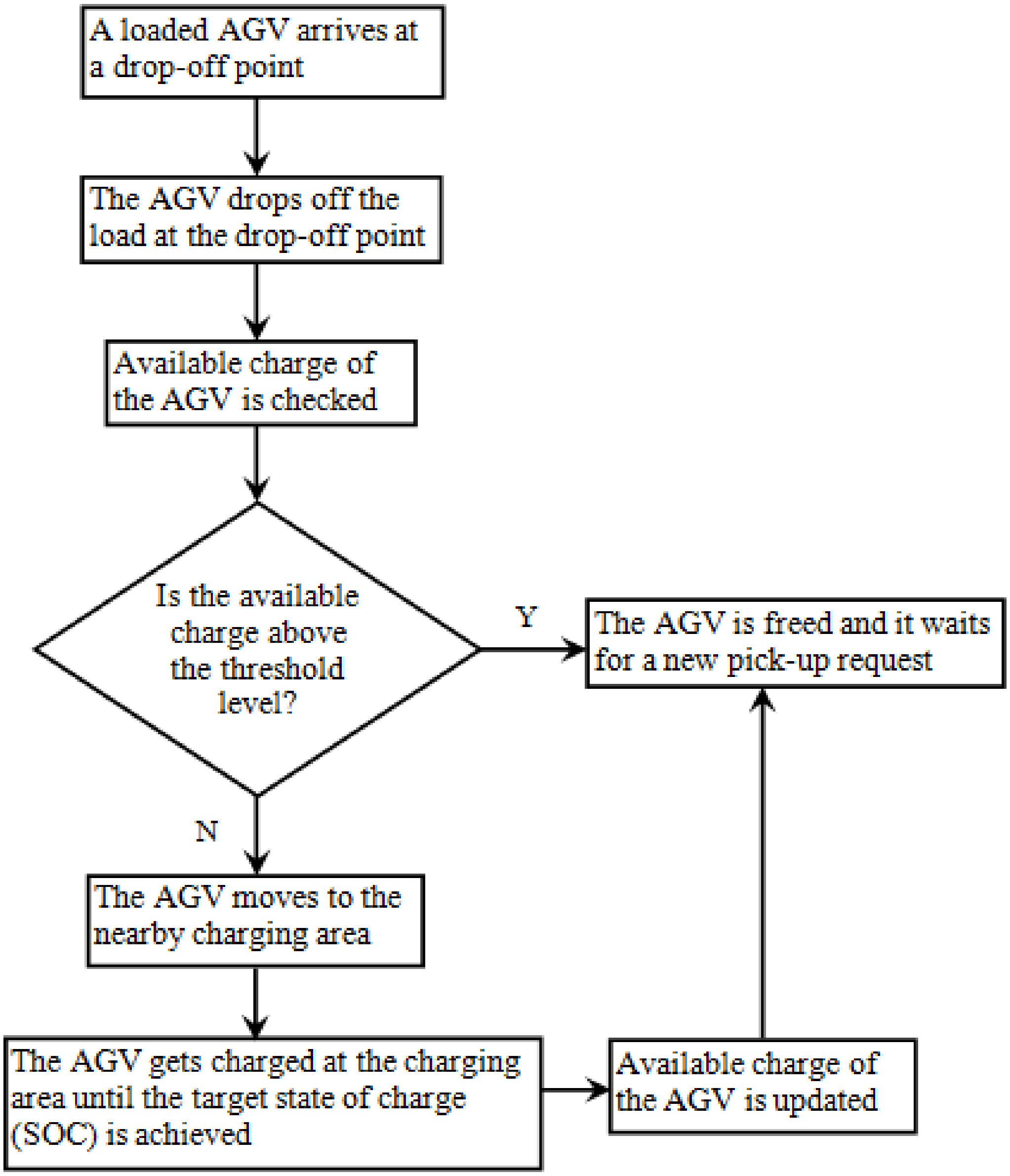


Figure 3.5: Travelling flowchart for a loaded AGV

3.6.4 Assumptions

The following assumptions, in line with Egbelu (1987), were made while developing the simulation model.

- All AGVs are identical.

- The AGVs travel at a speed of 150 feet per minute except during the time of acceleration and deceleration.
- Each loading and unloading task takes 15 seconds
- There is no time loss due to the breakdown of an AGV.
- Each AGV is a unit-load AGV. That is, the loads are directly transported from origin to destination without any stop in between.

Additionally, it is assumed that the facility operates 24 hours a day to meet the sudden increase in demand (i.e., continuous operations). Thus, there is no off-shift for any AGV. That is, if not being charged, an AGV is assigned (or waiting to be assigned) to work.

3.6.5 Ampere draws for different activities

Table 3.2 shows the ampere draws for different activities by an AGV. Except the ampere draw data for picking and dropping, all data of Table 3.2 are taken from Table 3 of McHaney (1995). The ampere draw data for picking and dropping are taken from Table 14 of the same paper.

Table 3.2: Ampere draws for different activities of an AGV (Source: McHaney, 1995)

AGV Activity	Ampere Draw from Battery
Blocking	5 amperes
Traveling Empty	40 amperes
Traveling Loaded	60 amperes
Accelerating Empty	55 amperes
Accelerating Loaded	75 amperes
Decelerating Empty	55 amperes
Decelerating Loaded	50 amperes
Picking	60 amperes
Dropping	40 amperes

Each time an AGV performs an activity, the corresponding ampere draw (loss) is calculated. The ampere-hours lost by the battery is calculated by multiplying the ampere draws for that activity by the number of hours the AGV performs that activity. For example: if an AGV remains blocked for 0.5 hours, it loses 2.5 ampere-hours (5 amperes × 0.5 hour).

3.6.6 Battery capacity and threshold level of charge

The AGV considered in this study has a battery capacity of 200 ampere-hours like model DC-60 of Savant Automation (Savant Automation, 2007). Data of Kawakami and Takata (2011) are used to determine the threshold level to recharge an AGV. The threshold level refers to the level of charge at which the AGV is sent for recharging.

Kawakami and Takata (2011), in their simulation experiment, used threshold levels ranging from 20% to 50% of nominal capacity of a VRLA battery. In that simulation experiment, however, battery swapping was used and an AGV had to travel to an end point to have its battery swapped. This means that in this study, in which automatic charging is considered and the chargers are available near every workstation, a smaller threshold value may be used. As such, a threshold level of 50 ampere-hours, or 25% of the nominal capacity of the battery, is used in this study. That is, if the battery of an AGV reaches a 75% depth of discharge (DOD), the AGV is sent to get recharged. Note, however, that as the low-charge AGV moves to a charging point, it will lose more charge (i.e., DOD can exceed 75%) because of the movement and possible blockage.

3.6.7 Calculating charge loss due to acceleration and deceleration

Every time an AGV starts traveling, it first accelerates to a uniform speed from the stationary condition. At the end of the travel, the AGV decelerates back to the stationary condition. An AGV also accelerates and decelerates every time it takes a turn. That is, an AGV decelerates before taking a turn and accelerates after taking the turn. Thus, while traveling from one intersection (origin) to another intersection (destination), the number of accelerations (or decelerations) for an AGV is equal to the number of turns it takes plus one (plus one is for the initial acceleration/terminal deceleration). Number of turns taken by an AGV depends on its origin and destination of travel. Table 3.3 shows the number of turns for every feasible origin-destination combinations. An example of how charge loss is calculated for acceleration/deceleration is given with that table.

Table 3.3: Number of turns for different origin-destination combinations (to calculate the charge loss due to acceleration and deceleration)

Travel Destination → ↓ **Travel Origin**	Order Release Station (I14)	WS1* (I3)	WS2 (I8)	WS3 (I10)	WS4 (I15)	WS5 (I12)	Finished Product Storage Area (I18)
Order Release Station (I14)	0	4	5	Won't happen	Won't happen	Won't happen	Won't happen
Workstation1 (I3)	2	0	2	1	3	1	Won't happen
Workstation2 (I8)	1	4	0	2	2	0	Won't happen
Workstation3 (I10)	0	3	4	0	1	1	Won't happen
Workstation4 (I15)	2	3	4	3	0	3	6
Workstation5 (I12)	2	5	6	1	3	0	2
Finished Product Storage Area (I18)	5	7	9	4	6	6	0

*WS = Workstation

Example: Table 3.2 shows that an empty AGV continuously draws 55 amperes of current to accelerate. So, if it takes 40 seconds (i.e., 0.0111 hours) for an empty AGV to accelerate from stationary position to a uniform speed, the loss for accelerating once will be 55 amperes × 0.0111 hours = 0.6111 ampere-hours. If the empty AGV moves from Workstation1 to Workstation2, it will take two turns as shown in the table above. Thus, the number of accelerations for this travel is 3 (2+1). Charge loss due to acceleration in this travel will then be 0.6111 ampere-hours × 3 = 1.8333 ampere-hours. Similar calculations are made for deceleration.

3.6.8 Experimental parameters

Multiple simulation experiments were conducted with different number of AGVs in the system. With each number of AGVs, performance of the system in terms of total output (total output = number of part 1 produced + number of part 2 produced + number of part 3 produced) was determined with three targeted values of SOC (state of charge). These are: 90% SOC, 95% SOC, and 100% SOC. Following Rossetti (2010), warm-up period for each simulation experiment was determined to be 60 hours and the number of replications for each simulation experiment was determined to be 40. Following Banks et al. (2005), length of each replication was determined to be 600 hours.

3.7 Result and Analysis

3.7.1 Change in total output

Total output values by available AGVs and targeted SOCs are shown graphically in figure 3.6. The exact values used to draw figure 3.6 are given in the appendix. Several interesting observations can be made from figure 3.6 as discussed below.

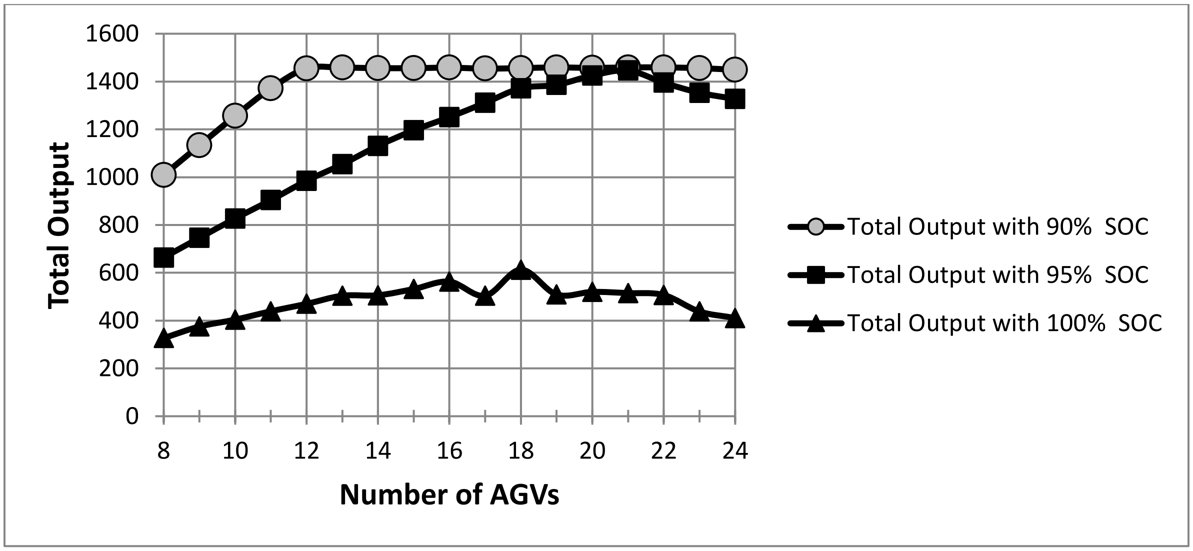


Figure 3.6: Change in output with different number of AGVs and with different SOCs

(1) Generally, total output increases as the target level of SOC is decreased (e.g., level of SOC is decreased from 100% to 95%). To illustrate this point, let us see the change in output when the number of AGVs is fixed at 8. With 8 AGVs, total output is over 650 if the system targets an SOC of 95%; whereas the total output goes below 350 if the system targets an SOC of 100%. This characteristic, which is generally prevalent in the results, indicates that the system can increase its productivity substantially by targeting a lower level of SOC. That way, the system will be more flexible with a lower level of SOC.

(2) Total output increases for each level of SOC (i.e., 90%, 95%, and 100%) when the number of AGVs is increased from 8 to 12. However, the rate of increase in total output (as the number of AGVs is gradually increased from 8 to 12) is highest for 90% SOC and lowest for 100% SOC.

(3) Generally, similar (or better) productivity can be achieved with lesser number of AGVs if a facility targets a lower level of SOC. For example: the highest output is around 1450, which can be achieved with 12 AGVs if an SOC of 90% is targeted. However, the required number of AGVs jumps to 21 if the similar level of output is to be achieved with a target SOC of 95%.

