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Invited Review

Survey of research in the design and control of automated guided vehicle systems

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Abstract

Automated guided vehicles (AGVs) are used for the internal and external transport of materials. Traditionally, AGVs were mostly used at manufacturing systems. Currently, AGVs are also used for repeating transportation tasks in other areas, such as warehouses, container terminals and external (underground) transportation systems. This paper discusses literature related to design and control issues of AGV systems at manufacturing, distribution, transshipment and transportation systems. It is concluded that most models can be applied for design problems at manufacturing centres. Some of these models and new models already proved to be successful in large AGV systems. In fact, new analytical and simulation models need to be developed for large AGV systems to overcome large computation times, NP-completeness, congestion, deadlocks and delays in the system and finite planning horizons. We specify more specific research perspectives in the design and control of AGV systems in distribution, transshipment and transportation systems.

Keywords: Automated guided vehicle systems; Literature survey; Design and control; Distribution; Transshipment and transportation systems

1. Introduction

An automated guided vehicle (AGV) is a driverless transport system used for horizontal movement of materials. AGVs were introduced in 1955 (Müller, 1983). The use of AGVs has grown enormously since their introduction. The number of areas of application and variation in types has increased significantly. AGVs can be used in inside and outside environments, such as manufacturing, distribution, transshipment and (external) transportation areas. At manufacturing areas,

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AGVs are used to transport all types of materials related to the manufacturing process. According to Götting (2000) over 20,000 AGVs are used in industrial applications. The author states that the usage of AGVs will pay off for environments with repeating transportation patterns. Examples of these environments are distribution, transshipment and transportation systems. Warehouses and cross docking centres are examples of distribution areas. AGVs are used in these areas for the internal transport of, for example, pallets between the various departments, such as receiving, storage, sorting and shipment areas. At transshipment systems, such as container terminals, AGVs take care of the transport of products between the various modes of transport. Götting (2000) presents an overview of available technology for automation in container terminals. Furthermore, navigation and vehicle guidance systems applicable in various indoor/outdoor environments are described. Haefner and Bieschke (1998) state that AGV systems can provide benefits to both the port and its customers by executing transportation requests between vessels and inland transportation. Namely, in non-automated terminals this transportation process is one of the least efficient and most costly processes. AGVs can also be used in the outdoor transportation process. An example of such a transportation system is an underground automated transportation system with AGVs travelling in tubes between companies and an airport (see Van der Heijden et al., 2002a,b). In such systems, we notice a high traffic density and long tube driving times. It has even been studied if AGVs can be used as a communication system between work stations (see Maughan and Lewis, 2000).

Clearly, the specifications of AGVs differ per environment. To transport a container, the capacity of an AGV should at least be equal to 40 tonnes. Less capacity is required for the transport of pallets at warehouses. Furthermore, at container terminals self lifting automated guided vehicles (ALVs) are used. For this type of AGV no other equipment is required to transfer a load to the vehicle. Vis and Harika (2004) and Yang et al. (2004) discuss this new type of AGVs in more detail.

In this paper, we will discuss literature concerning the usage of AGVs in manufacturing and the new areas of application, namely distribution, transshipment and transportation systems. The most important differences between traditional and new areas of application are the number of AGVs used, the number of transportation requests, the occupancy degree of AGVs, the distances to be travelled and the number of pick-up and delivery points where transportation requests become available. At manufacturing systems, a small number of AGVs with relatively low occupancy degrees are used to transport a small number of requests over short distances between a few pick-up and delivery points. For continuous mass transport in these systems conveyors are used instead of large numbers of AGVs (see Götting, 2000). In contrast to manufacturing systems, large numbers of AGVs (up to 400; Van der Heijden et al., 2002a) are used to execute a large number of repeating transportation tasks at container terminals and external transportation systems. Furthermore, operational conditions, such as weather conditions and spational dimensions, found in outside environments (container terminals and external transportation systems) differ from the operational conditions in inside areas (manufacturing and distribution systems).

In the various areas described, a number of AGVs are operating to transport jobs from one location to another. These AGVs belong to the *Automated Guided Vehicle System* (AGV system). The AGV system itself might be part of a larger system such as an intelligent flexible manufacturing system. Lim et al. (1989) describe such a system which consists, except for an AGV system, of an automated storage and retrieval system and machines. In an AGV system several parts can be distinguished, namely the *vehicles*, the *transportation network*, the *physical interface between the production/storage system* and the *control system*. The transportation network connects all stationary installations (e.g. machines) in the centre. At stations, *pick-up and delivery points* are installed that operate as interfaces between the production/storage system and the transportation system of the centre. At these points a load is transferred by, for example, a conveyor from the station to the

AGV and vice versa. AGVs travel from one pick-up and delivery point to another on fixed or free paths. Guidepaths are determined by, for example, wires in the ground or markings on the floor. More recent technologies allow AGVs to operate without physical guidepaths. We refer to these kind of AGVs as free-ranging AGVs.

AGVs are capable of transporting one or more loads at the same time. The size of the *unit load* has to be decided on by the management. A unit load refers to a number of items arranged in such a way that they can be transported as a single object. Examples of a unit load are a container or a pallet. Clearly, the larger the size of a unit load, the lower the transportation costs per individual item and the lower the number of vehicles required in the system. Methods to determine the size of a unit load have been given in Egbelu (1993a) and Moon and Hwang (1999). Hwang et al. (2002) extend the paper of Moon and Hwang (1999) by considering the simultaneous design of end-of-aisle order-picking and unit-load sizes of AGVs.

Furthermore, it has to be determined if *one-load-carrying* or *multiple-load-carrying AGVs* will be used in the system. Ozden (1988) indicates with a simulation study, that by transporting two loads at the same time instead of one, reductions in the vehicle fleet size can be obtained. Van der Meer (2000) shows that increasing the capacity of a vehicle results in a reduction of the average throughput time. However, in literature, one-load-carrying AGVs are mainly discussed.

The transportation process in which one-load-carrying AGVs are used, might consist of the following steps. The load demands at its release time for transportation at the pick-up and delivery point of its origin. Sometimes, a due time is also defined to ensure that the load is transported at the latest at this time-point. An available AGV is assigned to this load (see Section 7.1) to transport it. At the origin of the load, the load is placed on the AGV. Thereafter, a route from origin to destination and times for arrival and departure have to be determined via which the AGV travels to transport the load (see Section 7.2). At the destination of the load, the AGV is unloaded and ready to receive a new assignment. Clearly, many decisions have to be made for each transport of a load. Therefore, a high level of *control* is required in an AGV system for efficient routing, scheduling and dispatching of vehicles and deadlock avoidance (see Section 7).

In *designing* an AGV system many tactical (e.g. system design) and operational (e.g. routing) issues have to be addressed. In the remainder of this paper we will discuss both these tactical and operational issues, and related literature, in more detail. Several review papers on AGVs have already been published. Some of the older ones are Co and Tanchoco (1991), King and Wilson (1991), Ganesharajah and Sriskandarajah (1995), Johnson and Brandeau (1996), Manda and Palekar (1997) and Hoff and Sarker (1998). Co and Tanchoco (1991) discuss literature on the operational issues of dispatching, routing and scheduling of AGVs. King and Wilson (1991) discuss literature on system design and routing and scheduling of AGVs. In the area of system design they study the issues of vehicle requirements, flowpaths and types of AGVs used. Furthermore, they show the importance of the relationship between tactical and operational issues in the justification of the system. Ganesharajah and Sriskandarajah (1995) study the operational issues of scheduling, dispatching and routing of AGVs in various flowpath layouts. Johnson and Brandeau (1996) discuss stochastic models for the design and control of automated material handling systems. Except for AGVs they also discuss automated storage and retrieval systems. Manda and Palekar (1997) discuss design and control issues for material handling systems. They discuss some research on AGV design and AGV dispatching and routing. Hoff and Sarker (1998) review literature on the design of guidepaths and dispatching rules for AGVs.

More recently, reviews of Ganesharajah et al. (1998) and Qiu et al. (2002) have been published. Ganesharajah et al. (1998) discuss literature on design and operational issues in manufacturing systems. Tactical problems concerning fleet sizing and flowpath design have been discussed. From an operational perspective they study scheduling, dispatching and routing of AGVs. Qiu et al. (2002) address the operational issues of scheduling and routing of AGVs. In contrast to the other review papers on scheduling and routing they observe, instead of only manufacturing systems, also another area, namely container terminals.

From these review papers we can conclude that all papers select some of the existing operational and/or tactical decisions in AGV systems. Furthermore, except for Qiu et al. (2002) all papers only consider the usage of AGVs in manufacturing areas. In this paper, we will discuss a broader combination of tactical and operational issues. We will study literature on non-traditional subjects, such as vehicle control (Section 7), prediction and avoidance of collisions and deadlocks (Section 4), positioning of idle vehicles (Section 7.3) and battery and failure management (Section 8). We will also discuss the more traditional subjects, such as flowpath layout (Section 3), number and location of pick-up and delivery points (Section 5), vehicle requirements (Section 6), dispatching (Section 7.1) and routing and scheduling of vehicles (Section 7.2). In these areas we have also studied recently published papers in more detail. Furthermore, this paper studies, not only literature on manufacturing systems, but also on the usage of AGVs in other areas, such as distribution, transshipment and (underground) transportation systems. Differences in approaches for small AGV systems in manufacturing areas and the larger ones in transshipment and transportation systems are presented. In the various sections, research questions for design and control of AGVs at distribution, transportation and transshipment systems are indicated. Section 9 presents conclusions.

2. Design of an AGV system

In design problems many decision variables arise. The impact of decisions on mutual interactions and performance might be difficult to predict. It might be hard to decide on one thing without considering other decision variables. At least the following tactical and operational issues have to be addressed in designing an AGV system (see, for example, Malmborg, 1990; Koff, 1987):

- flowpath layout,
- traffic management: prediction and avoidance of collisions and deadlocks,
- number and location of pick-up and delivery points,
- vehicle requirements,
- vehicle dispatching,
- vehicle routing,
- vehicle scheduling,
- positioning of idle vehicles,
- battery management,
- failure management.

A flowpath layout compromises the fixed guided paths on which vehicles can travel to the various pick-up and delivery points of loads. Traffic management is required to avoid collisions and deadlock situations in which two or more vehicles are blocked completely. To ensure that loads are transported in time, sufficient vehicles should be available and the right vehicle should be dispatched to the right load. Furthermore, routes for vehicles to transport loads from their origins to their destinations have to be determined. Based on this routing information, scheduling decisions on, for example, the sequence in which jobs should be handled by a vehicle, can be made. After transporting a job, an idle vehicle has to wait on a new assignment at a certain position in the system.