3.7.2 Bottleneck resources

For each target of SOC, total number of outputs reaches a steady level with a certain number of AGVs. For example: with 90% SOC, total number of outputs reaches a steady level with 12 AGVs. After 12 AGVs, further addition of AGVs hardly contributes in increasing the total output. Similar phenomenon is present for target SOCs of 95% and 100%. This phenomenon may be explained by two factors: bottleneck resources and congestion. This section discusses the effect of bottleneck resources and the next section discusses the effect of congestion.

When number of AGVs is small, AGVs are likely to be the bottleneck in the facility. That is, when number of AGVs in the system is small, production volume is not likely to increase without the addition of more AGVs in the system. However, as more and more AGVs are added, another resource (i.e., a machine at a workstation) can become a bottleneck. If AGVs are not the bottleneck, then there is no benefit of increasing the number of AGVs. Rather, the new bottleneck resource should be increased. This kind of situation is explained below using table 3.4 for the target SOC of 90%.

Table 3.4: % Resource utilization for a target SOC of 90%

Number of AGVs	**Average utilization (%) with a target SOC of 90%**					
	AGVs	**Machine at WS1**	**Machine at WS2**	**Machine at WS3**	**Machine at WS4**	**Machine at WS5**
8	100.00%	33.66%	22.33%	68.79%	44.97%	26.65%
9	100.00%	37.99%	25.05%	77.67%	50.69%	29.92%
10	100.00%	41.94%	27.68%	86.12%	56.23%	33.18%
11	100.00%	46.09%	30.43%	94.05%	61.42%	36.19%
12	100.00%	50.79%	33.50%	99.96%	66.68%	38.45%
13	100.00%	57.32%	37.78%	100.00%	71.85%	38.48%
14	100.00%	63.44%	41.79%	100.00%	76.49%	38.46%
15	100.00%	69.41%	45.78%	100.00%	81.34%	38.44%
16	99.95%	75.35%	49.76%	100.00%	85.81%	38.50%
17	99.32%	80.82%	53.29%	100.00%	89.96%	38.45%
18	96.44%	82.96%	54.83%	100.00%	91.75%	38.46%
19	93.82%	83.55%	55.19%	100.00%	92.53%	38.48%
20	91.23%	83.89%	55.38%	100.00%	92.85%	38.50%
21	89.91%	83.68%	55.43%	100.00%	92.50%	38.49%
22	89.08%	83.61%	55.29%	100.00%	92.64%	38.52%
23	88.32%	83.89%	55.41%	100.00%	92.64%	38.49%
24	87.70%	83.42%	55.13%	100.00%	92.16%	38.31%

*WS = Workstation

Table 3.4 shows that initially average utilization of the AGVs is 100% (i.e., initially the AGVs are always busy). In other words, AGVs are the only bottleneck resource when number of AGVs is 12 or less. With 13 AGVs in the system, the machine at workstation 3 also becomes a bottleneck resource. Both the machine at workstation 3 and the AGVs are bottleneck (i.e., have 100% utilization) when there are 13, 14, or 15 AGVs in the system. If number of AGVs is 16 or more, the machine at workstation 3 becomes the only bottleneck resource with 100% utilization and the utilization of the AGVs goes below 100%. This happens because no machine is added at workstation 3 while number of AGVs keeps on increasing. The data of table 3.4 are shown graphically in figure 3.7 below.

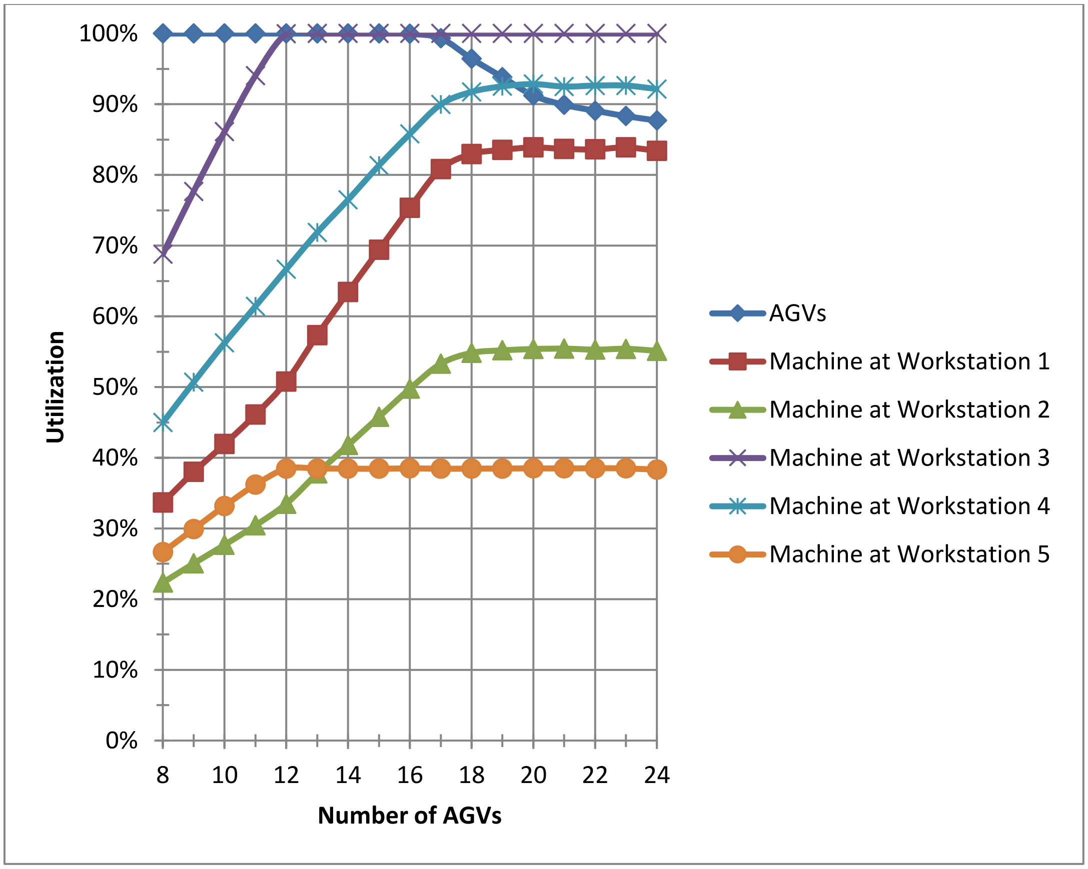


Figure 3.7: Bottleneck resources for a target SOC of 90%

3.7.3 Congestion

As number of AGVs continues to increase, the system faces more and more congestion due to blockage. After a certain point, the marginal benefit of adding an AGV in the system becomes negative because of the additional congestion created as a result of adding the AGV. Because of the congestion, an AGV has to spend a significant amount of time being blocked. This phenomenon is shown in table 3.6 for a target SOC of 95%.

Table 3.6: Effect of congestion due to the increase in number of AGVs (for target SOC of 95%)

Number of AGVs	**Average time (minutes) spent by each AGV being blocked while going to its destination**						**Total (minutes)**
	Destination is WS1*	**Destination is WS2**	**Destination is WS3**	**Destination is WS4**	**Destination is WS5**	**Destination is Storage Area**	
15	1.74	2.10	2.07	1.94	1.42	2.64	11.90
16	2.67	3.08	2.68	2.75	2.04	3.43	16.66
17	3.03	2.92	3.30	2.25	2.65	4.37	18.51
18	3.81	3.47	3.41	3.32	3.23	4.49	21.73
19	5.57	4.72	4.06	4.92	5.24	6.31	30.81
20	5.40	4.88	5.17	4.54	5.44	6.52	31.94
21	6.66	5.42	**4.70**	5.28	**5.13**	**6.21**	33.41
22	8.88	8.36	7.35	7.52	9.84	8.80	50.74
23	9.10	**7.24**	8.26	7.95	7.02	16.67	56.24
24	10.81	10.19	12.16	10.41	12.02	13.06	68.65

*WS = Workstation

Table 3.6 shows that average blockage time for an AGV generally increases for most destinations (drop-off points) as more and more AGVs are added in the system. There are few exceptions, which are shown in bold font in table 3.6, where the average blockage time for an AGV decreases a little for certain destinations. However, total blockage time for all the destinations, as shown in the last column of table 3.6, always increases with the increase of AGVs.

Blockage can be created due to multiple reasons. First, an AGV has to stop when another AGV in front of it is loading or unloading. Secondly, if an AGV remains idle at a point on the guide-path, that AGV can create blockage in the system. Such a blockage is more likely to happen if utilization of the AGVs is significantly less than 100%. That is why idle AGVs are usually sent to a parking area if there is a high likelihood of having idle AGVs in the system (idle AGVs do not create blockage on the guide-path if they are positioned in the parking area). Another option to position an idle AGV is to place it at or around a drop-off point after the AGV drops off at that point. Since this study considered a busy system with little likelihood that an AGV will remain idle for a long time, an idle AGV is positioned at the drop-off point after dropping off at that point (i.e., the idle AGV is not sent to a parking area). A third source of blockage is the charging area. As explained in section 3.6.1 (i.e., facility layout), blockage can be created if a low-charge AGV cannot access a nearby charging point. This is more likely to happen when the AGVs occupy charging points for a long time (particularly with target SOCs of 100%).

If AGVs remain blocked due to congestion in the system, the machine utilization may drop (i.e., machines starve because AGVs cannot bring the parts to the machines). Table 3.7 shows that for a target SOC of 95%, utilization of all the machines increases with the addition of AGVs as long as the number AGVs is 21 or less. After 21 AGVs, utilization of the machines starts falling though utilization of the AGVs remains 100% or nearly 100%. The likely reason of this occurrence is that AGVs are not able to deliver the parts to the machines due to congestion in the system. It may be noted that when an AGV gets blocked on its way to pick-up or drop-off, it is considered as being utilized (though the AGV is not moving due to blockage). On the contrary, if a machine does not have any part available to process, it is considered to be unutilized.

Table 3.7: % Resource utilization for a target SOC of 95%

Number of AGVs	**Average utilization (%) with a target SOC of 95%**					
	AGVs	**Machine at WS1**	**Machine at WS2**	**Machine at WS3**	**Machine at WS4**	**Machine at WS5**
8	100.00%	22.24%	14.69%	45.44%	29.68%	17.51%
9	100.00%	25.02%	16.54%	51.08%	33.41%	19.68%
10	100.00%	27.71%	18.28%	56.62%	37.05%	21.79%
11	100.00%	30.32%	20.07%	61.87%	40.50%	23.88%
12	100.00%	33.10%	21.80%	67.45%	44.20%	26.04%
13	100.00%	35.51%	23.46%	72.15%	47.25%	27.79%
14	100.00%	37.92%	25.11%	77.28%	50.69%	29.81%
15	100.00%	40.02%	26.63%	81.52%	53.30%	31.60%
16	100.00%	41.69%	27.61%	85.38%	55.76%	33.05%
17	100.00%	43.98%	29.01%	89.82%	58.56%	34.64%
18	100.00%	46.18%	30.63%	94.04%	61.45%	36.22%
19	100.00%	47.10%	31.17%	94.89%	62.35%	36.62%
20	100.00%	50.16%	33.35%	97.54%	65.68%	37.62%
21	100.00%	53.30%	35.21%	99.50%	68.56%	38.28%
22	100.00%	51.69%	34.15%	95.97%	66.25%	36.83%
23	100.00%	52.80%	34.76%	93.52%	66.41%	35.88%
24	99.98%	52.66%	34.65%	91.41%	65.38%	35.07%

*WS = Workstation

Table 3.8 shows how the addition of AGVs affects the utilization of machines when the target SOC is 100%. Since the target SOC of 100% takes the longest time to charge, the effect of congestion is the most severe in this case. As shown in table 3.8, average utilization is always under 50% for all the machines. Poor utilization of machines is most likely caused because of the blockage created by low-charge AGVs when the low-charge AGVs cannot access charging points. The details of how such a blockage can be created are given in section 3.6.1 (i.e., facility layout).

Table 3.8: % Resource utilization for a target SOC of 100%

Number of AGVs	**Average utilization (%) with a target SOC of 100%**					
	AGVs	**Machine at WS1**	**Machine at WS2**	**Machine at WS3**	**Machine at WS4**	**Machine at WS5**
8	100.00%	10.62%	7.13%	22.13%	14.49%	8.58%
9	100.00%	12.16%	8.16%	25.45%	16.68%	9.89%
10	100.00%	13.17%	8.81%	27.49%	17.98%	10.65%
11	100.00%	14.34%	9.58%	29.86%	19.56%	11.63%
12	100.00%	15.30%	10.23%	31.86%	20.91%	12.42%
13	100.00%	16.32%	11.00%	34.34%	22.52%	13.31%
14	100.00%	16.34%	10.99%	34.20%	22.44%	13.36%
15	100.00%	17.04%	11.53%	36.19%	23.71%	14.06%
16	100.00%	18.12%	12.26%	38.32%	25.16%	14.91%
17	100.00%	15.97%	10.92%	34.12%	22.38%	13.36%
18	100.00%	19.77%	13.36%	41.65%	27.31%	16.21%
19	100.00%	15.93%	11.03%	34.68%	22.78%	13.53%
20	100.00%	16.16%	11.22%	35.42%	23.19%	13.78%
21	100.00%	15.93%	11.06%	34.97%	22.90%	13.65%
22	100.00%	15.73%	10.86%	34.42%	22.59%	13.41%
23	100.00%	13.45%	9.39%	29.69%	19.53%	11.68%
24	100.00%	12.29%	8.73%	27.99%	18.37%	10.99%

*WS = Workstation

To reduce the impact of congestion when the target SOC is 100% (or 95%), a low-charge AGV can go to an accessible charging point located at another workstation instead of waiting at its current location after dropping-off a load. If no charging point is accessible, then the low-charge AGV can go to the parking area. If such measures are taken to reduce the congestion, performance differences among the target SOCs are likely to reduce noticeably. Future research can address this issue further.

3.8 Practical Implications

As mentioned before, it is good for the health of a battery to recharge it to its full capacity (i.e., charging a battery to 100% SOC). As such, regularly undercharging the batteries might require an AGV system to use more batteries in the long run. However, since the focus of this study is to explore the possibility of meeting sudden increase in demand in the short-term, the health of the battery is not likely to be a significant factor. While changing the charging duration to meet a sudden increase in demand, the firm should also try to develop a long-run solution to increase its capacity.

It is to be noted that, even if a firm needs to use more batteries because of reduced charging durations of AGV batteries (and thereby compromising the health of the batteries), the cost of the additional batteries may be quite small in comparison to the advantages gained (such as the increased profit in the short run, and increased market share in the long run). According to the example of Kawakami and Takata (2011), the cost of an AGV battery is 38,000 Yen (equivalent to approximately 322 US dollars), which is less than 5% of the cost of a typical AGV. As such, using few more batteries in the long run in exchange of increased production volume in the short run, which can be very important for strategic reasons, may be a cost-effective decision.

3.9 Conclusion and Limitation

The results of this study show that a firm can increase its manufacturing flexibility significantly if it reduces the targeted state of charge (SOC) for its AGV batteries. Such an approach is likely to help a firm in meeting sudden increases in the market demand in cases where AGVs are the bottleneck in the production facility. Being able to meet sudden increase in market demand by getting more productive hours from the AGVs can have a long term strategic implication for the firm. This study shows one such way to achieve more productive hours from the AGVs by changing the targeted SOC for the AGV batteries.

Though this research was conducted in a manufacturing environment, the results are likely to be similar for other systems as well (e.g., warehouse, container terminals, hospitals etc.). It would be interesting to see future research experiments focusing on other types of systems to explore how the duration of battery charging affects the performance of different systems.

This study has its limitations, which may be addressed in future research. First, the effect of break-down of AGVs was not considered in this study. Break-down of an AGV not only reduces the productive hours available from that AGV, but also creates congestion in the system causing other AGVs to be blocked. With continuous undercharging of the batteries, AGVs may have a somewhat higher probability of breakdown because continuous undercharging may, as discussed earlier, deteriorate the health of batteries. Consequently, it would be interesting to see the combined effect of break-down and battery undercharging of AGVs in a facility.

Second, this study uses the dispatching policy of the nearest empty AGV. That is, when a part needs to be picked-up, the nearest empty AGV is assigned to the task. But there are other dispatching policies like selecting an AGV randomly, following a cyclic order to select an AGV, or selecting an AGV that is located farthest. Use of different dispatching policies, in conjunction with the battery management strategy described in this study, may improve the productivity of a system further. Third, the layout used in this study has unidirectional guide-paths. It would be interesting, for example, to see if a layout with bidirectional guide-paths will have similar change in productivity when the battery charging time is changed.

Appendix 3A: Total output values used to draw figure 3.6 (each value was found by adding the number of different parts produced)

Number of AGVs	Total Output with 90% State of Charge	Total Output with 95% State of Charge	Total Output with 100% State of Charge
8	1009	664	327
9	1133	746	375
10	1256	827	404
11	1371	904	439
12	1455	985	470
13	1458	1054	504
14	1456	1131	506
15	1456	1196	532
16	1458	1251	563
17	1454	1311	504
18	1456	1372	613
19	1459	1386	509
20	1457	1425	520
21	1459	1446	515
22	1459	1395	507
23	1456	1353	438
24	1449	1327	411

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CHAPTER 4: COMPARATIVE ANALYSIS OF DIFFERENT ROUTING HEURISTICS FOR THE BATTERY MANAGEMENT OF AUTOMATED GUIDED VEHICLES

4.1 Abstract

This chapter explores how different routing techniques for the battery management of automated guided vehicles (AGVs) can affect the performance of a system. Four heuristics available in the literature were the basis of this study. Those heuristics were modified to fit the need of this study. Simulation models were developed to investigate how the routing of an AGV towards a battery station can affect the productivity of a manufacturing facility. Results show that the best productivity can be achieved when a routing heuristic tries to jointly minimize the total travel distance and waiting time at a battery station. The gain in productivity, when compared with the highest possible gain theoretically achievable, is quite substantial. It was also found that higher frequency of decision making (i.e., decisions with smaller time interval) about battery swapping helps to increase the productivity of a system.

4.2 Introduction

Automated guided vehicles (AGVs) are widely used in manufacturing systems, container terminals, warehouses, and service industries including hospitals in order to achieve flexibility and efficiency in the material handling operations (Nishi et al., 2011). Most of the AGVs have battery as their source of energy (Schulze et al., 2008). Consequently, it is important that battery management of the AGVs is addressed adequately to run an AGV system efficiently.

Battery management of AGVs deals with the issues like capacity of the battery stations (i.e., how many charging positions are available at a battery station), the location of battery stations, how long a particular AGV will operate before its battery is recharged or replaced, availability of idle time for the AGVs etc. (Le-Anh and De Koster, 2006). Literature on the battery management of AGVs is quite sparse. Particularly, there is hardly any study that explored how the routing performance of the AGVs can be affected by battery management.

Routing of an AGV deals with the selection of route the AGV should take and the sequence of jobs the AGV should perform (Le-Anh and De Koster, 2006). To improve the overall performance of an AGV system, routing problems of AGVs usually focus on the congestion in the system and the dynamically changing transportation requests (Vis, 2006). Scheduling of the AGVs is also sometimes considered simultaneously while deciding about routing (e.g., Corréa et al., 2007).

Battery management, an important aspect of an AGV system, has the potential to improve the performance of the system if it is incorporated with the routing decisions of the AGVs. One can be confident about such potential of battery management because AGV routing has a lot of similarity with traditional vehicle routing problems (more on this topic in the next section) and It is widely recognized that traditional vehicle routing problems can help a firm save a large portion of its logistics costs. In fact, real-life applications of computerized procedures for the distributions systems in North America and Europe showed that computerized procedures for the distribution process planning generally provides a savings from 5% to 20% (Toth and Vigo, 2002). So, it is important to explore if the routing for battery management of AGVs can help a firm reduce cost or increase productivity.

To fill-up the research gap on the battery management of AGVs, this study compares and contrasts different routing heuristics for the battery management of AGVs. Particularly, this study uses different heuristics to route the AGVs to battery stations at a manufacturing facility when the depleted batteries of the AGVs need to be replaced with a fully charged battery. The study then compares the effects of different routing heuristics on the productivity of the facility.

One of the few studies that addressed the routing of AGVs for battery management is Ebben (2001), from where the basic ideas of the routing heuristics used in this paper are taken. That study mentioned four heuristics for routing an AGV to a battery station at an underground transportation system. However, use of AGVs in transportation system is far less common than that in other types of systems like manufacturing, warehouse, and container terminals. Also, the layout of a transportation system is fundamentally different from that of a manufacturing facility or warehouse. This study focuses on a manufacturing facility and hence makes necessary modifications to the heuristics originally suggested by Ebben (2001).

Though Ebben (2001) mentioned four routing heuristics for the battery management of AGVs, only one heuristic was implemented and elaborately discussed in that study. This study implements all the four routing heuristics (with modifications) and explores how the choice of such a heuristic can affect the productivity of a system.

4.3 Study Scope and Related Literature

According to Egbelu and Tanchoco (1984), one can gain tremendous insight about AGV dispatching through the works done in the area of physical distribution and transportation. This means that there is a great deal of similarity between the routing of AGVs and the traditional vehicle routing problem (VRP). For example, material-handling systems with AGVs often resembles traveling salesman problem with time window (Ohlmann and Thomas, 2007).

VRP, a central phenomenon in physical distribution and logistics, refers to the problem of designing optimal routes for delivery or collection from one or several depots to a number of geographically dispersed locations, subject to side constraints (Laporte, 1992). VRP is very important because it has the potential to reduce the costs for transporting products to geographically dispersed customers (Bell and Griffis, 2010). Like VRP, routing of AGVs also often focus on developing algorithms and heuristics to reduce travel time (e.g., Sarker and Gurav, 2005) or waiting time in the system (e.g., Nishi et al., 2011). However, there are some significant differences as well between the routing of AGVs and a typical VRP.

According to Qiu et al. (2002), following are some major aspects for the routing of AGVs that differ from a traditional VRP.

- Length of the vehicle is significant for an AGV when compared with the distance it travels. So, the portion of the path occupied by an AGV cannot be ignored when deciding about the routing of AGVs.
- Collisions or congestions (particularly at the junctions or intersections of paths) are potential problems for an AGV system because of the limited path space in such a system.
- For an AGV system, shortest time path is usually not the shortest distance path.
- To improve the routing in an AGV system, layout of the path network in the system can be changed.

A wide range of methods have been proposed in the literature to address the routing of AGVs. Krishnamurthy et al. (1993) used column generation on a bidirectional AGV network to develop an implementable routing solution that takes a reasonable amount of computer time. Oboth et al. (1999) used simulation to develop a mechanism of conflict-free routings to fulfill the dynamic demand for AGVs. Soylu et al. (2000) suggested a neural network approach to find an optimum routing solution for an AGV system where a single vehicle is capable of carrying out one task at a time. To model AGV routing problem, Buyurgan et al. (2007) used an intelligent path planning model based on evolutionary algorithm with an objective to maximize the system throughput. Nishi et al. (2009) used Petri net and Lagrangian relaxation to solve the routing problems of AGVs.

Qiu et al. (2002) divided the routing algorithms for AGVs into the following three categories.

i. Static methods (the full path is considered occupied until an AGV completes its tour)
ii. Time-window based methods (a portion of the path may be used by different AGVs during different time windows)
iii. Dynamic methods (use of any path is dynamically determined during routing rather than before the routing starts)

Though there have been many scholarly studies on the routing of AGVs, battery management is usually ignored in such studies. There are two common reasons for which battery management is usually ignored in research related to AGV systems. These are:

i. The studies are considered for a limited time period like an 8-hour shift during which an AGV often does not require to recharge or replace its battery (e.g., Egbelu, 1987).
ii. For systems with enough idle time, battery management can be done during the idle time not affecting the performance of the system (McHaney, 1995).

However, there are many systems that operate 24 hours a day (or long enough) so that AGVs must get their batteries replaced or recharged during that time period. Such systems also may not have enough idle time to use for battery management without affecting the system performance (particularly during the peak season). Also, routing to a battery station for replacing the depleted battery with a fully charged battery is different from typical tasks of pick-up or drop-off because there is a potential of congestion at the battery station if many AGVs go there at the same time. Such congestion does not occur at a pick-up or drop-off point since multiple AGVs are not scheduled to pick/drop from/to a point at the same time. Thus, finding an efficient way of routing an AGV to a battery station may help a firm to improve its productivity.

In the literature, only one study could be found where the routing of AGVs for battery management was discussed in detail. That study was Ebben (2001), where the nearest battery station was selected to route an AGV for battery management. However, Ebben (2001) mentioned, but did not implement, three other heuristic principles that can be used to route an AGV towards battery station. All these four heuristics are mentioned below.

(i) Selecting the nearest battery station.

(ii) Selecting a battery station that will cause minimum delay considering both travel time and waiting time in a queue.

(iii) Selecting the first battery station on the current route.

(iv) Selecting the farthest reachable battery station on the current route

The heuristics suggested by Ebben (2001) will make-up the basic framework of this study. These heuristics were suggested on the basis of an underground transportation system. But this study is based on a manufacturing facility. Consequently, necessary modifications will be made on these heuristics to make them distinct and applicable for a manufacturing facility (detail on the modified heuristics are given in the next section).

4.4 Routing Heuristics for the Battery Management of AGVs

As mentioned before, Ebben (2001) studied an underground transportation system, where all the four heuristics mentioned earlier can be used in distinctive ways. However, the same cannot be said for a manufacturing system because the layout of a typical manufacturing system is fundamentally different from that of an underground transportation system. To distinctively use the last two heuristics mentioned earlier (i.e., selecting the first battery station and the farthest reachable battery station on the current route), an AGV needs to have at least two battery stations on its current route - one being the first battery station and the other being the farthest reachable battery station. But an AGV operating at a manufacturing facility is very unlikely to have two or more battery stations along its current route. Often, there may be no battery station at all on the current route while an AGV serves a manufacturing facility. Consequently, the terms ‘first battery station’ and ‘farthest battery station’ need to be modified to apply the heuristics distinctively at a manufacturing facility.