To simultaneously address some of these design problems, simulation models (see, for example, King and Kim, 1995; Kim and Jae, 2003) or combinations of simulation and analytical models might be used (see, for example, Mahadevan and Narendran, 1990; Malmborg, 1990). Van der Heijden et al. (2002a) built a simulation model for an automated underground transportation system. 200–400 AGVs will be used around Schiphol Airport (The Netherlands) in the near future to transport up to 3.5 million tons of cargo through tubes with lengths of 16–25 km which connect 5–20 terminals. Compared to traditional AGV systems, this system is much larger in the number of vehicles, number of terminals, number of loads and distances to be travelled. The simulation model addresses questions concerning vehicle requirements, terminal design and the method to provide energy and control systems for AGVs. Aiello et al. (2002) study the problem of simultaneously determining the location of departments in a facility and designing the material handling system. The authors formulate a genetic algorithm which determines the location of departments, location of pick-up and delivery points and direction of guide-paths, such that material handling costs are minimised. It has been shown that this algorithm outperforms the classical approach of first determining location of departments and thereafter designing the material handling system.

With numerous assumptions, the design problems can be simplified and formulated as an analytical model. For example, Johnson and Brandeau (1993) suggest formulating the problem of designing an AGV system as a binary integer programming model and solving it with enumeration algorithms. The algorithms have been tested on real-life problems with 15–25 workstations and 1–5 vehicles. Computation times increase enormously if the number of stations increase. Therefore, it might be questioned if the analytical method is still useful in the new areas of application with hundreds of AGVs. Johnson and Brandeau (1999) incorporate inventory decisions in the design of an AGV system. According to the authors, a trade-off exists between the amount of inventory and the number of vehicles required to provide adequate service. It has been shown that by integrating inventory and design issues, significant reductions in overall production costs can be obtained. Most papers concerning the design of AGV systems ignore or simplify empty vehicle traffic. Johnson (2001) studies the impact of empty vehicle traffic on flow path design and vehicle requirements. The author shows that the usage of empty trip information significantly improves the performance of the systems design. Tsai and Wang (1999) show how modular-based design can be used in designing an AGV system.

To measure the performance of the system, various criteria can be used. For example, Bozer et al. (1994) propose an analytical model to estimate the expected waiting times of loads to be transported. Koo and Jang (2002) present stochastic travel time models for AGVs to determine loaded and empty vehicle travel times. It has been shown that the models perform well for various dispatching rules in general cases with 50 workstations and 10 AGVs. Nakano and Ohno (1999) give a decomposition algorithm to evaluate the performance of an AGV system measured in terms of the average utilisation of machines in the system. According to the literature discussed in this paper, some of the objectives of an AGV system are:

- maximise throughput of the system (i.e. number of loads handled per time unit),
- minimise time required to complete all jobs (i.e. makespan),
- minimise vehicle travel times (empty or/and loaded),
- evenly distribute workload over AGVs,
- minimise total costs of movement,
- minimise time job is handled after its due time (i.e. tardiness),
- minimise maximum or average throughput times of AGVs to travel to the destination of new jobs,
- minimise expected waiting times of loads.

Concluding, a few authors simultaneously address various design problems of AGV systems by using simulation. Some analytical models have been developed which can be applied for AGV systems with a relatively small number of AGVs and workstations. However, layout problems and control problems, which are highly interrelated, are often separated. By doing this, attention should still be paid to the overall performance of the system. A well developed layout with a bad control rule might result in a decrease of the performance of the system. Performance of operations becomes more and more important, especially from an economic point of view. This mainly applies to non-value added activities such as transportation and transshipment. As a result, the performance of an AGV system operating in distribution, transshipment and transportation areas should be high. Therefore, more attempts should be made to simultaneously address multiple design problems. Either by applying analytical methods or simulation. Furthermore, the mutual relationship with the design of other material handling systems, such as storage systems, should be considered. Literature on the separate decision variables will be discussed in the remaining sections of this paper.

3. Design of a flowpath layout

AGVs can travel along fixed guidepaths, which are indicated by, for example, wires in the ground. A flowpath layout connects machines, processing centres, stations and other fixed structures along aisles. This layout is usually represented by a directed network in which aisles intersections and pick up and delivery locations can be considered as nodes. The arcs represent the guidepath the AGVs can travel on. Directed arcs indicate the direction of travel of vehicles in the system. The layout of this flowpath directly influences the performance of the system. For example, it impacts the travel time to transport a load from its origin to its destination, the number of vehicles required (see Section 6) and the degree of congestion (see Section 4).

The layout of the flowpath can be designed in various ways. Firstly, the layout of the building, the layout of the flowpath and the location of pick-up and delivery points can be simultaneously determined. Secondly, the design of the flowpath and the location of pick-up and delivery points can be determined by considering the layout of the facility as an input factor. Thirdly, the flowpath can be designed, considering the layout of the facility and the location of pick-up and delivery points as input factors.

Using the information on the layout of the facility and the number and location of aisles and pick-up and delivery points, a fully connected network consisting of arcs and nodes can be created. Nodes represent corners of aisles, intersections between aisles and pick-up and delivery points. In this network each node is connected with any other node and the complete path between two nodes can be traversed by a load without changing of vehicles. Directed arcs indicate possible directions of travel through the aisles. The direction of travel along these arcs can be *unidirectional* and *bidirectional*. If vehicles are allowed to travel in only one direction, arcs are unidirectional. On the other hand, if vehicles are allowed to travel in both directions, bidirectional flow on arcs might occur. By using bidirectional traffic flows, instead of unidirectional flows, reductions in travel distance can be obtained due to the possibility of making short cuts. On the other hand, the control of unidirectional flows is easier due to the fact that no opposite traffic of AGVs is allowed. To obtain advantages of both options, *multiple lane guidepaths* can be introduced. If enough space is available, multiple paths with opposite traffic flows can be inserted in one aisle. Furthermore, in one flowpath layout, it can be decided to use a *mix* of unidirectional and bidirectional paths. Traffic control simplicity and benefits from shorter distances can be obtained in this way. Finally, during operation it can be decided to change direction of certain unidirectional flows to meet the demand of the system. The problem for all described layouts is to determine direction of travel on the flowpath by minimising vehicle travel times and by ensuring ability to reach all pick-up and delivery points in the network. Sinriech (1995) presents an overview of literature on several approaches for the design of flow networks. In this section, firstly, literature will be discussed on the layout problem with unidirectional, bidirectional, multiple lane and mixed uni-/bidirectional flowpaths. Thereafter, attention will be paid to developments in flowpath layouts, like single loop layouts.

Gaskins and Tanchoco (1987) were one of the first to discuss the AGV guidepath layout problem with *unidirectional arcs*. The problem is presented as a network and formulated as a 0–1 integer linear programming model. The objective is to minimise the total loaded transportation distance of AGVs (i.e. transportation costs). The solution of this model indicates the optimal direction of travel of each arc. For practical problems, the number of variables and related computation times increase enormously. Therefore, Kaspi and Tanchoco (1990) describe a model with extra constraints and give a computationally efficient procedure, namely a branch and bound approach. This model has been extended by Kim and Tanchoco (1993a) by also considering the fixed costs for construction, control and space of the system. It has been concluded that, for large-sized problems with 10–16 intersections, a better computational performance is obtained by applying their approach instead of the model of Kaspi and Tanchoco (1990). Also based on the model of Kaspi and Tanchoco (1990) is the work of Sinriech and

Tanchoco (1991). They propose a branch and bound method which has to deal with a smaller set of nodes in the flowpath network. As a result, the branch and bound process has been sped up. The construction algorithm of Lim et al. (2002a,b) outperforms the algorithm of Kim and Tanchoco (1993a) by considering the total travel time as an objective instead of the total travel distance. Venkataramanan and Wilson (1991) also propose a branch and bound algorithm for unidirectional flow path design. Kouvelis et al. (1992) develop different heuristics to determine unidirectional flowpath layouts while minimising the total distance travelled by vehicles. Shiizuka and Suzuki (1994) use petri nets to model AGV networks.

In above-mentioned papers, only the impact of the flow of loaded vehicles has been taken into account. In Sun and Tchernev (1996) the problem for unidirectional flowpath design is generalised by also taking into account the impact of empty vehicle flow. By applying a branch and bound algorithm based on a depth-first search method, the optimal direction for each arc can be found. Kaspi et al. (2002) present a model which is based on the 0–1 integer linear programming model of Kaspi and Tanchoco (1990). However, Kaspi et al. (2002) take into account both empty and loaded vehicles. A branch and bound approach has been presented to deal in a computationally efficient procedure with an unknown flow of empty vehicles and a given flow of loaded vehicles. A solution indicates the direction of travel of all arcs and an optimal flow of unloaded vehicles between delivery and pick-up stations.

Above-mentioned papers address, in general, a static production environment with fixed product mixes and fixed routes between machines. Ko and Egbelu (2003) state that in today's dynamic production environment changing product mixes and machines routes are realistic. They propose and test a heuristic for the design of AGV networks that can respond to changes in production volume and flow patterns.

A second approach to establish the design of the flowpath network is by simultaneously determining the direction of traffic flow in a unidirectional network and the location of pick-up and delivery points (see also Section 5). Goetz and Egbelu (1990) modelled this problem as a linear integer programming model. The objective is to minimise the total distance travelled. The main focus of this approach is on systems with major flows of traffic and a large number of pick-up and delivery points. The problem of simultaneously assigning a machine for each operation, determining the machine visiting sequence and designing the unidirectional guidepath is studied in Seo and Egbelu (1999). The objective is to minimise the total process and transport times of all parts in the system. Global solutions have been found by splitting the problem into two subproblems and applying a heuristic.

In a *bidirectional network*, traffic flow takes place in either direction in each aisle. However, vehicles are not allowed to travel in opposite directions at the same time. Therefore, buffer areas exist for temporary parking of vehicles. Questions, that arise in this context, are: how many nodes will have a buffering facility? Which kind of buffer areas will be used? At which places will the buffer areas be located? Egbelu and Tanchoco (1986) discuss three different designs of buffer areas, namely *loop design*, *siding design* and *spur design*. In a *loop design*, two unidirectional loops are located at the end of each aisle. A unidirectional siding is located at the end of each aisle in a *siding design*. A siding serves AGVs travelling in the same direction. Finally, in *spur design*, dead end spurs, capable of being transferred in both directions, are located at the end of each aisle. In contrast to the other options, vehicles will leave the spurs according to the last in-first out principle. Egbelu and Tanchoco (1986) also discuss a model which describes the flow and control of AGVs in a bidirectional network. With simulation, it has been shown that in a specified situation, the use of bidirectional guidepaths in networks with few AGVs can lead to an increase in productivity. Kim and Tanchoco (1993b) also present simulation results to compare the performance of unidirectional and bidirectional layouts in a particular network. For this network, it has been shown that the bidirectional layout outperforms the unidirectional one in terms of the number of jobs completed per time unit.

In the *multiple lane guidepaths*, various flowpaths exist between nodes (pick-up and delivery points, intersections) of the network. Commonly, there are two or more unidirectional paths in the same aisle. The problem is to determine the number and direction of feasible flowpaths. Gaskins et al. (1989) present this problem as a multi commodity flow problem and formulate it as a linear integer programming model. Both loaded and empty vehicle data can be used in the model. Weaknesses of this approach are computational difficulties and the fact that the interaction of vehicles is not taken into account in the model. Therefore, the solution from the models should be evaluated with simulation before applying them in practice.