A complete route for an AGV operating at a manufacturing facility consists of three points (i.e., three nodes of a network): initial point, pick-up point, and drop-off point. Initial point refers to the place where a free and empty AGV is located when it is asked to pick-up a load from one point (pick-up point) and carry it to another point (drop-off point). For the first leg of the journey, the AGV travels from initial point to pick-up point. And for the second leg of the journey, the AGV travels from pick-up point to drop-off point.

For a manufacturing facility, the nearest battery station from the initial point of an AGV may be synonymous to the first battery station on its current route. Also, the nearest battery station to the drop-off point may be synonymous to the farthest battery station on the current route. With these modifications to the terms ‘first battery station’ and ‘farthest battery station’, the modified heuristics can be applied distinctively at a manufacturing facility. All the four heuristics (including the modified ones) that have been used in this study are briefly described below.

(i) *Selecting the nearest battery station (NBS):* This is the same heuristic as applied by Ebben (2001). According to this heuristic, an AGV first checks its available charge after receiving a new job (when it is located at the initial point). The AGV moves from the initial point to the pick-up point (without going to a battery station) if the available charge is sufficient to go to the pick-up point and from there to the nearest battery station. Otherwise, the AGV moves to the nearest battery station from the initial point. The same process is repeated when the AGV arrives at the pick-up point. So, the decision of going (or not going) to a battery station is taken twice during the complete route of an AGV (i.e., first when the AGV is at the initial point, and second when it is at the pick-up point).

(ii) *Selecting minimum delay battery station (MDBS)*: Like NBS, this heuristic also makes the AGV check its available charge twice. The decision making process is also similar to that of NBS. That is, the AGV goes to a battery station from its current location (i.e. initial point or pick-up point) if the available charge is not sufficient to go to the destination (i.e. pick-up point or drop-off point) and from there to the nearest battery station. However, this heuristic differs from NBS in selecting the battery station. MDBS selects the battery station that will minimize total time for traveling and waiting at the battery station.

(iii) *Selecting the nearest battery station from initial point (NBSIP)*: This heuristic is based on the heuristic of selecting the first battery station on the current route suggested by Ebben (2001). However, it has been modified to make it applicable to a manufacturing facility and to make it different from other heuristics. This heuristic differs from NBS and MDBS in two ways. First: for a complete route of moving from initial point to pick-up point and from pick-up point to drop-off point, the decision to go to a battery station is taken only once – when the battery is at the initial point (NBS and MDBS take decision twice – at initial point and at pick-up point). Second: the decision to go to a battery station is not dependent on how much charge is required to go to the destination and from there to the nearest battery station. Rather, a concept of trigger level charge is introduced to decide about going to a battery station. That is, if the available charge is less than or equal to a pre-specified trigger level charge (e.g., 28% charge), the AGV moves from initial point to the nearest battery station. Otherwise, the AGV completes the route. Using a trigger level charge makes the decision making process simpler.

(iv) *Selecting the nearest battery station to drop-off point (NBSDP)*: This heuristic is based on the heuristic of selecting the farthest reachable battery station on the current route suggested by Ebben (2001). It has been also modified to make it applicable to a manufacturing facility and to make it different from other heuristics. Like NBSIP, this heuristic decides to go to a battery station only once during the complete route – when the AGV is at the initial point. Also, like NBSIP, this heuristic uses a pre-specified trigger level charge to decide whether to go to a battery station. However, it differs from NBSIP in the case of selecting a battery station. If an AGV finds its available charge to be less than or equal to the trigger level charge (e.g., 33% charge), the AGV first moves from the initial point to the pick-up point. After picking up the load, the low charge AGV moves to the battery station from where the drop-off point is nearest.

A common criterion for all the heuristics as used in this study is that the depleted battery of an AGV needs to be replaced (i.e., swapped) with a fully charged battery before the residual capacity of the depleted battery goes below 20%. Residual capacity of a battery refers to the amount of charge available in a battery after discharge (Technical Marketing Staff of Gates Energy Products, 1992). If the charge level of a battery goes below 20%, the battery is said to have deep discharge. According to C&D Technologies (2012), deep discharge of a valve regulated lead acid (VRLA) battery can cause corrosion of the grids onto which the active materials (i.e., lead and lead dioxide) of the battery are pasted. This study will consider VRLA batteries, the most widely used battery type for the AGVs. Hence, it is important that the depleted batteries are replaced before they have deep discharge. So, threshold level charge for this study is 20%. In other words, the heuristics were applied (and adjusted) in this study so that the residual charge of a depleted battery is always above the threshold level of 20%.

For NBSIP and NBSDP, trigger level needs to be adjusted so that the batteries are not deeply discharged by the time an AGV reaches a battery station. It was found by trial and error that with trigger levels of 28% and 33% for NBSIP and NBSDP respectively, no instance of deep discharge occurs for this study. Also, while calculating charge required for NBS and MDBS, an estimate needs to be made for charge loss by the AGVs due to unpredictable blockage on the way. For this study, these estimates are 1% and 2% of the battery capacity for NBS and MDBS respectively.

Flowchart diagrams for all the four heuristics (NBS, MDBS, NBSIP, and NBSDP) are given below.

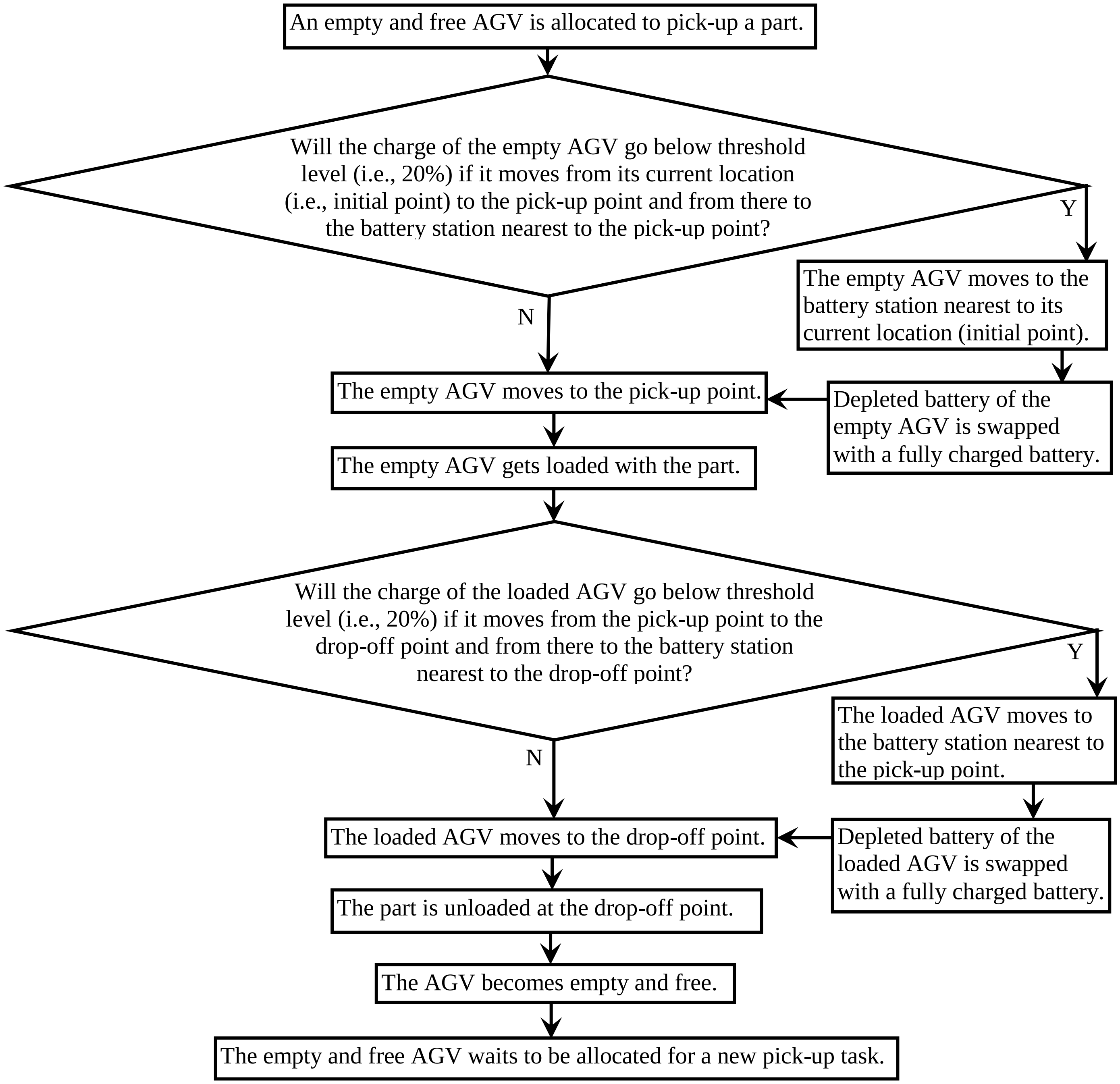


Figure 4.1: Flowchart for the heuristic of NBS (nearest battery station)

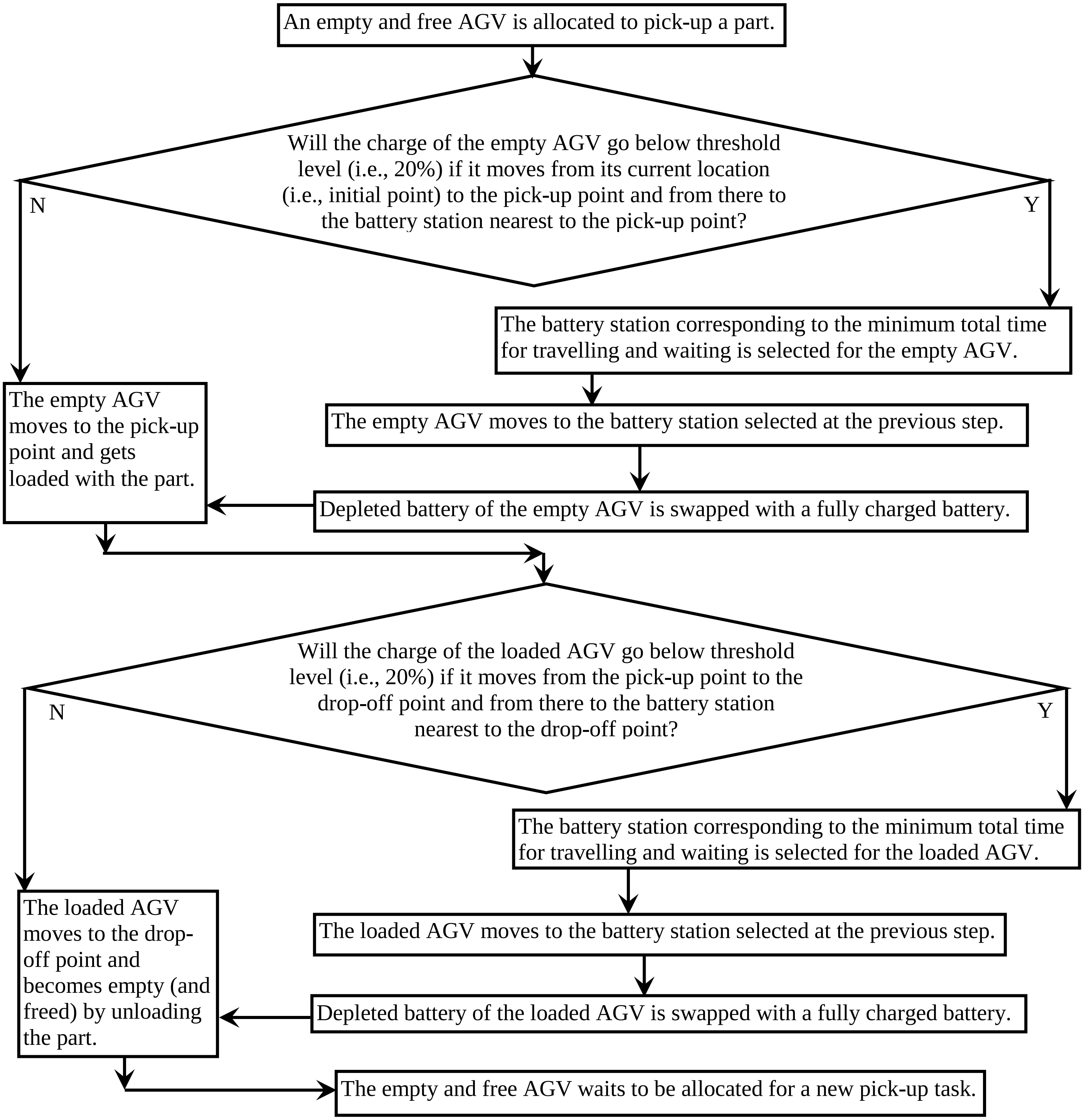


Figure 4.2: Flowchart for the heuristic of MDBS (minimum delay battery station)

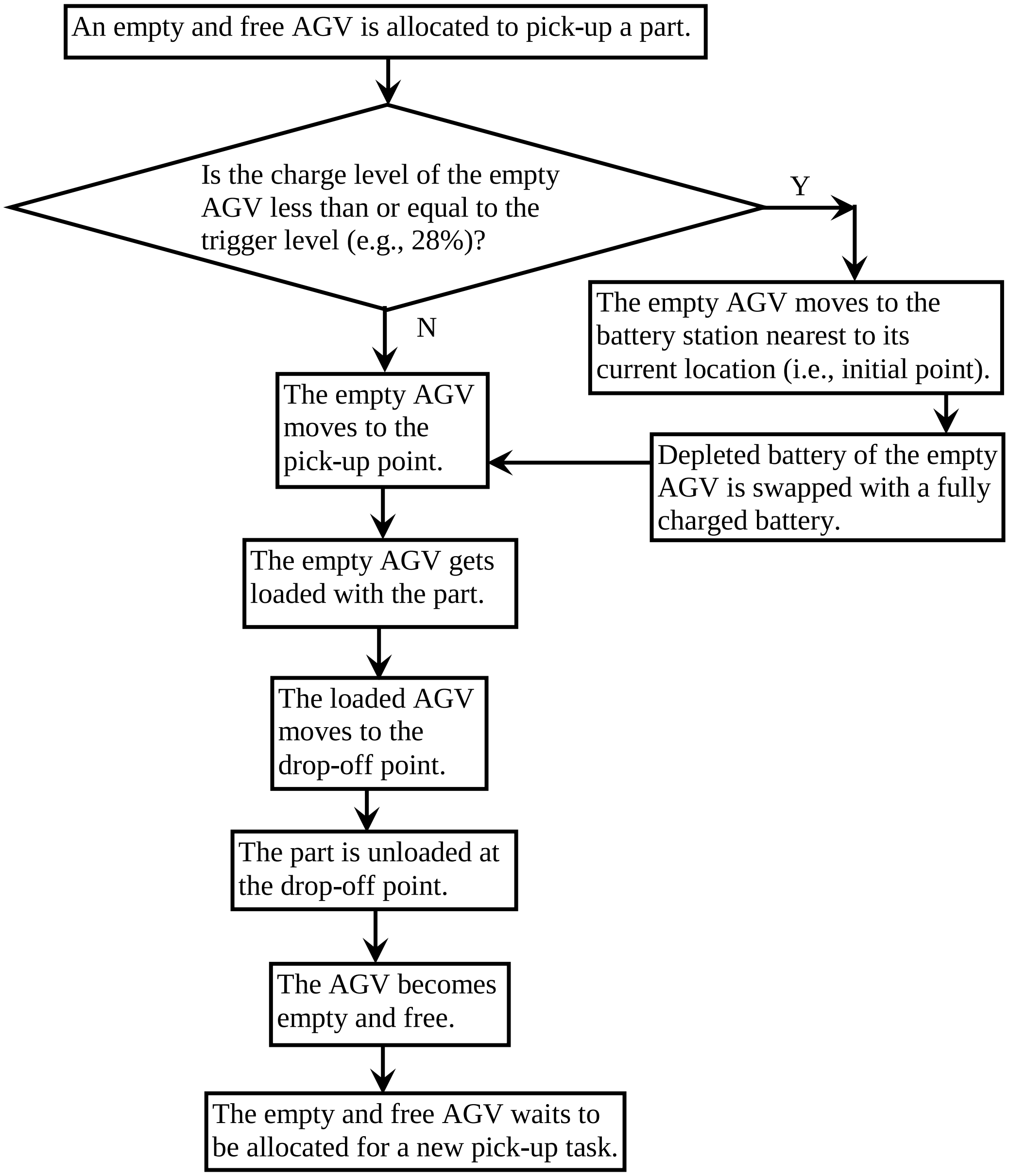


Figure 4.3: Flowchart for the heuristic of NBSIP (nearest battery station from initial point)

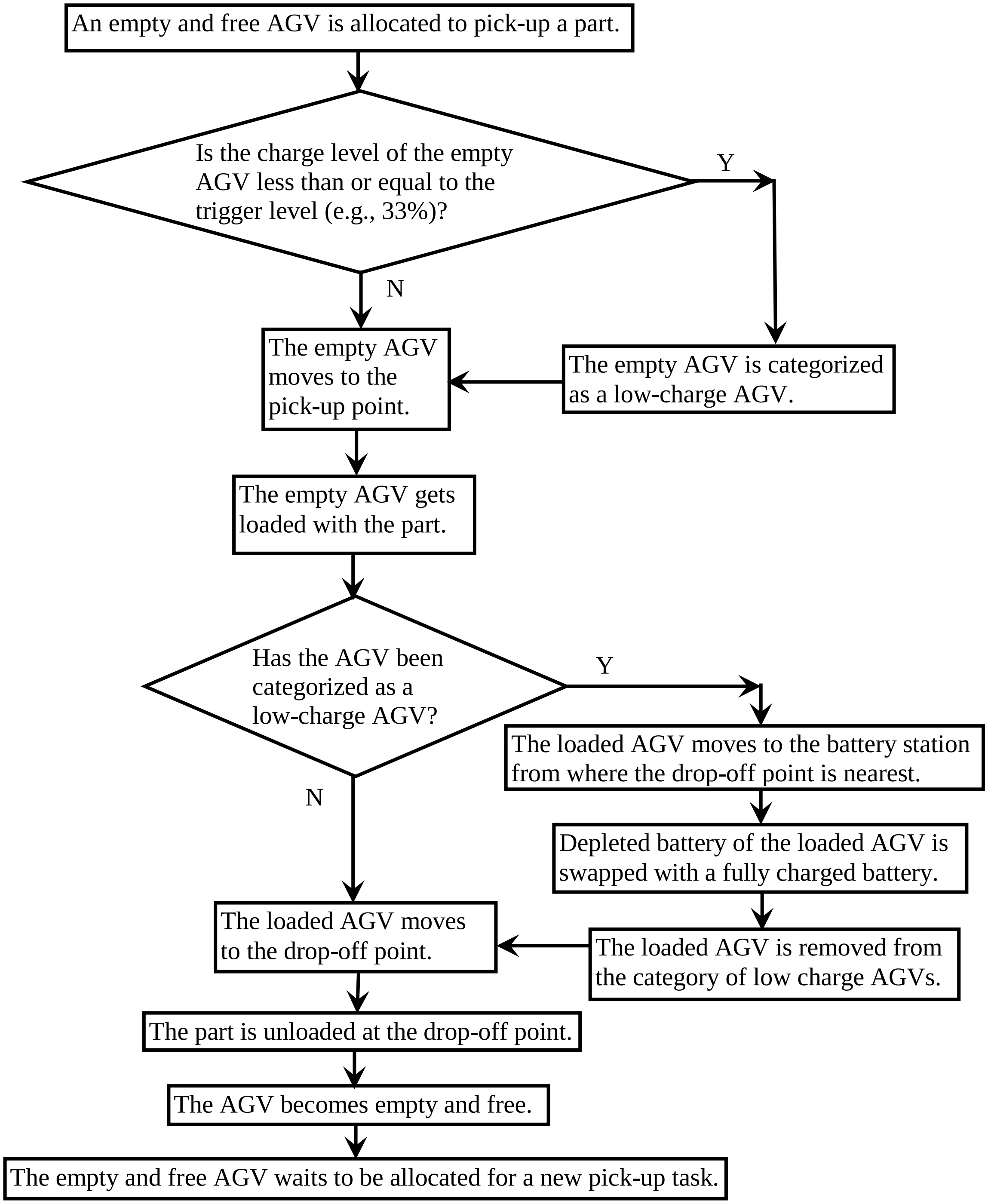


Figure 4.4: Flowchart for the heuristic of NBSDP (nearest battery station to drop-off point)

4.5 Experimental Design

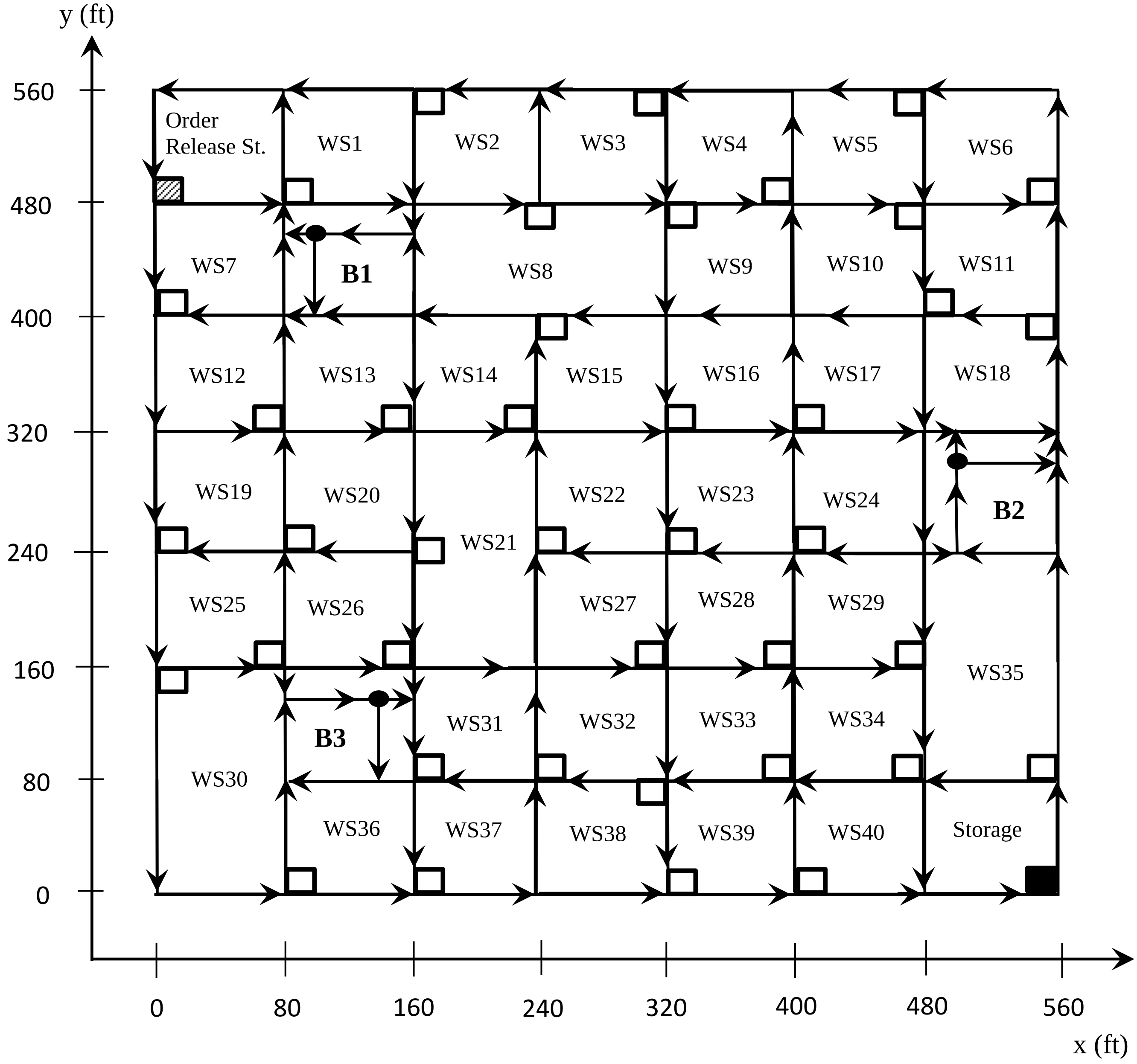
This research was conducted through discrete event simulation. Separate simulation models were developed for each of the four heuristics. It may be mentioned that using simulation as the methodology for conducting research on AGV systems is quite common. Examples of such research works include McHaney (1995), Ebben (2001), Mahadevan and Narendran (1994), Rajotia et al. (1998), Ji and Xia (2010), and Kawakami and Takata (2011).

Simulation software of Arena (version 14.7) was used to develop the simulation models of this study. The models were run in a notebook computer with 3.00 GHz Intel Core i7 processor and 8 GB of RAM. Most of the data to conduct this study were obtained from secondary sources. However, some of the data were obtained through interviewing selected vendors of battery and AGV systems.

4.6 Experimental Setting

4.6.1 Facility layout

A hypothetical manufacturing facility is considered for this study. Using hypothetical AGV system is quite common in the literature (see for example, Taghaboni-Dutta and Tanchoco, 1995; Hwang and Kim, 1998). The facility considered in this study is large in size with many nodes and edges as shown in figure 4.5. Using such a large layout is not unusual for the study of AGV routing (see for example: Nishi et al., 2009; and Oboth et al., 1999). Guide-path of the facility is unidirectional and there are three battery stations at the facility. The facility has 45 stations consisting of 40 workstations, 3 battery stations, 1 order release station, and 1 storage station.



WS = Workstation, B = Battery station

☐ Point where both pick-up and drop-off take place

▨ Point where only pick-up takes place

■ Point where only drop-off takes place

● Dock at the battery station (point of battery swapping)

Figure 4.5: Layout of the facility

Order release station is the place where the parts first arrive and then get released to different workstations; the workstations are the places where the parts get processed; battery stations are the places where an AGV goes for swapping its depleted battery with a fully charged battery; and storage station is the place where finished parts are stored after being processed. The AGVs arrive at the order release station only to pick-up the parts (but no drop-off) and go to the storage station only to drop-off the parts (but no pick-up). Both pick-up and drop-off take place at all the workstations.