The configuration of a *mixed uni-/bidirectional flowpath* is studied in Rajotia et al. (1998a). A unidirectional flowpath layout is taken as input. A heuristic method has been developed to configure some unidirectional paths to bidirectional ones. Candidates for this configuration are paths from centre i to j with the highest value of the product of the material flow from centre i to j and the reverse flow from j to i. The purpose of this configuration is to reduce travel distances. It has been indicated that benefits can be obtained in throughput rates and size of the vehicle fleet. However, the rate of vehicle congestion increases and, as a result, traffic control becomes more important.

Other developments in flowpath design are *single loops, tandem configurations* and *segmented flow configurations*. In a *single loop layout* AGVs travel in a (unidirectional) loop. This loop is a fixed sequence of processing centres which need to be visited. Single loops are comparable to networks for equipment like conveyors. Advantages of the single loop layout are diverse. For example, all vehicles travel in the same loop, and blocking of vehicles only occurs when a vehicle has to stop to pick-up or deliver a load. Furthermore, due to lack of alternative paths in the layout, control of AGVs is relatively easy. Disadvantages of single loop systems also exist, compared to above mentioned flowpaths layouts. For example, due to vehicle failure, the complete loop will be unusable. Furthermore, once a station is passed, an AGV has to travel the complete loop, before it reaches the station again. Finally, the throughput of the system will be lower (see Sinriech and Tanchoco, 1992a; Tanchoco and Sinriech, 1992).

The problem of finding a valid single loop guidepath is comparable to the Travelling Salesman Problem, except for the fact that the number of places to visit is bounded and not fixed, the start point of the loop is not fixed and the solution is a set of arcs forming a closed loop (see also Tanchoco and Sinriech, 1992). The research for single loop layouts can roughly be divided into two categories. One is the simultaneous determination of the guidepath for the AGVs serving all production cells of a manufacturing area and the locations of pick up and delivery points within this area. The objective in this case is to minimise the length of the total loop. Secondly, research has been carried out to the single loop layout within specific production cells. In this case n stations need to be positioned on n prespecified locations. The objective in this type of research is in most papers defined as minimising total weighted travel distances for AGVs.

De Guzman et al. (1997) proof that finding optimal solutions for single loop configurations from the first category is NP-complete, due to the constraint that all stations in the layout should be included in the loop. The authors encourage the development of efficient heuristics to solve this specific problem. Already in 1992, Tanchoco and Sinriech (1992) discuss the design of single loop guidepaths and the location of pick-up and delivery points such that the flow of parts in the system is minimised. They propose to solve the problem by applying enumeration. In Sinriech and Tanchoco (1993) suggestions have been given to speed up this enumeration method. The authors recognise the difficulty of the problem and the possibility that no optimal solutions are obtained by applying their methods. Furthermore, it is not clear if their methods can be used to solve large problem sizes. This question becomes more and more interesting with the increased usage of AGVs in large transshipment and transportation systems. Asef-Vaziri et al. (2000) formulate the shortest loop design problem as a integer linear programming model. With some simplifications, the size of the problem can be reduced effectively. Instances with a maximum of 40 cells in a production area can be solved to optimality by standard solvers. Sinriech et al. (1996) study bidirectional single loops. The problem has been formulated as a 0–1 mixed integer formulation.

Afentakis (1989) was the first to study the single loop layout problem as defined in the second category. The author presents a mathematical formulation and an interchange heuristic to solve the problem. Kouvelis and Kim (1992) proved that also assigning machines to prespecified locations in a unidirectional loop while minimising costs is *NP*-complete. The authors propose heuristics which provide nearly optimal results for realistically sized problems. A critical remark in this context is that the authors only test their heuristics in realistic manufacturing areas with at most 12 workstations. The performance in large AGV systems is an open question. Kiran et al. (1992) show that the problem can be formulated as a quadratic assignment problem. Their solution method which uses LP relaxations, has been tested for problems with a small number of workstations (maximum of 7). No mathematical proof is provided, which shows that the relaxations always solve this problem to optimality. However, their empirical evidence suggests that LP relaxation solutions for this problem are optimal. To show the usefulness of this approach in large AGV systems, either a proof should be formulated or more testing should be performed for large AGV systems with a large number of stations. Lee et al. (1996) develop a decision support system to examine the location problem of workstations in a closed loop. Sharp and Liu (1990) propose an analytical model to configure a closed-loop system with the ability to decide on adding shortcuts. Bozer and Rim (1996) use a branch and bound method to solve the bidirectional variant of this problem. Vehicles can travel in the clockwise or counter clockwise direction whichever is shorter. This problem can also be seen as a special case of the quadratic assignment problem (QAP). The authors show that, for problem sizes with a maximum of 10 stations and with relatively short distances between two stations, their algorithm outperforms a general algorithm which can be used to solve QAPs. Also, in this case it is interesting to test if the algorithm can be applied successfully and efficiently for large AGV systems in transshipment and transportation areas with a large number of stations and large distances between two stations.

A *tandem configuration flowpath design* consists of non-overlapping single vehicle loops with load transfer stations in between. To transport a load from its origin to its destination, more than one AGV might be required. At the end of each zone, the load is transferred from one AGV to another. This layout is proposed by Bozer and Srinivasan (1989, 1991, 1992). To test the viability of tandem configurations, Farling et al. (2001) perform a simulation study to evaluate the impact of system size, machine failure rate and unload/load time on the performance of three AGV configurations. Namely, traditional (parallel unidirectional flows), the tandem flowpath and the tandem loop. In a tandem loop flowpath there exists an express loop which connects each loop (see Ross et al., 1996). The authors conclude that traditional layouts perform better in small systems and tandem loop configurations perform better in large systems. Hsieh and Shah (1996) present a model to design tandem AGV systems while minimising the number of loops.

The layout of the flowpath can also be designed by using a *segmented flow approach*. Sinriech and Tanchoco (1995) introduce the concept of segmented flows. Mutually independent zones are divided in non-overlapping single vehicle segments. Congestion of vehicles can be reduced with both types of layouts. Therefore, these types of layout are discussed in more detail in Section 4.

Most of the literature mentioned in this section considers the flowpath layout of manufacturing systems. For all different types of layout problems mathematical formulations such as (integer) linear programming or quadratic assignment problems can be given. To overcome large computation times and NP-completeness of some of the problems, heuristics have been developed. The usefulness of these heuristics in practice has only been tested for small AGV systems in manufacturing areas with a small number of AGVs, workstations and short distances between the workstations. With the increased usage of large numbers of AGVs in other environments, in which travel distances are high, large numbers of jobs need to be transported via a large number of workstations, new research themes arise. Can existing methods from manufacturing areas still be used? Which modifications need to be made to solve large problems efficiently? Do we need to develop new types of layouts?

4. Traffic management: Prediction and avoidance of collisions and deadlocks

In controlling and designing AGV systems the problem of prevention of AGV collisions and deadlocks should be addressed. By attaching sensors on AGVs, physical collisions can be avoided. An AGV should have the ability to avoid obstacles and the ability to return to its original path without any collisions. Xu et al. (2003) discuss concepts for this dynamic obstacle avoidance.

However, if AGVs moving in opposite directions are forced to stop in front of each other, blocking of vehicles occurs and no further transport is possible. Without manual intervention a deadlock situation is caused. Deadlocks can also occur at buffer areas of pick-up and delivery points. If a load is available for transport at a pick-up and delivery point and a loaded AGV is the first in line before an empty AGV, then the loaded AGV cannot be unloaded and the new load cannot be transported. As a result, the performance of the system will decrease. In designing the system it is tried to avoid the occurrence of deadlock situations during operation. During operation, deadlocks and collisions are either detected and resolved by rerouting vehicles to buffer areas or deadlocks and collisions are predicted and avoided by preplanning of routes (see Section 7.2). Detection and solving instead of avoidance of deadlocks results in a lower performance of the system. Therefore, methods have been developed to avoid collisions and deadlocks.

Literature in this area can be divided into three categories. Firstly, the layout of guidepaths can be designed in such a way that collisions and deadlocks are avoided. Secondly, dividing the traffic area into several *non-overlapping control zones* can contribute to avoidance of deadlocks and collisions. Thirdly, routing strategies can be developed to prevent collisions and deadlocks. Literature from the third category will be discussed in Section 7.2. The layout of the guidepaths has already been discussed in Section 3. Literature from the second category is discussed below.

In this case, the flowpath network consists of a number of control zones. Only one vehicle at the same time is allowed to travel through the control zone. Consequently, at most one vehicle occupies a zone and other vehicles willing to enter the zone are stopped. One or more vehicles can wait outside a zone in a buffer area to enter the zone if the previous vehicle has left it. Vehicles are allowed to travel from one zone into another one. As a result, no transfer stations between zones are required to move a load from one vehicle to another. For example, Malmborg (1990) discusses this kind of zone strategy. In practice zone control is the most popular and widely used type of traffic management (see SiemensDematic, 2004). Similar to this kind of strategy, Faraji and Batta (1994) use a flowpath network consisting of cells. According to Kim et al. (1997) and Lee and Lin (1995) deadlocks can still occur with this zone strategy, namely by competing vehicles willing to enter a zone from different directions. Lee and Lin (1995) propose an algorithm to avoid deadlocks in unidirectional control zone networks. Petri Nets are used to represent the current state and to generate future states of the system to analyse deadlocks. Petri Nets are graphical modelling tools, which are ideal for representing flexible manufacturing systems (see Zeng et al., 1991; Hsieh and Kang, 1998). The algorithm, in which deadlock prediction and travelling decisions are included, should be executed each time an AGV tries to travel from one zone to another. Yeh and Yeh (1998) also address deadlock problems of unidirectional control zone AGV systems and they propose an algorithm to deal with it. The current states of the system are represented in a directed graph. This graph can also be used to generate future states of the system. The algorithm should be applied each time a vehicle travels to a new zone and looks ahead to all future zones that have to be travelled by the vehicle. Moorthy et al. (2003) study the prediction and avoidance of deadlocks for a zone-controlled AGV system at a container terminal. Existing algorithms have been developed for small AGV systems and their complexity depends in general on the number of zones. Therefore, these algorithms can hardly be used at large systems, such as container terminals where the numbers of AGVs are smaller than the numbers of zones. The authors propose a new cyclic detection algorithm which dynamically projects the position of each vehicle after one zone step, and which detects chains of vehicles requesting zones in a cyclic form. The complexity of this algorithm is $O(V^2)$, where V equals the number of vehicles in the system.

Several variations exist on this traditional zone strategy, namely *tandem guidepath configurations* and *segmented flowpaths*. In a *tandem configuration* non-overlapping single AGV loops covering all stations exist. Between adjacent loops, pick-up and delivery points are situated to transfer the load from one vehicle to another. Each station is included in exactly one loop and only one AGV is used per loop. More details on this kind of configuration have been given in Bozer and Srinivasan (1989, 1991). Collisions and deadlocks will not occur due to the fact that only one AGV operates in each zone. Therefore, a less complicated control system is required in tandem configurations. Adding one or more new loops to the system is possible without disruption of existing loops. However, there are also several limitations to tandem configurations (see Bozer and Srinivasan, 1991; Ventura and Lee, 2001). Loads may have to be handled by a number of vehicles before they arrive at their destination. To solve this problem efficiently, Lin et al. (1994) propose a two phase approach to route loads by multiple vehicles in different zones through the network. Furthermore, vehicle breakdowns result in inaccessible stations. A zone can become the bottleneck of the system if the workload of an AGV is much higher than the workload of AGVs in other zones. More floor space as well as extra pick up and delivery points may be required. To handle these disadvantages the design of a tandem configuration layout could be examined critically. Decisions have to be taken on, for example, the number of zones and which stations are located in each zone. Bozer and Srinivasan (1992) have developed a method to configure tandem AGV systems. The objective is to distribute evenly the workload among all AGVs in the system. The model is a variation of the set partitioning problem. With simulation studies it is indicated that in some situations, from the perspective of throughput, tandem systems can be very competitive to other flowpath layouts. Castillo et al. (2001) present a generalised stochastic Petri net model to analyse tandem AGV systems. This model considers multi-load vehicles, multi-machine processing workstations, finite queue capacities and constant work-in-process. A drawback of this model is the requirements of extensive computer power and resources. Liu and Hung (2001) develop a real-time deadlock free control strategy for a multi-load AGV which travels in a single loop positioned in a more complex layout such as a tandem loop. Ventura and Lee (2001) analyse the tandem loop with multiple vehicles, which is useful for large systems. In a loop bidirectional guidepaths with buffers can be used. Advantages over a traditional tandem loop with just one vehicle, is the fact that these layouts can easily be upgraded and that they are less sensitive to vehicle failures. The authors performed a simulation study to show that the tandem loop with multiple vehicles is an effective guidepath layout alternative compared to three other layouts, namely conventional, single loop and tandem loop. Yu and Egbelu (2001) study a tandem layout with variable paths instead of loops. They propose a heuristic to partition a conventional layout into a variable path tandem layout. Work stations are grouped into single vehicle zones while minimising the number of zones and satisfying the total workload. It has been shown that the number of vehicles required and the vehicle usage time decrease. Furthermore, control problems become less complex by transferring a conventional layout into a variable path tandem layout.

The *segmented flowpath layout* consists of one or more mutually independent zones. There does not exist a flow of materials from one zone to another. Each zone is separated into non-overlapping segments. Each segment is served by a single AGV, which can travel in both directions on the segment. Between the ends of two segments, stations are located where loads can be transferred from one AGV to another AGV. The stations are capable of serving AGVs from both sides simultaneously. By using this approach, loads can be transported from their origin to their destination by using the shortest path. Furthermore, no congestion or deadlocks will occur. More information on this kind of zone strategy has been given in Sinriech and Tanchoco (1995). Methods to design this kind of layout have been described in, for example, Barad and Sinriech (1998) and Sinriech and Tanchoco (1997).

All described zone strategies have one thing in common, namely the fact that the area of the zone cannot be changed. As a result, a bottleneck zone cannot be relieved from some workload by other zones. To overcome this problem Ho (2000) developed a strategy to allow the system to adjust itself to accommodate to workload changes of vehicles. The objective is to approximately maintain the workload of each vehicle the same. With this dynamic zone strategy zones are redesigned during operation to avoid significant differences in workload between the different zones. Real-time feedback on the traffic in the system is also used in the dynamic close loop system of Reveliotis (2000). At the end of each zone, either a new zone is allocated to the AGV or the AGV is commanded to wait in its current zone. This decision is based on safety and performance considerations. Fanti (2002) also proposes a real-time control strategy to avoid deadlocks in zone AGV systems. Controller algorithms make decisions based on the operative conditions of the system. These decisions concern both the validity of assignments of paths to vehicles and moves of vehicles. Wu and Zeng (2002) developed a petri net model for deadlock control of AGVs in a manufacturing system with unidirectional guidepaths. They propose a control law which observes the state of the system and checks the number of free positions. The model is expected to be useful in real time control systems.

Most of the literature discussed, propose methods for (manufacturing) systems with small numbers of AGVs and small numbers of zones. Within traditional control zone layouts, graphical modelling tools, such as petri nets and graph based algorithms are used to deal with deadlock problems. In tandem and segmented layouts petri net models can also be used. However, already in relatively small manufacturing AGV systems, extensive computer power is required to solve the problem. Several solutions are proposed to also use these existing methods in large AGV systems. For example, multiple vehicles can be used within a single loop. Buffer zones are incorporated in the loop such that the vehicles can pass each other without causing delays. However, the usage of buffers might result in deadlock situations. Due to the limited capacity of buffers, vehicles are competing to re-enter the loop or buffer. More research should be performed for layouts in which buffer areas with capacity restrictions are used. Another drawback of applying existing methods to large AGV systems, is the fact that the complexity of the algorithms depends on the numbers of zones in the network. In large AGV systems we have to deal with a large numbers of zones. One algorithm has been developed of which the complexity depends on the numbers of vehicles. This might be interesting if the numbers of AGVs in the system is smaller than the numbers of zones. Future research should concern the development of new algorithms with efficient computation times in relation to both large numbers of vehicles and zones.

5. Location of pick-up and delivery points

In the design of the layout of the AGV system the locations of pick-up and delivery points have to be determined. The pick-up and delivery points connect the AGV network to, for example, machines, (un)load stations, inspection stations and places of storage. Furthermore, the pick-up and delivery point can be used as a transfer station from one material handling network to another. For example, goods are transferred from an AS/RS to an AGV. The pick-up and delivery points are present in all different flowpath layouts described in Section 3.

The choice of the location of these points is important. It influences the operational performance, for example, measured in terms of total distance travelled, waiting times of loads, of the system. According to Maxwell and Muckstadt (1982), Goetz and Egbelu (1990) and Asef-Vaziri et al. (2001) the choice of the locations can be decided on during the design of the system. Furthermore, the location of the pick-up and delivery points may be decided on in addition to an existing system. According to Kiran and Tansel (1989) only a small number of pick-up and delivery points should be assigned to a location at this late stage to obtain a better performance.

Kiran and Tansel (1989) developed a facility location model for a directed network (also with loops and parallel arcs) to choose locations for the pick-up and delivery points in an existing layout. The objective is to minimise the total costs of the movement of material in the system. Kim and Klein (1996) also formulate the problem as a facility location problem to minimise the total distance of materials transported by AGVs in a flowpath network with n departments. Firstly, the problem is presented as a quadratic assignment problem, which is NP-complete. Therefore, two heuristics have been developed to solve the problem. The first heuristic takes an interactive search approach with high computation times. The second heuristic exploits the layout pattern and returns a solution in $O(mn)$ time, where m equals the maximum number of pick-up and delivery points in the system. Both heuristics have been tested for problems with 4–12 departments. The second heuristic has an average error of 0.32% for 7 test problems compared to the best solution found with the first heuristic. The authors conclude that these error rates are acceptable considering the time savings involved.

In tandem configurations (see Section 4) pick-up and delivery points are used to transfer loads from an AGV in one zone to an AGV in another zone. In Huang (1997) a design concept has been proposed to find the optimal location of the pick-up and delivery point for each zone. For each zone just a single the pick-up and delivery point is assigned. As a result, a simple traffic control for the movement of materials between zones is obtained.

No research has been performed on location decisions for pick-up and delivery points in large AGV systems. With an increase in the number of all types of stations in the network an large increase in the number of pick-up and delivery points might be expected. To avoid bottlenecks at pick-up and delivery points, due to large numbers of AGVs in the system, and to reduce waiting times of loads, the location decision is even more important for large AGV systems. It needs to be studied if existing methods can still be applied for AGV systems with large numbers of AGVs or that new methods have to be developed.

6. Vehicle requirements

The minimum number of vehicles required in the system has to be determined when the AGV system is designed. To ensure that all tasks are performed within time, sufficient vehicles have to be available. However, for economical reasons the number of vehicles should not be overestimated. Furthermore, too many vehicles in the system leads to more congestion.

To determine an optimal AGV fleet size, capable of meeting all requirements, many factors have to be taken into account. Several of these factors are:

- number of units to be transported,
- points in time at which units can be or need to be transported,
- capacity of the vehicle,
- speed of the vehicle,
- costs of the system,
- layout of the system and guidepath,
- traffic congestion,
- vehicle dispatching strategies,
- number and location of pick-up and delivery points.

The point in time at which a job could be transported can be indicated in various ways. Firstly, a single time point is given at which the transport should start. Earlier or later transport is not allowed. Secondly, for each job a time-window with a release time and due time is indicated in which the transport of the job should start. Transport before the release time and transport after the due time is not allowed. In most cases, the layout of the system and the guidepath has already been defined before the minimum number of vehicles is determined. The way in which vehicles travel through the system (one way, bidirectional and so on) influences the vehicle fleet size. More information on guidepath design and the number and locations of the pick-up and delivery points is given in Sections 3 and 5. The capacity of the vehicle is, in most cases, a single load. Vehicle dispatching strategies are discussed in more detail in Section 7.1. Most models in literature consider the performance of the system by determining the minimum number of vehicles. The costs of this performance are neglected in most cases.

A procedure to determine the minimum number of vehicles required can be initiated by identifying a complete vehicle journey for transportation tasks. At a certain location the vehicle is assigned to a load. The vehicle drives to the pick-up point of this specific load. After receiving the load, the vehicle drives to the delivery point of this load. At the delivery point the vehicle is unloaded. Subsequently, this delivery point is the origin of the next journey of the vehicle. Consequently, the journey consists of empty travel time (i.e. origin journey to pick-up point), full travel time (i.e. pick-up to delivery) and waiting time (i.e. time at origin until assignment). Using this data Müller (1983) proposes a simple formula to obtain a rough calculation of the number of vehicles required by taking into account rough estimates of total travel times and frequency of transport requests. However, the total travel time depends on the randomness in the system and the amount of congestion. Due to randomness in the arrival pattern of loads to be transported, the empty travel time is difficult to determine. The full travel time is influenced by the amount of congestion in the system (see also Section 4). The speed of the vehicle will vary, depending on the number of vehicles travelling on the same AGV path, the layout of the system and whether the AGV is loaded or not. Fitzgerald (1985) also proposes a simple formula based on loaded travel times, total travel times, transport times of loads and vehicle competition for usage of the guidepaths.

As a result, many stochastic inferences are present in AGV systems. Therefore, stochastic models can be used to determine vehicle requirements. However, in the literature a number of deterministic approaches can also be found. To solve the problem of the determination of the minimum number of vehicles, deterministic assumptions are made on the randomness of the arrival pattern of jobs and speed of vehicles. In this way, methods can be developed to determine the minimum number of vehicles in an optimal way and in polynomial time. Besides these two mathematical ways, simulation studies can be performed to approach this problem. With a simulation model, the entire system can be observed. However, this is a time-consuming job. The results of analytical models and simulation models can be compared. For example, Egbelu (1987) concludes that some analytical techniques underestimate vehicle requirements. Literature from these three categories will be discussed below.