Replacing the depleted battery of an AGV with a fully charged battery is known as battery swapping and recharging the battery while it is still inside the AGV is known as automatic charging. These two are the common forms of battery charging (for further discussion on different types of battery charging schemes, please see McHaney, 1995; Ebben, 2001; and Savant Automation, 2015). This study will consider battery swapping while exploring how the routing decision for battery swapping affect the performance of a manufacturing system. Battery swapping is preferred in a facility where there is not enough idle time to let the AGVs remain inactive while their batteries get charged (for automatic charging, an AGV remains inactive while its battery gets recharged).

After dropping-off a load, an AGV waits at the drop-off point for its next pick-up request. Since it is a busy facility with continuous production, the AGVs are in high demand. Hence, it is reasonable to keep an empty and free AGV at the drop-off point (after the AGV unloads at that point) as opposed to sending the AGV to a parking area.

Number of battery stations considered in this study is three. Each battery station can replace the battery of only one AGV at any point in time (i.e., each battery station has one dock).

If more than one AGV comes at the same time to get their battery swapped, the AGV(s) coming later will wait in queue until the AGV(s) coming earlier gets its battery swapped. In line with Ebben (2001), it is assumed that battery can be swapped for both an empty AGV and a loaded AGV.

As shown in figure 4.5, each workstation has its pick-up point and drop-off point located at the same place. In other words, each workstation has a single point from where both pick-up and drop-off take place. Keeping the location of pick-up point and drop-off point at the same place is in line with the examples of Kelton et al. (2015) and Gaskins and Tanchoco (1987).

4.6.2 Part routing and processing time

The manufacturing facility used in this study produces ten different part types: part 1, part 2,..… up-to part 10. Each part type has a ratio of 0.1 (i.e., probability that the next arrival is a given part is 0.1). The inter-arrival times between successive part arrivals, considering all part types together, are exponentially distributed with a mean of 3 minutes. The first part arrives at time zero.

Table 4.1 shows the routing of the parts in the facility (order release station and storage station are not shown in table 4.1 because they are always the first station and last station respectively). Part 1 is first routed from order release station to WS1 (workstation 1). After getting processed at WS1, part 1 is routed from WS1 to WS3 (as shown in table 4.1). Similar routing process continues for part 1 until it is processed at WS2 and routed from there to the storage station (WS2 is the last workstation for part 1 to get processed). Other parts also follow their respective routing sequence as given in table 4.1. All process times are in minutes and they have triangular distributions as shown in table 4.1. For example: at WS1, part 1 has a process time distribution of 10 minutes (minimum), 11 minutes (mode), and 12 minutes (maximum). Each workstation has one machine to process the parts.

Table 4.1: Part routing and processing time distributions in minutes

Part	**Ratio**	**WS* (PTD**)**	**WS (PTD)**	**WS (PTD)**	**WS (PTD)**	**WS (PTD)**	**WS (PTD)**	**WS (PTD)**
1	0.1	WS1 (10, 11, 12)	WS3 (6, 8, 9)	WS5 (6, 7, 9)	WS4 (3, 5, 6)	WS7 (10, 12, 13)	WS6 (12, 14, 17)	WS2 (10, 14, 16)
2	0.1	WS1 (15, 16, 18)	WS2 (8, 9, 11)	WS4 (21, 22, 23)	WS3 (25, 26, 28)	WS5 (11, 13, 14)	WS8 (11, 14, 16)	WS7 (10, 13, 14)
3	0.1	WS6 (11, 15, 18)	WS12 (13, 15, 16)	WS10 (20, 23, 24)	WS8 (10, 12, 14)	WS14 (13, 16, 18)	WS11 (10, 13, 15)	WS9 (11, 12, 14)
4	0.1	WS10 (10, 12, 13)	WS12 (15, 16, 18)	WS11 (11, 12, 14)	WS9 (20, 21, 22)	WS14 (17, 19, 21)	WS13 (5, 6, 8)	WS15 (9, 11, 12)
5	0.1	WS18 (7, 8, 10)	WS20 (9, 11, 12)	WS15 (20, 21, 23)	WS16 (8, 11, 12)	WS19 (10, 14, 17)	WS13 (10, 11, 13)	WS17 (9, 11, 12)
6	0.1	WS20 (7, 10, 13)	WS22 (9, 11, 12)	WS23 (14, 16, 17)	WS24 (18, 21, 23)	WS19 (10, 13, 15)	WS18 (9, 11, 12)	WS25 (8, 12, 15)
7	0.1	WS21 (8, 12, 14)	WS23 (10, 12, 13)	WS26 (15, 19, 21)	WS27 (11, 14, 16)	WS29 (6, 8, 9)	WS28 (11, 14, 15)	WS30 (8, 10, 12)
8	0.1	WS31 (12, 15, 17)	WS29 (10, 12, 14)	WS34 (11, 13, 15)	WS35 (16, 17, 19)	WS39 (10, 12, 13)	WS38 (10, 11, 14)	WS37 (8, 12, 15)
9	0.1	WS30 (9, 12, 15)	WS32 (10, 11, 12)	WS33 (15, 17, 20)	WS35 (11, 13, 16)	WS34 (7, 8, 9)	WS31 (12, 14, 17)	WS36 (9, 10, 12)
10	0.1	WS38 (15, 16, 18)	WS39 (10, 14, 17)	WS37 (20, 22, 25)	WS32 (8, 11, 13)	WS36 (5, 8, 12)	WS33 (10, 13, 15)	WS40 (10, 12, 15)

*WS : Workstation
**PTD : Processing Time Distribution (minutes)

4.6.3 Assumptions

The following assumptions are made for the simulation model. These assumptions are in line with Egbelu (1987).

- All AGVs are identical.
- All AGVs travel at a uniform speed of 150 feet per minute.
- An AGV spends 15 seconds every time it picks or drops a load
- There is no time loss due to breakdown or failure of an AGV.

- All the AGVs are unit-load AGVs. That is, the loads are carried from the pick-up point to the drop-off point without any stop in between (except stopping for battery swapping, if needed).

Also, the facility operates 24 hours a day (i.e., continuous operations). Consequently, any time spent by an AGV for battery swapping is likely to reduce the productive hours available from that AGV, which, in turn, will adversely affect the production volume of the system. After an AGV reaches a battery station, it takes 5 minutes to swap the depleted battery at the battery station.

4.6.4 Battery capacity and ampere draws for different activities

Battery capacity for the AGV considered in this study is 200 ampere-hours like that of model DC-60 of Savant Automation (Savant Automation, 2007). Table 4.2 shows the ampere draws for different activities by an AGV. With the exception of the ampere draw data for picking and dropping, all data of table 4.2 are obtained from table 3 of McHaney (1995). Ampere draw data for picking and dropping as shown in table 4.2 are obtained from table 14 of the same paper.

Every time an AGV does a job, the corresponding ampere draw (charge loss) is calculated. The ampere-hours lost by the battery is calculated by multiplying the ampere draws for that job by the number of hours the AGV does that job. For example: if an AGV gets blocked for 0.4 hours, 2 ampere-hours (5 amperes × 0.4 hour) is lost due to that blockage.

It may be noted that charge losses due to acceleration and deceleration are ignored in this study. This is because charge loss due to acceleration and deceleration are likely to impact the performance of all the heuristics in a similar way and the objective of this study is to make a comparative analysis of the heuristics - not to find any absolute value. Besides, considering the charge loss for acceleration and deceleration will make the simulation model unnecessarily complicated. It may be mentioned that many other studies on AGV systems also ignored acceleration and deceleration (e.g., Hwang and Kim, 1998).

Table 4.2: Ampere draws for different activities of an AGV (Source: McHaney, 1995)

Part	**Ratio**
Blocking	5 amperes
Traveling Empty	40 amperes
Traveling Loaded	60 amperes
Picking	60 amperes
Dropping	40 amperes

4.6.5 Number of AGVs

Using all the four heuristics, change in total output of the system was observed as number of AGVs was gradually increased. Here, total output refers to the total number of all the parts produced in the system (i.e., total output = number of part 1 produced + number of part 2 produced + ……+ number of part 10 produced).

It was found that irrespective of the type of heuristic used, total output continuously increases with the addition of AGVs up-to a certain point. After that point, total output comes to a steady state when there is hardly any increase in total output if more AGVs are added. This phenomenon, as shown in figure 4.6 below, occurs because of the increased congestion created by additional AGVs. It may be noted that figure 4.6 represents the heuristic of MDBS (minimum delay battery station); but total outputs using other heuristics also show a similar pattern.

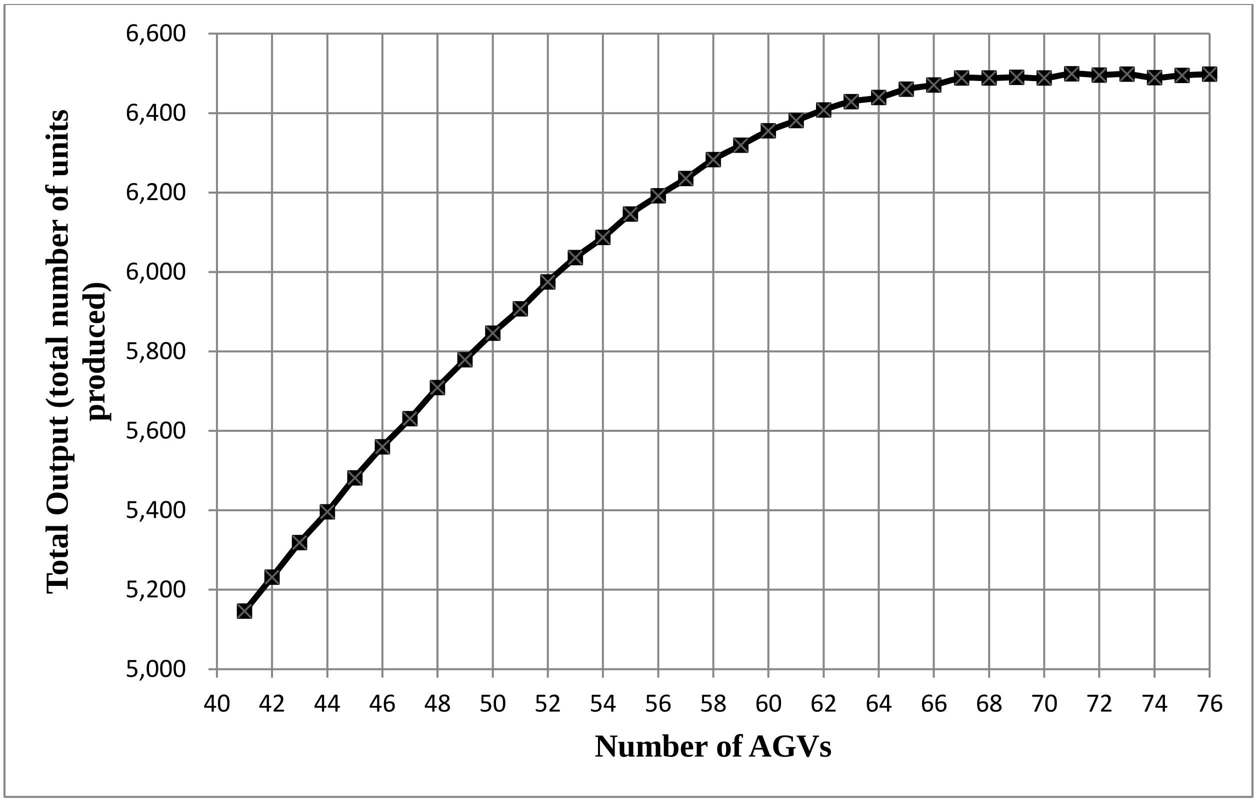


Figure 4.6: Change in total output as number of AGVs increases (using MDBS heuristic)

It is clear from figure 4.6, that the marginal benefit of adding an AGV when the system already has 62 AGVS is minimal. There is hardly any practical reason to deploy more than 62 AGVs at this manufacturing facility. Hence, the analysis for this study has been made with a range between 41 and 62 AGVs in the system.

4.6.6 Experimental parameters

Using all the four heuristics, multiple simulation experiments were conducted with different number of AGVs in the system (ranging from 41 AGVs to 62 AGVs). With each number of AGVs, the performance of the system in terms of total output was determined for each of the heuristics. In accordance with Rossetti (2010), the warm-up period for each simulation experiment was determined to be 40 hours and the number of replications for each simulation experiment was determined to be 40. Following Banks et al. (2005), length of each replication was fixed as 400 hours.

4.7 Result and Analysis

4.7.1 Change in total output

Table 4.3 shows total outputs produced by the facility with different number of AGVs using all the four routing heuristics. Also, the table shows the largest and second largest total outputs for each number of AGVs in regular bold font and italic bold font respectively.