The deterministic case of the determination of the minimum number of vehicles operating on unidirectional flowpaths (see also Section 3) is studied in Maxwell and Muckstadt (1982). They use an integer programming formulation for seeking the optimum solution. Leung et al. (1987) extended this model to situations where the capacity, as well as the operating speeds of each vehicle type, differs. The authors developed a mixed integer linear programming model with the objective to minimise the total vehicle transportation time. According to Ilić (1994), the total number of vehicles in simple systems can be estimated by the number of round-trips that each vehicle can make per hour and the total number of round-trips. In Rajotia et al. (1998b) a mixed integer programming model has been discussed. Considering load handling time, empty travel time, waiting and congestion time the objective of the model is to minimise empty trips of the vehicles. The results of the model have been compared with the results of a simulation study. It has been concluded that the vehicle fleet size is underestimated with the analytical methods. In Dell'Amico et al. (1993) the problem in which a given set of jobs with fixed start instants have to be assigned to vehicles at different depots has been studied. A heuristic has been given which guarantees to find the minimum number of vehicles in polynomial time. Sinriech and Tanchoco

(1992b) developed a model which combines the throughput performance of the system and the costs related to this performance. The number of AGVs required has been determined by using a trade-off between the two objectives. Several options have been suggested in a decision table such that the management can make the final decision on the required number of vehicles. Mahadevan and Narendran (1993, 1994) developed an analytical model which takes the routeing flexibility of AGVs into account. Hall et al. (2001a) proposed an approach for finding an (near) optimal fleet size of AGVs travelling in a loop layout while minimising cycle times. In Vis et al. (2001) a method has been described to determine the minimum number of vehicles required in the AGV system of a container terminal if each job has to be transported at its known release time. A minimum flow algorithm has been presented to solve the problem in polynomial time. In Vis et al. (in press) an integer linear programming model has been presented, which can be used to determine the number of automated lifting vehicles required at a container terminal, if each job has to be transported within its time window. Both models of Vis et al. (2001, in press) provide the terminal management with a lower bound for the number of vehicles required beforehand the start of the unloading and loading of a ship. During the real operation the number of vehicles can still be adjusted to unexpected events. Koo et al. (2004) try to incorporate this adjustment in the number of vehicles in their model. The first step of their model consists of determining the lower bound on the fleet size at a container terminal. In phase two a tabu search algorithm is applied to route the vehicles such that all transportation jobs are finished in time. The number of vehicles is step wise increased by one until this time-constraint is satisfied. However, the added value of this second step need to be studied in more detail. Namely, the authors consider the terminal as a static environment in which all requests are known. It might be expected that not only the number of vehicles required need to be adjusted in practice, but also the constructed routes.

In stochastic cases the problem can be solved by using queueing networks. For example, Mantel and Landeweerd (1995) used a hierarchical queueing network approach to determine the number of AGVs. Tanchoco et al. (1987) also developed a queueing theory based model. It is an approximation model based on the steady state behaviour of the system. Compared to results obtained with simulation, the model underestimates the number of vehicles required. Wysk et al. (1987) also discuss queueing models for determining vehicle requirements.

The problem can also be studied with the use of simulation. Models of real systems are designed and experiments are performed with these models to gain an understanding of the behaviour of AGV systems. Gobal and Kasilingam (1991) and Kasilingam and Gobal (1996) present a simulation model that gives an estimation of the number of AGVs needed to meet material handling requirements. This estimate is based on the sum of the idle times of vehicles and machines and waiting times of the transported parts. An increase in the number of vehicles reduces the waiting times of parts and the idle times of machines. However, it results in an increase in the idle times of the vehicles. Newton (1985) shows how a continuous based simulation model can be used to calculate how many AGVs are needed.

Summarising, deterministic, stochastic and simulation models exist to determine AGV fleet sizes in different types of environments. Deterministic approaches, such as network flow models and (integer) linear programming models, can be used before hand the start of the real operation to estimate the number of vehicles required. Stochastic models, such as queueing networks, try to incorporate external influences. Most analytical models underestimate the number of vehicles required compared to simulation results. Some of the research already focused on large AGV systems. However, one of the main differences between manufacturing areas and transshipment and transportation areas are outside conditions, such as weather conditions. In which way do these conditions influence the results? The interface between AGV systems and other types of material handling equipment should also be studied. Namely, AGVs transport loads which are available at pick-up and delivery points of other material handling systems (e.g. automated storage and retrieval systems). The pick-up time of loads, which become available for transport, depends on the schedule of the loads at the other system. An interesting research question in this context is simultaneously determining vehicle requirements and scheduling of jobs at other material handling systems.

7. Control of AGVs

One of the main objectives of a control policy is to satisfy demands for transportation as fast as possible and without occurrence of conflicts among AGVs. Therefore, at least the following activities need to be performed by a controller of the system:

- dispatching of loads to AGVs,
- route selection,
- scheduling of AGVs,
- dispatching of AGVs to parking locations (i.e. locations where idle vehicles are positioned).

Firstly, a vehicle is dispatched to a new transportation demand. The selected vehicle is assigned a route and schedule for the transportation task, such that the transport can be executed without occurrence of deadlocks and collisions. If no new jobs are available, an AGV can be routed to a parking location to wait for a new transportation demand.

If all transportation demands with origin, destination, release time and transportation time are known in advance, *off-line control* of the system is possible. Transportation requests need to be perfectly predictable and information in the system needs to be accurate. Then all decisions on dispatching, routing and scheduling can be made in advance in off-line control systems. Otherwise, due to the stochastic nature of the transportation process, control systems capable of making real-time decisions are required. These so-called *on-line control systems* can be used *decentrally* and *centrally*. According to Müller (1983) AGVs can be controlled decentrally on board of the vehicles or from decentralised control systems located at several places in the system. Decentralised control can, in practice, be used at single path layouts and tandem configurations. Berman and Edan (2002) propose a complete control methodology for decentralised autonomous control of dynamic manufacturing AGV systems. Watanabe et al. (2001) use Q-learning to control AGVs decentrally. If a single control system simultaneously controls all AGVs in the system, we refer to centralised control. The central control system needs to frequently retrieve up-to-date information on the traffic situation at large numbers of points in the AGV network. Furthermore, in the control system a database is available with information on, for example, pick-up and delivery point of loads and vehicle positions. According to Bozer and Srinivasan (1989) the control systems used in practice are getting increasingly complicated and more expensive to be developed. The keep it simple principles in control systems are being replaced by smart systems which continuously monitor all vehicles and the status of the system.

The control problem can be associated with the flowpath networks discussed in Section 3. For example, Ebben et al. (2004a) study the problem of real-time one-way traffic control in underground automated transportation systems with large numbers of AGVs. Bidirectional underground tubes with alternating traffic are used to connect double tube systems with two unidirectional lanes for opposite traffic. In controlling the flows of traffic through the connecting tube, decisions concerning the traffic direction need to be made. The objective in constructing decision rules is to minimise average waiting times before entering the connecting tube. The decision rule based on dynamic programming with acceptable computation times, outperforms the other rules. Increases in performance between 10% and 25% can be obtained. Clearly, the complexity of the control problem varies per type of layout. The control of vehicles in a single loop without intersections is easier than the control of vehicles in large bidirectional networks (see also Section 3).

Dispatching, routing and scheduling decisions can be made simultaneously or separately. In Taghaboni and Tanchoco (1988) an intelligent control system has been developed to dispatch, route and schedule a fleet of free ranging AGVs in a non-conflicting way, based on real-time information. The vehicle chosen to perform a certain transportation task is the one which can satisfy demand in the shortest time. Furthermore, the route with the shortest travel time is selected. The vehicle is scheduled along this route in a way that no conflicts with other AGVs will occur. The control system can be used in bidirectional and unidirectional flowpaths. Wallace (2001) uses artificial intelligence to develop an AGV controller for large complex guidepaths. Agents are used as traffic managers which allow AGVs access to points and segments of the guidepath. Wijesoma et al. (2002) propose another intelligent control scheme for outdoor AGVs. Fuzzy logic control techniques are used to control an automated golf car. Basu et al. (1999) present an integrated approach to model all control aspects of goods and equipment at automated distribution centres.

Blazewicz et al. (1994) study the problem of integrating machines scheduling and AGV routing. In busy systems with frequent supply demands, AGVs need to supply materials at the right time and the right place. The authors consider a decentralised control system with two interconnected cycles. The authors propose a method to route the AGVs collision free through the system. Collisions are avoided by maintaining regular cycle flows of all vehicles at constant time distances. One might expect that more efficient methods exist. However, according to the authors this can only be achieved by implementing a centralised control system. A dynamic programming algorithm has been developed to check if the schedules ensure in time supplies. If no feasible schedules exist the objective is changed to minimising the maximum tardiness of each task. In this paper the integration of vehicle and machine scheduling is solved in two steps. In this approach the AGV system is inferior to the machines. It will be better to develop an efficient procedure to solve both problems simultaneously. This problem has been studied by Bilge and Ulusoy (1995), Ulusoy and Bilge (1993) and Ulusoy et al. (1997). Starting and completion times of operations for jobs at machines and of the transport of these jobs between workcentres are determined together with the assignment of jobs to vehicles. Genetic algorithms and iterative heuristics are used to generate machine schedules with completion times which are transformed into time-windows for each transport. The objective is to minimise the makespan. Ro and Kim (1990) developed on-line scheduling and control rules for AGVs and machines by simultaneously considering the performance measures makespan, mean flowtime, mean tardiness, maximum tardiness and system utilisation. Shah et al. (1997) developed a control model to integrate a production planning system such as material requirements planning (MRP) and an AGV system. The MRP system places orders which are retrieved by AGVs. AGVs are dispatched to orders such that overall due dates of orders are minimised. Soukhal et al. (2005) address the problem of integrating machine scheduling and transportation of finished products in a flexible manufacturing system (FMS). Despite their definition of an FMS the internal AGV system is not taken into account in the discussion on complexity.

In Evers and Koppers (1996) the traffic control of large numbers of AGVs has been studied. A formal tool to describe traffic infrastructure and its control has been developed by using four types of entities: node, track, area and semaphore (i.e. a non-negative integer variable which can be interpreted as free capacity). The tool has been evaluated with simulation. It can be concluded that the technique is a powerful tool for modelling transportation infrastructure and its control and that the performance and the capacity of the area increases.

Most of the literature, however, study one or two of the problems at the same time. In fact, to avoid deadlock situations in large AGV systems it might be advisable to extend research activities for the joint optimisation of dispatching, routing and scheduling problems. In the next sections dispatching, routing and scheduling and idle positioning decisions will be discussed in more detail.

7.1. Dispatching of AGVs

Dispatching refers to a rule used to select a vehicle to execute a transportation demand. This problem exists already as long as people or goods have to be transported from one destination to another by, for example, public transport systems, trucks, trains and airlines (see, for example, Bodin et al., 1983; Hane et al., 1995; Rexing et al., 2000). In this section we observe literature on the dispatching problem in AGV systems.