According to the total output values of table 4.3, MDBS (minimum delay battery station) achieves the largest total output in 20 out of 22 instances. In two instances (with 50 AGVs, and 57 AGVs), MDBS is outperformed by NBSDP (nearest battery station to drop-off point). Overall, NBSDP performs second best in terms of total output. The table also shows that NBSIP (nearest battery station from initial point) always results in the smallest total output.

Between NBS (nearest battery station) and NBSDP, NBSDP usually performs better than NBS at the initial stage when congestion is less because of lower number of AGVs in the system. But as congestion in the system increases with higher number of AGVs, there is hardly any distinction between NBS and NBSDP in terms of productivity (i.e., total output). This happens because in comparison to NBS, NBSDP needs longer and more frequent travel to battery stations (consequently, more congestion is faced by an AGV that follows NBSDP).

Table 4.3: Total output for the four heuristics with different number of AGVs

No. of AGVs	**Total output (no. of part 1 produced + no. of part 2 produced +……… + no. of part 10 produced)**			
	NBS	**MDBS**	**NBSIP**	**NBSDP**
41	5,134	**5,146***	5096	***5,138*****
42	***5,228***	**5,232**	5175	5,226
43	5,309	**5,319**	5259	***5,314***
44	5,389	**5,396**	5346	***5,392***
45	***5,474***	**5,482**	5422	5,471
46	5,546	**5,560**	5495	***5,552***
47	5,622	**5,631**	5575	***5,623***
48	***5,699***	**5,709**	5639	5,698
49	***5,771***	**5,779**	5713	***5,771***
50	5,831	***5,846***	5778	**5,847**
51	5,901	**5,907**	5842	***5,902***
52	5,965	**5,975**	5906	***5,972***
53	6,024	**6,036**	5966	***6,027***
54	6,078	**6,087**	6018	***6,082***
55	6,139	**6,146**	6077	***6,140***
56	6,179	**6,192**	6120	***6,190***
57	6,232	***6,235***	6167	**6,239**
58	6,273	**6,283**	6209	***6,280***
59	6,309	**6,319**	6245	***6,316***
60	***6,344***	**6,355**	6287	6,343
61	***6,373***	**6,381**	6308	***6,373***
62	***6,405***	**6,408**	6343	***6,405***

***** Largest among all the total outputs found from four heuristics (i.e., in **bold font**)

****** Second largest among all the total outputs found from four heuristics (i.e., in ***bold italic font***)

4.7.2 Relative importance of the gain achieved through MDBS

Based on the results of table 4.3, it is quite clear that MDBS would be the best option among these four routing heuristics for battery management. However, one may argue that the difference in productivity gain by choosing MDBS is not large enough to make an impact on the overall performance of a firm. But it is to be noted that there is hardly any additional resource needed for the potential gain achievable through MDBS. Also, there are situations (e.g., peak season) when a firm makes every effort to increase its productivity as much as possible. In such circumstances, even a small increase in productivity can help a firm to maintain or grow its market share. Most importantly, as explained below, the increase in productivity gained through MDBS is not a small one if the maximum potential gain is considered.

Table 4.4 shows the total output for three scenarios: using NBSIP, using MDBS, and using “no-charging-scenario” where batteries do not need to be replaced or recharged ever (so, no time is lost for battery management in case of no-charging-scenario). The no-charging-scenario represents the upper limit for the total output of the facility. That is, the values for no-charging-scenario show the maximum productivity that the facility can theoretically achieve by simply changing its routing technique for the battery management of AGVs.

As shown in the last row of table 4.4, average increase in total output is 2.6% when a (hypothetical) switch is made from NBSIP to the no-charging-scenario. In other words, the facility can expect to increase its productivity by 2.6% if it moves from NBSIP to no-charging-scenario. However, switching from NBSIP to no-charging-scenario is unrealistic, but switching to MDBS is quite realistic and by doing so the facility can capture a big portion of the upper limit as shown in the last column of the table. By switching from NBSIP to MDBS, the facility can expect to capture on average 44.58% of the upper limit (with a minimum capture of 32.26%).

Table 4.4: Relative importance of the gain achieved through MDBS

No. of AGVs	Total output (no. of part 1 produced + no. of part 2 produced +……… + no. of part 10 produced)			% Increase in total output if switched from NBSIP		% of upper limit captured by switching to MDBS
	NBSIP	**MDBS**	**No-charging-scenario (no time spent for battery swapping)**	**to MDBS**	**to No-charging-scenario (Upper limit for the increase in total output)**	
41	5096	5,146	5247	0.98	2.96	33.11
42	5175	5,232	5336	1.10	3.11	35.40
43	5259	5,319	5418	1.14	3.02	37.74
44	5346	5,396	5501	0.94	2.90	32.26
45	5422	5,482	5578	1.11	2.88	38.46
46	5495	5,560	5656	1.18	2.93	40.37
47	5575	5,631	5730	1.00	2.78	36.13
48	5639	5,709	5808	1.24	3.00	41.42
49	5713	5,779	5872	1.16	2.78	41.51
50	5778	5,846	5944	1.18	2.87	40.96
51	5842	5,907	6010	1.11	2.88	38.69
52	5906	5,975	6066	1.17	2.71	43.13
53	5966	6,036	6125	1.17	2.67	44.03
54	6018	6,087	6182	1.15	2.73	42.07
55	6077	6,146	6225	1.14	2.44	46.62
56	6120	6,192	6267	1.18	2.40	48.98
57	6167	6,235	6309	1.10	2.30	47.89
58	6209	6,283	6349	1.19	2.25	52.86
59	6245	6,319	6380	1.18	2.16	54.81
60	6287	6,355	6399	1.08	1.78	60.71
61	6308	6,381	6430	1.16	1.93	59.84
62	6343	6,408	6445	1.02	1.61	63.73
			Average =>	**1.12**	**2.60**	**44.58**

4.7.3 Benefit of more frequent decision making

NBS performs better than NBSIP because the decision of battery swapping (or not swapping) is taken more frequently for NBS than that for NBSIP. As explained in section 4.4, for a complete route of NBS, decision of battery swapping (or not swapping) is considered twice: first, when the empty AGV is asked to pick-up a part (the empty AGV can then move to the battery station nearest from the initial point before coming to the pick-up point); and second, after the AGV is loaded with the part at the pick-up point (the loaded AGV can then move to the battery station from the pick-up point before coming to the drop-off point). On the contrary, for a complete route of NBSIP, decision of battery swapping (or not swapping) is considered only once: when the empty AGV is asked to pick-up a part (the empty AGV can then move to the battery station nearest from the initial point before coming to the pick-up point).

Because of less frequent opportunity to decide about swapping (or not swapping), the trigger level charge for NBSIP has to be kept quite high (28%) so that a battery does not face deep discharge. The values for minimum residual battery capacity, as shown in table 4.5, indicate that if trigger level is lowered for NBSIP, there would be instances when the battery will face deep discharge (i.e., the charge level will go below 20%). With a high trigger level for NBSIP, minimum residual battery capacity for both NBS and NBSIP are quite close (always remaining little over 20%). On the contrary, maximum and average residual battery capacities are always higher for NBSIP in comparison to those for NBS (the highest average residual battery capacity for NBS is 23.07%, whereas the lowest average residual battery capacity for NBSIP is 25.69%).

The high trigger level for NBSIP is reached more quickly than a similar situation arises for NBS. As a result, the number of battery swaps for NBSIP is always higher than that for NBS as shown in the last two columns of table 4.5. In fact, average number of battery swaps across different number of AGVs for NBSIP is nearly 3% higher than that for NBS. Because of spending more time for battery swapping, NBSIP could never outperform NBS in terms of total output (as shown in table 4.3). Like NBS, MDBS also has the advantage of more frequent decision making (NBSIP and NBSDP make less frequent decisions).

Table 4.5: Effect of more frequent decision making

No. of AGVs	**Minimum residual battery capacity (%)**		**Average residual battery capacity (%)**		**Maximum residual battery capacity (%)**		**Total number of battery swaps**	
	NBS	**NBSIP**	**NBS**	**NBSIP**	**NBS**	**NBSIP**	**NBS**	**NBSIP**
41	20.94	21.25	23.06	25.72	26.35	27.82	1400	1450
42	21.03	21.36	23.06	25.72	26.35	27.82	1426	1473
43	21.35	21.49	23.07	25.73	26.35	27.82	1450	1500
44	21.35	21.03	23.06	25.71	26.35	27.82	1468	1520
45	21.36	21.37	23.06	25.72	26.35	27.82	1488	1538
46	21.39	21.27	23.05	25.72	26.35	27.82	1513	1563
47	21.24	21.29	23.06	25.71	26.35	27.82	1532	1583
48	21.28	21.55	23.06	25.71	26.35	27.82	1546	1598
49	21.25	21.03	23.06	25.72	26.35	27.82	1567	1620
50	21.29	21.38	23.05	25.71	26.35	27.82	1586	1641
51	21.37	21.37	23.05	25.71	26.35	27.82	1601	1654
52	21.22	21.18	23.05	25.71	26.33	27.82	1618	1671
53	21.30	21.21	23.06	25.71	26.35	27.82	1639	1693
54	21.34	21.09	23.06	25.71	26.35	27.81	1655	1707
55	21.08	21.35	23.06	25.70	26.35	27.82	1668	1718
56	21.36	21.16	23.06	25.70	26.35	27.82	1686	1736
57	21.11	21.19	23.04	25.70	26.35	27.82	1708	1753
58	21.16	21.05	23.06	25.70	26.34	27.82	1718	1765
59	20.99	21.15	23.05	25.70	26.35	27.82	1734	1782
60	21.20	21.29	23.05	25.70	26.35	27.82	1759	1802
61	21.26	21.04	23.05	25.69	26.35	27.82	1773	1813
62	21.21	21.00	23.04	25.69	26.35	27.81	1781	1826

4.7.4 NBSIP vs. NBSDP

As explained earlier, both NBSIP and NBSDP decide about swapping the battery once during the complete route. Also, they both use trigger level charge to decide whether to go for battery swapping. Yet, NBSDP consistently outperforms NBSIP in terms of productivity (i.e., total output). So, it is worth exploring the reason(s) behind such difference in productivity to get an insight about the dynamics of AGV movement.

The difference in productivity between NBSIP and NBSDP may be caused by two factors: (i) selection rule to allocate an AGV, and (ii) overlapping of initial point and pick-up point. Effects of these factors are discussed below.

(i) *Effect of the selection rule to allocate an AGV:* When a part is ready to be picked up at a station, an empty and free AGV is selected to pick-up that part. If multiple AGVs are empty and free at that time, a selection rule needs to be used to allocate an AGV for that pick-up task. There are different selection rules available (e.g., smallest distance, largest distance, cyclical, random etc.).

In this study, the selection rule of smallest distance is used. That is, the empty and free AGV that needs to travel the smallest distance to go from initial point to pick-up point is selected for the pick-up task. Thus, it is ensured that the best possible option (in terms of travel distance) is adopted when an AGV goes directly from initial point to pick-up point. This advantage of guaranteed smallest distance is always taken by NBSDP since NBSDP directs the allocated AGV to go directly from initial point to pick-up point irrespective of the amount of available charge of that AGV. On the contrary, NBSIP never takes this advantage of guaranteed smallest distance for a low-charge AGV. In that case (i.e., for NBSIP), the low-charge AGV goes to the battery station nearest from initial point (instead of going directly from initial point to pick-up point). To get a clearer picture, let us compare the travel segments of both the heuristics for a low-charge AGV.

During a complete journey of a low-charge AGV following NBSIP, the AGV gets three travel segments: (i) from initial point to the nearest battery station, (ii) from the battery station to pick-up point, and (iii) from pick-up point to drop-off point. Among these three travel segments, the first one ensures that the smallest distance is selected out of multiple options. For the second segment, there is no guarantee that the distance between the battery station and pick-up point will be a small one (it may be noted that because of unidirectional guide-path of this facility, an AGV cannot use the same path in reverse direction). For the third segment, the selection of pick-up points and drop-off points are not determined by NBSIP or the selection rule of allocating AGVs. Rather, pick-up points and drop-off points are determined by sequence of processing the parts at different workstations. Section 4.6.2 (part routing and processing time) of this dissertation discusses about the sequence of processing, but that section does not say that the distance between pick-up point and drop-off point for a part would be small. That is, there is no guarantee that the third segment for a low-charge AGV following NBSIP will have a small distance.

Like that for NBSIP, a low-charge AGV following NBSDP also has three travel segments for the complete journey: (i) from initial point to pick-up point, (ii) from pick-up point to the battery station from where drop-off point is the nearest, and (iii) from the battery station to drop-off point. Among these three segments, NBSDP gets advantage of the smallest distance for two travel segments (i.e., the first and the third segments). The smallest distance for the third segment of NBSDP is part of its logic. It may be noted that NBSIP also has a smallest distance travel segment as part of its logic (i.e., the segment from initial point to the nearest battery station). But NBSDP gets advantage of the smallest travel distance for the first segment (i.e., initial point to pick-up point) because of the selection rule for allocating an AGV. So, in comparison to NBSIP, NBSDP is likely to have more travel segments where the smallest distance is selected for a low-charge AGV (i.e., one for NBSIP vs. two for NBSDP).