The dispatching problem can be observed from different points of view. Firstly, a load is available for transport and needs to be assigned to an idle AGV. Secondly, a vehicle becomes idle and need to be assigned to a new task. Consequently, the dispatching problem is divided into two categories, namely *workcentre initiated dispatching* and *vehicle initiated dispatching* rules (see Egbelu and Tanchoco, 1984). The problem is workcentre initiated if the vehicle has to be selected from a set of idle vehicles to transport a load. The problem is vehicle initiated if an idle AGV has to choose a load from a set of transportation requests.

In off-line control systems all data on transportation requests are available at the start of the transportation process. As a result, vehicles can be assigned to loads in an optimal way by formulating the dispatching problem as an assignment problem. The set of transportation requests and the set of vehicles form a complete bipartite graph with a weight (for example, transportation times) assigned to each arc. By applying the Hungarian method, the problem can be solved efficiently.

A simple heuristic used in on-line control systems is the *first-come-first-served rule*, which dispatches a free AGV to the load that requested transport at the earliest time. Bartholdi and Platzman (1989) present the *first-encountered-first-served rule*, which can be applied for decentralised on-line control for AGVs travelling in a single loop. The AGV with multiple loads continually travels in a single loop and picks up, if space is available on the vehicle, the first load it encounters. The load is unloaded at its destination. With simulation it has been shown that this heuristic outperforms other heuristics, like the first-come-first-served rule, if it is applied in a single loop.

According to Egbelu and Tanchoco (1984) the following heuristic rules can be applied in decentralised control systems for workcentre initiated dispatching:

- *random vehicle rule*: pick-up task is randomly assigned to any available vehicle regardless of the location of the vehicle and the load,
- *nearest vehicle rule*: the vehicle at the shortest distance of the load is assigned to the load,
- *farthest vehicle rule*: the vehicle at the greatest distance of the load is assigned to the new transportation request,
- *longest idle vehicle rule*: the vehicle that has remained idle for the longest time among all idle vehicles is dispatched to the load,
- *least utilised vehicle rule*: the vehicle with the minimum mean utilisation is assigned to the new job.

These last two rules contribute to balance the workload among all AGVs in the system. Dispatching rules for vehicles to choose a load from transportation requests are also discussed in Egbelu and Tanchoco (1984). Some of these assignment rules for the vehicle initiated dispatching problem are:

- *random workcentre rule*: a workcentre with a transportation requests is randomly chosen and the vehicle is dispatched to the load at this workcentre,
- *shortest travel times/distance rule*: the vehicle is dispatched to the workcentre closest by. The objective of this rule is to minimise empty travel times of vehicles,
- *maximum outgoing queue size rule*: the vehicle is dispatched to the centre with the largest number of loads awaiting transport,
- *modified first-come-first-served rule*: vehicles are assigned to centres, in chronological order to their time of request for transport. A workcentre can have only one request at this list at a time.

With simulation Egbelu and Tanchoco (1984) tested the performance of some of these rules. It has been shown that rules based on distance measures had some drawbacks if layout conditions are not met.

Another modification of the *first-come-first-served rule* has been given in Srinivasan et al. (1994). An empty AGV first inspects if loads are available for transport at the station the AGV just delivered its previous job. If one or more loads are available for transport, the AGV starts transporting the first in line at this station. Otherwise, the AGV is dispatched to the oldest unassigned request in the system. With this rule an attempt is made to reduce unnecessary empty travel times of AGVs by, if possible, dispatching the AGV to a load at its destination. Furthermore, it has been tried to distribute workload evenly over all AGVs. With empirical results it has been shown that the performance of this rule is nearly as good as the performance of the shortest-travel-time-first rule. Yamashita (2001) proposed two variations on first-come-first-served policies. These policies dispatch empty vehicles such that variations in waiting times of the various pick-up and delivery points are minimised. Hodgson et al. (1987) model an AGV system as a Markov decision process. Dispatching policies resulting from the semi-Markov decision model have been described and have been tested for single load and dual load vehicles. Kim et al. (1999) proposed an AGV dispatching procedure based on the objective to balance workload in the system. A dispatching rule with self-adaptive capability has been introduced in Kim and Hwang (1999). A knowledge-based system for selecting an AGV and selecting a workcentre from a set of workcentres requesting transport simultaneously is presented in Kodali (1997). Yim and Linn (1993) test the performance of various heuristics with petri net models. Bozer and Yen (1996) presented dispatching rules which take advantage of information available in centrally controlled systems. Tan and Tang (2001) used fuzzy logic to dispatch AGVs in a manufacturing environment. Concepts of the Taguchi method have been used to determine an optimal set of weights for various decision criteria. Aytug et al. (2003) investigated interactions between dispatching rules and deadlock avoidance policies. Jeong and Randhawa (2001) developed a multi-attribute dispatching rule which considers three criteria simultaneously. These criteria are the unloaded travel distance of an AGV to the pick-up point, the remaining space in the input buffer of a delivery point and the remaining space in the outgoing buffer of a pick-up point. A neural network approach has been used to assign weights to each of the criteria based on the current status of the system. These weights are continuously changing in the multi-attribute rule. It has been shown that this rule performs better than single attribute rules and a multi-attribute rule with fixed weights, from the perspective of various performance measures such as block time of an AGV. Hall et al. (2001b) consider a manufacturing system with AGVs travelling in unidirectional loops. The authors analysed three widely used dispatching policies. They developed a genetic algorithm to sequence jobs on machines in relation to the dispatching policies of AGVs, while minimising cycle times.

In contrast to vehicle dispatching in manufacturing areas not much attention has been paid to dispatching AGVs in the new areas of application. Van der Heijden et al. (2002b) developed and tested dispatching policies for empty AGVs at underground AGV systems. It has been shown that intelligent rules using information on future orders give considerable advantages above simple rules from perspective of filling rates of AGVs. In Kim and Bae (1999) mixed integer linear programming formulations and a heuristic method have been given for dispatching containers to AGVs such that the delay of the ship and the total travel time of the AGVs is minimised. In Chen et al. (1998) a greedy dispatching rule has been given that assigns AGVs to containers. Bish et al. (2001) observed an extension of this problem, namely the dispatching of vehicles to containers in combination with the assignment of containers to locations in the storage area. Grunow et al. (2004) study the dispatching of multi-load AGVs in container terminals. In contrast to single load vehicles a multi-load vehicle can still be partially available to load another container if one of its positions is free. This results in a new decision which can be made in the assignment procedure, namely how to insert a new request in the already scheduled route. A mixed integer linear programming model has been formulated to dispatch multi-load AGVS such that the lateness of AGVs is minimised. Furthermore, the authors proposed a new heuristic based on a myopic priority rule. The optimal approach outperforms the heuristic in terms of AGV lateness. However, the optimal approach only considers a finite planning horizon. Furthermore, the authors showed that the heuristic, in contrast to the optimal approach, can efficiently be applied to real-life container terminals with large numbers of AGVs and high workloads for the AGV system. Van der Meer (2000) discussed how some of the previously described vehicle dispatching rules behave in such environments as distribution centres and container terminals. It has been shown that vehicle initiated rules are outperformed by load initiated rules in these kinds of environments. De Koster et al. (2004) extend this research by evaluating the performance of several real-time vehicle dispatching rules in three different environments, namely an European distribution centre, a container terminal and a production site. The authors showed that pre-arrival information of loads leads to a significant improvement in performance. However, also with the availability of pre-arrival information simple rules based on load and vehicle proximity perform best for all cases. Kim and Bae (2004) also recognised the importance of pre-arrival information on location and time. They try to synchronise the dispatching of AGVs and ship operations. A mixed integer programming model has been given to model the problem. To overcome the problem of large computation times in dynamic environments in real-life, they also propose a look ahead heuristic. They draw the same conclusion as De Koster et al. (2004), namely that look ahead heuristics perform better than the conventional dispatching rules.

Summarising, in the area of manufacturing numerous research has been executed on the dispatching of vehicles to jobs. The solution methods vary from simple dispatching heuristic rules, Markov decision processes, to fuzzy logic and neural network approaches. Whereas it can be concluded that these new concepts hardly outperform traditional heuristic rules and their modifications. The dispatching of AGVs in distribution, transshipment and transportation systems is less explored. Well known dispatching rules from manufacturing applications are applied to the new areas of application. However, for real-life systems with large numbers of AGVs more research for advanced heuristics or optimal approaches is required. In this context the following aspects are of utmost importance: low computation times for large systems with high workloads, interface with other vehicles to avoid congestion, deadlocks and delays, infinite or rolling planning horizons, and a small gap between optimal solutions and solutions of heuristics. In the new areas of application the interface with the other types of equipment, such as storage and (un)loading equipment is very important. Hardly any attention has been paid in literature to the simultaneous dispatching of multiple types of material handling equipment. In integral dispatching of vehicles and other types of equipment in large AGV systems, side constraints are very important. One could think of capacity restrictions at the transfer buffer from storage equipment to AGVs or priority of one type of equipment above another one.

7.2. Routing and scheduling of AGVs

If the dispatching decision is made, a route and schedule should be planned for the AGV to transport the job from its origin to its destination over the AGV network. A route indicates the path which should be taken by the AGV when making a pick-up or delivery. The related schedule gives arrival and departure times of the AGV at each segment, pick-up and delivery point and intersection during the route to ensure collision free routing. The selection of a certain route and schedule influences the performance of the system. The longer it takes to transport a job, the fewer the jobs that can be handled within a certain time. Therefore, one of the objectives of the routing of AGVs is to minimise transportation times of loads. Algorithms have to be developed to solve the routing problem. Two categories of algorithms can be distinguished, namely *static* and *dynamic* algorithms. With static algorithms the route from node i to node j is determined in advance and is always used if a load has to be transported from i to j. In this way, a simple assumption is to choose the route with the shortest distance from i to j. However, these static algorithms are not able to adapt to changes in the system and traffic conditions.

In dynamic routing, the routing decision is made based on real-time information and, as a result, various routes between i and j can be chosen.

Static routing problems in AGV systems are related to *vehicle routing problems* (VRP) studied in transportation literature. In the vehicle routing problem a set of n clients with known demands need to be served by a fleet of m vehicles with limited capacity. The vehicles are all housed at one depot. The route of each vehicle starts and ends at this depot. m least costs (length) routes have to be planned such that each customer is served exactly once and that the total demand of the customers served by each vehicle does not exceed the capacity of each vehicle. The objective is to minimise the total distance of all m routes under previously mentioned conditions. This is an NP-hard problem to solve. The vehicle routing problem has been studied extensively in literature. Bodin et al. (1983), Laporte (1992) and Fisher (1995) provided an overview of literature in this area. A more recent paper observing this problem is from Kelly and Xu (1999). They proposed a set partitioning based heuristic. In a systematic way fragments of routes are combined to obtain high-quality solutions. *Vehicle scheduling problems* can be seen as routing problems with additional constraints concerning times at which certain activities (e.g. delivery of a load) have to be executed. Vehicle activities have to be sequenced both in time and space. An overview of methods to solve vehicle scheduling problems has been given in Bodin et al. (1983). Genetic algorithms can also be used to solve vehicle scheduling problems (see, for example, Baita et al., 2000).

The *vehicle routing problem with time windows* (VRPTW) is a generalisation of the vehicle routing problem. For each customer a time window is defined. The time window $[s,t]$ restricts the service time of the customer to fall into the time interval from s to t. Such time-windows arise, for example, due to traffic restrictions or fixed time schedules of customers and their products. Finding a feasible solution to the vehicle routing problem with time windows is an NP-complete problem. Numerous studies on the vehicle routing problem with time windows have been executed.

Branch and bound methods (Kolen et al., 1987), insertion heuristics (Solomon, 1987), extensions of vehicle routing problem heuristics (Solomon et al., 1988), Lagrangian relaxation (Fisher et al., 1997; Kohl and Madsen, 1997), constrained shortest path relaxation (Desrochers et al., 1992; Kohl et al., 1999) and set covering formulations (Bramel and Simchi-Levi, 1997) can be used to find solutions to the problem. Desrochers et al. (1988) provide an overview of solution methods. More recently, Cordeau et al. (2002) present a survey of approximation and optimal approaches to solve the vehicle routing problem with time windows. The methods of Desrochers et al. (1992) and Fisher et al. (1997) are capable of solving the problem to optimality for a problem size with 100 customers. Kohl et al. (1999) even solve a problem with 150 customers by using a strong valid inequality, the 2-path cut, to produce better lower bounds and by using an effective separation algorithm. Due to the difficulty of the problem, solving larger problems in reasonable times is difficult.

Dynamic vehicle routing problems are also studied in transportation literature. Multiple demands for service envolving in a real-time way have to be satisfied by vehicles. Psaraftis (1988) indicates the differences between static and dynamic vehicle routing. Gendreau et al. (1999) propose a parallel tabu search method for real-time vehicle routing and dispatching. According to Savelsbergh and Sol (1998) the dynamic routing of independent vehicles can be solved by applying a branch and price algorithm. Gans and Van Ryzin (1999) represent the problem as a classical set covering model. Performance is measured in terms of congestion.

A generalisation of the vehicle routing problem with time windows is the *pick-up and delivery problem with time windows* (PDPTW). Optimal routes have to be constructed such that transportation requests requiring pick-up and delivery are met. The VRPTW is a special case of the PDPTW, in which all destinations are the same depot. Dumas et al. (1991) present an algorithm using column generation to solve the problem. Overviews of literature in this area have been given in Solomon and Desrosiers (1988) and Savelsbergh and Sol (1995).

A special version of the pick-up and delivery problem and a combination of a vehicle routing and a vehicle scheduling problem is the *dial-a-ride problem*. This kind of problem is concerned with dynamic routing of vehicles and real-time response to customers. Each customer should be served within a time-window and penalty functions are used to minimise waiting times of customers.

Analogies between these problems from transportation literature and routing and scheduling problems for AGVs in automated guided vehicle systems are clear. A number of loads at various locations have to be transported by vehicles at a certain start time or at a certain moment within a time window. However, the use of the described models from transportation literature is not always possible. These models do not take into account congestion in the system. Furthermore, most models are not developed to deal with real time response to dynamically changing transportation requests. Therefore, attention is paid in the literature to developing *non-conflicting routes* for AGVs. With a non-conflicting route, an AGV arrives as early as possible at the destination without conflicting with other AGVs. Krishnamurthy et al. (1993) observe a static routing problem in which AGVs have to be routed on a bidirectional network in a conflict-free way such that the makespan is minimised. The problem is solved by applying column generation. Kim and Tanchoco (1991) also discuss the problem of finding conflict free routes in a bidirectional network. The algorithm they propose, is based on the shortest path methods of Dijkstra.

According to Taghaboni-Dutta and Tanchoco (1995) dynamic route planning can be done in two ways, namely *complete route planning* and *incremental route planning*. With complete route planning the entire route from origin to the final destination is determined at once. With incremental route planning, the route is planned segment for segment until the vehicle reaches its destination. The disadvantage of complete route planning is that a route may become invalid during operation due to unexpected events. However, with applying incremental route planning, the optimality of the complete route is disregarded. Taghaboni-Dutta and Tanchoco (1995) give a dynamic approach to incremental route planning. The traffic control is estimated by modelling the guidepath as a queueing network. Oboth et al. (1999) discuss the problem of dynamic conflict routing of AGVs in bidirectional networks. The solution methodologies from Krishnamurthy et al. (1993) are implemented in a dynamic environment. By also using petri nets, conflict free routes can be determined (see Zeng et al., 1991). Seifert et al. (1998) introduce a dynamic vehicle routing strategy based on hierarchical simulation. At each time a route decision has to be made, simulations are performed to evaluate a set of possible routes. The route with the smallest estimated travel time is chosen. Rajotia et al. (1998c) add time windows to nodes to represent arrival and departure times of the vehicle which is going to occupy the node. Other vehicles are allowed to travel through the specific node at a time point not included in one of the time windows. Furthermore, the direction on an arc for an arriving vehicle is indicated with a time window. Dijkstra's algorithm is applied on this network with time windows to find the least congested and fastest routes for AGVs. Qiu and Hsu (2001) present an algorithm to route large numbers of AGVs conflict-free over a bidirectional guidepath while minimising travel times. Singh and Tiwari (2002) present an intelligent agent framework to find a conflict-free shortest-time path for an AGV travelling in a bi- or unidirectional network.

Except for finding conflict free routes, attention should be paid to the presence of interruptions in the system. Interruptions might occur due to, for example, vehicle breakdowns, objects on AGV paths and manual intervention. As a result of interruptions, AGVs may be blocked and routes cannot be finished. Therefore, if an AGV encounters an interruption it has to be rerouted in such a way that no conflicts with other AGVs occur. Narasimhan et al. (1999) use simulation to analyse rerouting of AGVs. Failure management is also discussed in Section 8.2.

Literature on intelligent routing of AGVs includes Dhouib and Kadi (1994), Soylu et al. (2000) and Wu et al. (1999). Levitin and Abezgaouz (2003) study the routing of multiple load AGVs. Han and McGinnis (1989) and Bookbinder and Krik (1997) present heuristics for routing vehicles. Analytical algorithms are presented in Blair et al. (1987) and Chen (1996).

Gaur et al. (2003) study the problem of scheduling an AGV in a flexible manufacturing system while minimising completion times. A vehicle needs to visit each site only after its release time and before its due time. Sabuncuoglu (1998) uses simulation to test various AGV scheduling rules. Bing (1998), Veeravalli et al. (2002) and Zaremba et al. (1997) propose analytical models for the scheduling of AGVs. Sinriech and Palni (1998) develop an optimal scheduling algorithm for a single multiple-load vehicle travelling in a closed loop during a finite planning horizon. The arrival time and processing time of each job are known. Sinriech and Kotlarski (2002) extend this algorithm such that it can be used to schedule dynamically multiple-load vehicles in a single loop while minimising transfer times of jobs and the number of loops travelled by the vehicle. Due to the dynamic nature of the algorithm, changes in the scheduling plan can be made to react to unexpected events. It has been shown that this dynamic algorithm outperforms existing commonly used non-dynamic scheduling rules from a perspective of cycle times and work in progress. Hartmann (2004) introduces a general model for scheduling of material handling equipment at container terminals such that the average lateness of a job and the average set up time are minimised. The model is, in contrast to other literature, not applicable for a single type of equipment, but it can be used for various types of equipment, such as AGVs and straddle carriers.

The literature discussed so far on scheduling of AGVs hardly considers (side) constraints such as capacity constraints of the machines where transportation jobs become available, schedules of other types of equipment and limited parking space for vehicles. These side constraints become more and more important in real life situations with large AGV systems. To take these constraints into account more attention should be paid to integrated scheduling of different types of material handling equipment, which also meet space and capacity requirements.

Meersmans (2002) gives mathematical models for the integrated scheduling of automated handling equipment at container terminals, such as AGVs and automated stacking cranes. Exact and heuristic algorithms are presented to solve these models. To test the performance of these algorithms computational studies are performed. Meersmans and Wagelmans (2001) propose a model that deals with the integrated scheduling of all types of material handling equipments at an automated container terminal. The objective is to optimise the overall performance of the container terminal, by minimising the makespan of the schedule. A branch and bound algorithm is proposed which produces optimal or near optimal schedules. For large problems a beam search heuristic is presented. It has been shown that with the heuristic solutions, close to optimal solutions can be obtained in reasonable computation times. Both the integrated approach of Meersmans (2002) and Meersmans and Wagelmans (2001) do not take into account that there is a limited space for AGVs waiting to be (un)loaded at the cranes. Ebben et al. (2004b) present a generic approach to model integrated scheduling problems with a finite horizon such that capacity, parking space and release time constraints are met. The main decision within the model concerns when and how to transport all jobs from their origins to their destinations. The output of the model includes an assignment of orders to vehicles, a route for each vehicle and an assignment of vehicles to parking areas. Clearly, in this solution routing and scheduling aspects are combined. A constructive heuristic is presented which transforms sequences resulting from an (infeasible) solution to better and feasible solutions. Both the model and heuristic are applied for an automated underground transportation system. It has been shown that computation times are small.

Summarising, in the context of manufacturing areas, static and dynamic algorithms have been developed to solve the routing of vehicles. Network models, queueing networks, simulation and intelligent routing techniques are used to route AGVs conflict free through the network. The routing of AGVs through distribution, transshipment and transportation systems is hardly studied. From the literature discussed above, we conclude that scheduling and routing issues are often studied separately. The integration of scheduling and routing aspects however forms a challenging problem. Ebben et al. (2004b) propose a first heuristic. However, more research on integration of scheduling and routing problems is required. Furthermore, more attention should be paid to the simultaneous scheduling of different types of material handling equipment in large AGV systems. Incorporating capacity, space and time constraints in models becomes more and more important with the introduction of large AGV systems. New approaches for rolling and infinite time horizons should also be developed.

7.3. Positioning of idle vehicles

An AGV becomes idle if it has delivered a job at its destination and it is not immediately assigned to a new job. One of the decisions to make is where to locate idle AGVs such that they can react as efficiently as possible to a new assignment. The locations where an idle vehicle can park are indicated with various names such as parking locations, dwell points or depots. Once an assignment of a parking location is made to an AGV, the trip to this location usually may not be interrupted by a new assignment. As a result, the idle AGV can only travel to the pick-up point of the new job, if it has reached the parking location. A related research area is the problem of determining a dwell-point for an idle AS/RS.

To reduce waiting times of loads for transport, AGVs need to respond as quickly as possible to a new assignment. Therefore, the location of idle vehicles should be chosen well. Some criteria used in selecting a parking location are (Egbelu, 1993b):

- minimisation of the maximum response time of the vehicle to travel empty from the parking location to the pick-up point of the load,
- minimisation of the average vehicle response time,
- even distribution of idle of vehicles over the network.

According to Egbelu (1993b) the following rules are mostly used for positioning idle vehicles:

- central zone positioning rule,
- circulatory loop positioning rule,
- point of release positioning rule.