(ii) *Effect of the overlapping of initial point and pick-up point:* Since the facility used in this study is a busy facility, the workstations of the facility often have some parts waiting to be picked up (after getting processed by that workstation). When an AGV becomes empty and free after dropping off at a workstation, it is assigned immediately to pick-up from the same workstation if a part had been waiting there to be picked up (the facility uses the same point for pick-up and drop-off at a workstation). This assignment can happen because the selection rule of smallest distance is used to allocate an AGV (here, the distance is zero because initial point and pick-up point refer to the same point).

For a situation where initial point and pick-up point overlap (i.e., when an AGV picks up from the same point where it has just dropped off a load), NBSDP always takes the advantage of zero travel distance between initial point and pick-up point. This is because NBSDP, irrespective of the available charge of an AGV, directs the AGV to pick-up the load from pick-up point. As shown in table 4.6 below, for nearly 10% of all the pick-ups, NBSDP gets the advantage of overlapping of initial point and pick-up point.

On the contrary, for a situation when initial point and pick-up point coincide for NBSIP, a low-charge AGV is directed to first go to the nearest battery station (without picking up the load from the pick-up point) and then come back from the battery station to the same point to pick-up the load. As a result, travel distance for a low charge AGV following NBSIP can be substantially larger than that for a low-charge AGV following NBSDP during first leg of the journey (during first leg, initial point is the point of origin and pick-up point is the final point of destination).

Table 4.6: Percentage of pick-ups for NBSDP when overlap occurs

No. of AGVs	**% of pick-ups for NBSDP when initial point and pick-up point overlap**
41	9.78
42	8.08
43	9.82
44	10.56
45	10.19
46	10.91
47	9.86
48	10.58
49	10.52
50	10.26
51	10.90
52	9.90
53	10.22
54	10.57
55	10.21
56	10.57
57	11.29
58	11.27
59	9.17
60	11.90
61	11.89
62	9.21
Average =>	**10.35**

NBSDP, unlike NBSIP, directs a low-charge AGV to go to a battery station during second leg of the journey (during second leg, pick-up point is the point of origin and drop-off point is the final point of destination). Consequently, distance travelled by a low-charge AGV during the second leg would be larger for NBSDP than that for NBSIP. In other words, NBSIP is likely to cause additional travel distance than that caused by NBSDP during first leg of the journey and the reverse will happen during second leg of the journey. However, as shown in table 4.7 below, the additional travel distance for NBSIP in the first leg was found to be consistently larger than that for NBSDP during the second leg.

Table 4.7: NBSIP vs. NBSDP

No. of AGVs	**Additional distance travelled by the AGVs for each unit produced (ft)**		**Total number of battery swaps**		**Total output (no. of part 1 produced + no. of part 2 produced + ….. + no. of part 10 produced)**		**% increase in total output if switched from NBSIP to NBSDP**
	for NBSIP, in comparison to NBSDP (during 1st leg of journey)	***for NBSDP, in comparison to NBSIP (during 2nd leg of journey)***	***NBSIP***	***NBSDP***	***NBSIP***	***NBSDP***	
41	190	118	1,450	1,525	5,096	5,138	0.82
42	204	111	1,473	1,553	5,175	5,226	0.99
43	200	121	1,500	1,583	5,259	5,314	1.05
44	193	130	1,520	1,607	5,346	5,392	0.86
45	193	121	1,538	1,629	5,422	5,471	0.90
46	208	126	1,563	1,655	5,495	5,552	1.04
47	193	126	1,583	1,680	5,575	5,623	0.86
48	197	120	1,598	1,698	5,639	5,698	1.05
49	184	119	1,620	1,720	5,713	5,771	1.02
50	205	122	1,641	1,745	5,778	5,847	1.19
51	195	103	1,654	1,760	5,842	5,902	1.03
52	193	118	1,671	1,778	5,906	5,972	1.12
53	201	121	1,693	1,798	5,966	6,027	1.02
54	200	114	1,707	1,813	6,018	6,082	1.06
55	198	121	1,718	1,828	6,077	6,140	1.04
56	203	134	1,736	1,848	6,120	6,190	1.14
57	198	129	1,753	1,865	6,167	6,239	1.17
58	187	124	1,765	1,875	6,209	6,280	1.14
59	183	123	1,782	1,891	6,245	6,316	1.14
60	181	141	1,802	1,906	6,287	6,343	0.89
61	183	142	1,813	1,918	6,308	6,373	1.03
62	198	121	1,826	1,931	6,343	6,405	0.98
						Average =>	**1.02**

Table 4.7 also shows that total number of battery swaps for NBSDP is always higher than that for NBSIP. That is, NBSDP requires the AGVs to spend more time at the battery stations than that required by NBSIP. Yet, the total output as shown in table 4.7 (repeated from table 4.3) is always higher for NBSDP in comparison to that for NBSIP. Possible reason of this higher productivity is that NBSDP requires less travelling (combining both legs of the journey) for each unit produced in comparison to that required by NBSIP. The last row of table 4.7 shows that by

switching from NBSIP to NBSDP, this manufacturing facility can expect to increase its average productivity by 1.02%.

4.8 Conclusion and Future Research

This study makes a comparative analysis of different routing heuristics for the battery management of AGVs at a manufacturing facility. Four routing heuristics available in the literature were the basis of this study. Those heuristics were modified to make them applicable and distinct for a manufacturing system.

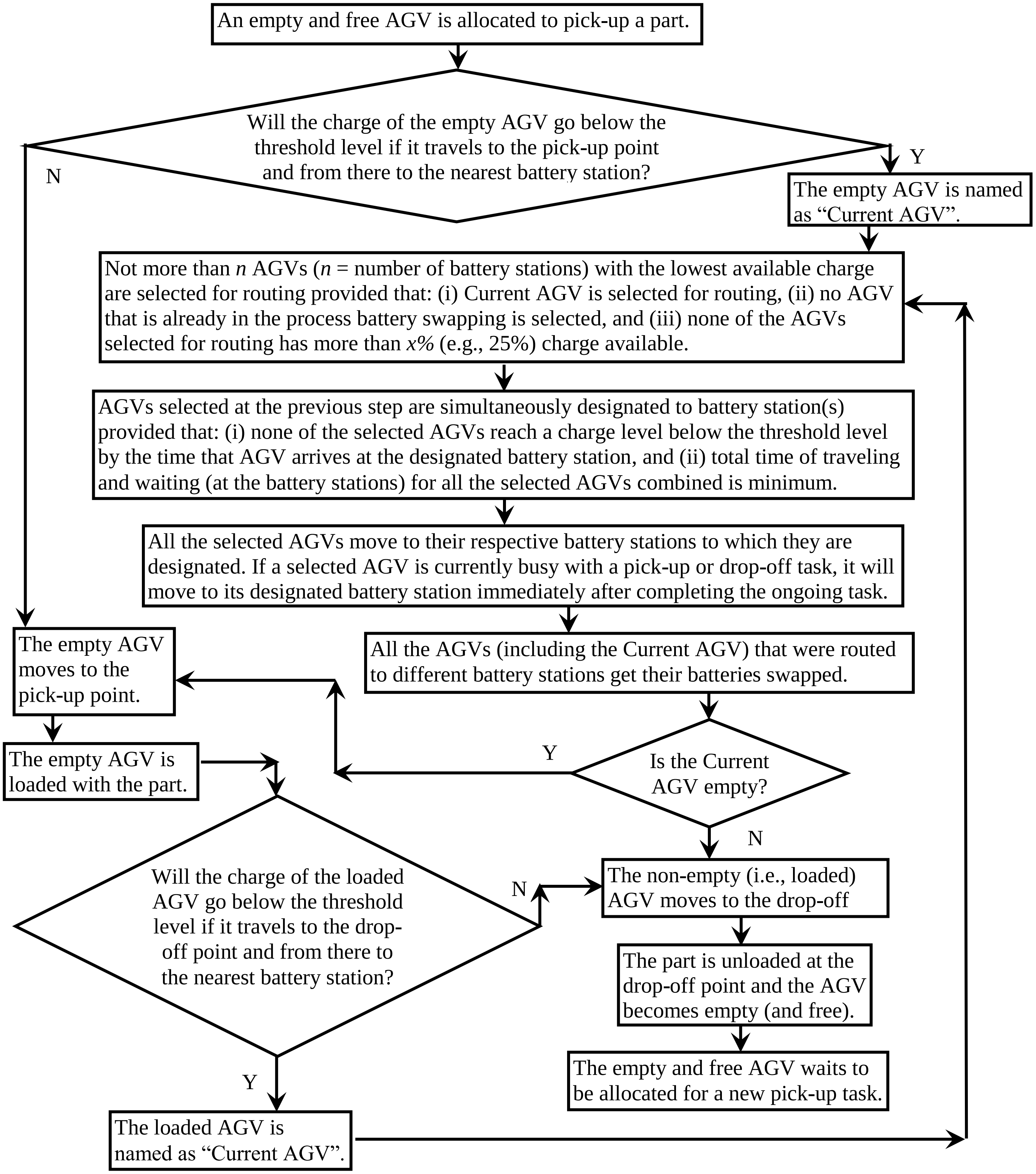
The results show that MDBS performs the best and NBSIP performs the worst in terms of productivity of the system. The productivity difference between MDBS and NBSIP does not appear to be very large in terms of absolute value. But comparison with the no-charging-scenario (i.e. scenario where no time is spent for battery management) showed that by switching from NBSIP to MDBS, a firm can expect to capture more than 40% of the productivity increase that is possible by switching from NBSIP to the best case scenario. It may also be noted that even if the absolute increase in productivity is not very large, a firm should always take such a benefit because changing the routing technique does not require any additional investment. A small increment in productivity is likely to improve the competitiveness of the firm in the long run.

Through the comparison between NBS and NBSIP, it was found that the more frequently a system allows its AGVs to make decisions about battery swapping (or not swapping), the better the productivity of that system is. Also, the comparison between NBSIP and NBSDP revealed that settings of a system like how busy the system is, whether the same locations are used for pick-up and drop-off, and which selection rule is used for allocating the AGVs can play important roles in determining the effectiveness of a heuristic. Further research should be conducted in this regard.

It may be noted that MDBS, the best performing heuristic in this study, routed one AGV for battery management at any point in time (the same is true for other heuristics of this study). There is a possibility to improve the productivity of the system further (i.e., outperforming MDBS) by simultaneously routing multiple AGVs for battery management. One such potential heuristic is proposed in the appendix. The proposed heuristic considers not only the AGV that needs to replace its depleted battery immediately, but also considers other AGVs that will reach a similar situation in near future. Consequently, multiple AGVs are routed simultaneously to all the battery stations to balance the workload for the battery stations. It would be interesting to see how such a heuristic performs in comparison to the other heuristics.

This research did not consider opportunity swap (i.e., when AGVs swap their depleted batteries during their idle time). This is because this research is based on a busy facility where the AGVs hardly have any idle time. Future research can incorporate opportunity swap to see how different routing heuristics perform in presence of idle time. Also, other types of facilities (e.g., warehouse, container terminals) can be used in future to study how routing heuristics perform in different types of facilities.

Appendix 4A: Proposed heuristic of SRMA (simultaneous routing of multiple AGVs)



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CHAPTER 5: GENERAL CONCLUSION

This dissertation was designed to improve the body of knowledge on the battery management of automated guided vehicles (AGVs). Chapter 2 set the conceptual stage for the successive chapters through an extensive literature review. The literature review, supplemented by information from practitioners, generated two themes for the battery management of an AGV system. These themes are: (i) improving battery management practices, and (ii) integrating battery management with other components of an AGV system. Chapter 2 discussed these themes including different options available for battery management (e.g., depending on the technological and financial resources available, a firm can buy batteries or lease batteries with full service).

Chapter 3 investigated how the duration of battery charging for AGVs can be varied to increase flexibility of a manufacturing system. The key concept used in chapter 3 is that a lead acid battery, the most widely used battery type for AGVs, receives most of its charge during the initial phase (time) of charging as opposed to the later phase. Simulation results of chapter 3 show that productivity of a manufacturing facility increases significantly if the duration of battery charging is reduced for the AGVs (i.e., recharging the batteries to less than full capacity). The results also show that simply adding AGVs in a facility can be counterproductive after a certain point, when the productivity of the facility starts to decrease because of the bottleneck and congestion in the system.

Chapter 4 focuses on the routing of AGVs for battery management. Four heuristics available in the literature were used as the starting point for this chapter. These heuristics were modified to make them suitable for a manufacturing facility (the heuristics were originally suggested on the basis of an underground transportation system). Simulation models were developed to investigate the effect of the modified heuristics on the productivity of a manufacturing facility. Results showed that a firm can have better productivity consistently if it considers the travel distance and waiting time while routing an AGV for battery replacement. This is important because hardly any additional expense is required to attain this increase in productivity.

Overall, this dissertation showed that a firm can gain in multiple ways through effective and efficient battery management of its AGVs. Also, the dissertation raised some interesting research questions by focusing on different dimensions of battery management. Hence, it is expected that the dissertation would be able to contribute both to the academia and to the industry.