With a *central zone positioning rule* central parking areas are designated for buffering idle vehicles. Empty vehicles are routed to these areas regardless of their current destination. With a *circulatory loop positioning rule*, one or more loops of the flowpath network are used as loops for positioning idle vehicles. AGVs travel on these loops until an assignment to a new job is made. Finally, with the *point of release positioning rule*, AGVs remain at the point where they are unloaded and the new assignment is received. However, by applying this rule, it might occur that one AGV blocks other AGVs on the same path.

Egbelu (1993b) was one of the first in literature to study the problem of positioning an idle AGV in a loop layout. By minimising the maximum response time, how to determine parking locations for m AGVs in both unidirectional and bidirectional loop layouts with n pick-up points can be studied. If one AGV is used, the problem can be solved in polynomial time. For more than one AGV the problem for unidirectional layouts can be formulated as an integer non-linear programming model. Further, the problem for the bidirectional layout can be solved by applying heuristics.

Gademann and Van de Velde (2000), however, prove that the problems of minimising maximum and average response time in unidirectional loop layouts can be solved in polynomial time for a fixed number of m AGVs. If it is assumed that AGVs travel at constant speed, even the problem of determining parking locations in a bidirectional loop layout with m AGV can be solved in polynomial time.

In Kim (1995) and Kim and Kim (1997) a static positioning strategy is proposed. In such a strategy, the location of a parking area is not changed. This version of the problem with one vehicle can be solved in polynomial time, by modelling it as a discrete time stationary Markov chain.

Lee and Ventura (2001) develop a dynamic programming algorithm to determine dwell points for AGVs in uni- and bidirectional loop layouts while minimising mean weighted response times. Ventura and Lee (2001) show that this algorithm can also be used in a tandem loop layout with multiple vehicles.

A dynamic positioning strategy for m vehicles in which a new positioning location is assigned to each vehicle that becomes idle, is introduced by Kim (1995). The author also considers unidirectional and bidirectional single loop layouts. The objective is to minimise mean response time. The case in which already $m-1$ AGVs have been located can be solved in polynomial time.

Chang and Egbelu (1996) observe the problem of determining parking locations under the assumption that the number of loads to be picked up dynamically changes over time. Location models are presented based on the objective to minimise expected response times. Simulation studies indicate that, by applying these location models, the response times can be improved. Lu and Gerchak (1998) indicate that delays occur if the AGV has to travel all its way to the parking location and new jobs are already assigned to it. Therefore, they propose an analytical model to choose an optimal anticipatory destination of an idle vehicle based on the location where it became idle and parameters of the system. However, their approach is only applicable for one-dimensional AGV systems.

At a certain time, idle vehicles at a parking area or loop have to perform a new job. Consequently, new loads that have to be transported, have to be assigned to an idle vehicle. A question that arises is, for example, which idle vehicle should transport which job? Dispatching rules in this context are discussed in Section 7.1.

Summarising, analytical approaches, such as dynamic programming and Markov chains, have been used to position idle AGVs in various layouts in manufacturing areas. For a fixed number of AGVs the problem can be solved to optimality in polynomial time. Within large AGV systems, AGVs need to travel large distances before they reach a parking location. For these types of systems it is of great importance that an AGV can be disturbed in its route to a parking area and can be rerouted to a new job. New efficient algorithms should be developed to deal with these dynamic aspects.

8. Technological aspects

In modelling AGVs systems two specific characteristics of automated systems need to be taken into account. Driverless vehicles usually use batteries, which need to be charged or changed. The time required to perform these operations might impact the performance of the system. Section 8.1 discusses battery management in more detail. In section 8.2 we discuss another aspect impacting the performance of AGV systems, namely failures of the AGVs.

8.1. Battery management

If AGVs use batteries, frequent battery changing might be required. McHaney (1995) presents an overview of AGV battery technology. The time required for replacing or charging batteries can impact the number of vehicles required. Simulation results from McHaney (1995) indicate a significant increase in the number of AGVs required while incorporating battery management issues in the simulation study compared to neglecting these issues in the studies. Furthermore, the time required for charging batteries impacts throughput, congestion and costs.

In most manufacturing and distribution areas AGVs travel over relatively short distances and during idle times batteries can be replaced or charged. However, in manufacturing systems with non-predictable AGV routes and at container terminals and transportation systems AGVs need to travel long distances and, as a result, have short idle times. McHaney (1995) is right in arguing that battery usage is frequently omitted in AGV research. The author provides the reader with guidelines when to incorporate battery management issues in simulation studies. He indicates that it might not be necessary to incorporate these issues for systems with off-shift times for AGVs, low utilisation of AGVs (less than 50%) and on-line charging systems. Ebben (2001) develops control rules to take battery constraints into account in an underground transportation system with large numbers of AGVs. With simulation, the author compares the performance and costs for systems in which batteries are charged during travelling and systems in which batteries are replaced.

We conclude that battery management is hardly addressed in AGV research. However, according to the results of McHaney (1995) the performance of AGV systems with high utilisation and hardly any off shift times, is influenced by incorporating battery management. These characteristics belong especially to AGV systems in transportation and transshipment areas. Thus, in future research for large AGV systems, it is of great importance to incorporate battery management decisions. These decisions should be integrated with decisions on routing, scheduling and dispatching of full and empty AGVs.

8.2. Equipment failures

In most literature the impact of equipment failures on the system is neglected. If only few AGVs are used, failures will have little effect on the occurrence of congestion in the system and, as a result, on the performance of the system. In contrast to manufacturing areas large numbers of AGVs are used at container terminals and outdoor transport systems. For these systems failures may occur more often. These failures might cause congestion and deadlocks in the system. Ebben (2001) developed control methods to deal with failures of full and empty AGVs in underground transportation systems.

Hardly any literature has been found on this subject. In research more attention should be paid to the relationship between control of AGVs and the occurrence of failures to ensure a high reliability of the AGV system.

9. Conclusions

Research on AGV systems is entering a new phase with the increased usage of large numbers of AGVs in new areas of application. AGVs are currently used for repeating transportation tasks in distribution, transshipment and (external) transportation areas. The most important differences between the usage of AGVs in manufacturing areas and in these new environments can be noticed in the number of AGVs used, their utilisation, the number of transportation tasks, distances to be travelled, the number of pick-up and delivery points, amount of congestion, spatial dimensions and operational conditions.

From the literature survey we can conclude that most of the literature address design and control problems at manufacturing systems. Almost all papers address one or two decision problems at the same time. Furthermore, hardly any attention has been paid to the relationship between AGV systems and other material handling systems.

Both analytical approaches and simulation are used to solve decision problems. Mathematical programming, queueing theory, network models and Markov decision processes have been used to solve relatively small problems to optimality. Heuristics are proposed to overcome high computation times and NP completeness problems. Some of these techniques already proved to be successful in large AGV systems. Furthermore, some new solution approaches have been introduced for large AGV systems which are capable of handling large numbers of AGVs efficiently. However, most design and control problems in large AGV systems in these new areas of application require further research:

- Can existing models (with small modifications) for manufacturing systems, directly be used for AGV systems at container terminals, warehouses and (underground) transportation systems?
- Analytical and simulation models which simultaneously address multiple design and control problems.
- Analytical and simulation models which consider the joint optimisation of design problems at AGV systems and design problems of other material handling systems.
- Do we need to develop new types of flowpath layouts for large AGV systems with high travel distances and large numbers of AGVs, transportation requests and pick-up and delivery points?
- Efficient analytical models for traffic management in AGV systems with large numbers of AGVs, zones and buffer areas with capacity constraints.

- Research on location decisions for pick-up and delivery points in AGV systems with large numbers of AGVs, such that bottlenecks are avoided and waiting times of loads are reduced.
- Research on influence of outside conditions, such as weather conditions, on design issues (e.g. minimum vehicle fleet size).
- Models for joint optimisation of dispatching, scheduling and routing problems.
- Development of advanced heuristics for dispatching of AGVs in large AGV systems which ensure low computation times, avoidance of congestion, deadlocks and delays and infinite or rolling planning horizons.
- Dynamic approaches for parking decisions of idle vehicles which need to travel large distances, such that AGVs can easily be rerouted to a new job.
- Models which incorporate battery management decisions and equipment failures in design and control problems.

References

Afentakis, P., 1989. A loop layout design problem for flexible manufacturing systems. International Journal of Flexible Manufacturing Systems 1, 175–196.

Aiello, G., Enea, M., Galante, G., 2002. An integrated approach to the facilities and material handling system design. International Journal of Production Research 40 (15), 4007–4017.

Asef-Vaziri, A., Dessouky, M., Sriskandarajah, C., 2001. A loop material flow system design for automated guided vehicles. International Journal of Flexible Manufacturing Systems 13 (1), 33–48.

Asef-Vaziri, A., Laporte, G., Sriskandarajah, C., 2000. The block layout shortest loop design problem. IIE Transactions 32, 727–734.

Aytug, H., Barua, A., Lawley, M., Uzsoy, R., 2003. Observations on the interactions among deadlock avoidance policies and dispatching rules in automated manufacturing systems. International Journal of Production Research 41 (1), 81–95.

Baita, F., Pesenti, R., Ukovich, W., Favaretto, D., 2000. A comparison of different solution approaches to the vehicle scheduling problem in a practical case. Computers and Operations Research 27, 1249–1269.

Barad, M., Sinriech, D., 1998. A petri net model for the operational design and analysis of segmented flow topology (SFT) AGV systems. International Journal of Production Research 36 (5), 1401–1425.

Bartholdi, J.J., Platzman, L.K., 1989. Decentralized control of automated guided vehicles on a simple loop. IIE Transactions 21 (1), 76–81.

Basu, S., Dutta, S.P., North, W.P.T., 1999. A process modelling framework for AGV control. International Journal of Production Research 37 (16), 3671–3696.

Berman, S., Edan, Y., 2002. Decentralized autonomous AGV system for material handling. International Journal of Production Research 40 (15), 3995–4006.

Bilge, Ü., Ulusoy, G., 1995. A time window approach to simultaneous scheduling of machines and material handling system in an FMS. Operations Research 43 (6), 1058–1070.

Bing, W.X., 1998. The application of analytic process of resource in an AGV scheduling. Computers and Industrial Engineering 35 (1–2), 169–172.

Bish, E.K., Leong, T.Y., Li, C.L., Cheong Ng, J.W., Simchi-Levi, D., 2001. Analysis of a new vehicle scheduling and location problem. Naval Research Logistics 48, 363–385.

Blair, E.L., Charnsethikul, P., Vasques, A., 1987. Optimal routing of driverless vehicles in a flexible material handling system. Material Flow 4, 73–83.

Blazewicz, J., Burkard, R.E., Finke, G., Woeginger, G.J., 1994. Vehicle scheduling in two-cycle flexible manufacturing systems. Mathematical and Computer Modelling 20 (2), 19–31.

Bodin, L.D., Golden, B.L., Assad, A.A., Ball, M.O., 1983. Routing and scheduling of vehicles and crews: The state of the art. Computers and Operations Research 10 (2), 63–211.

Bookbinder, J.H., Krik, M.D., 1997. Lane selection in an AGV-based asynchronous parallel assembly line. Computers and Industrial Engineering 32 (4), 927–938.

Bozer, Y.A., Cho, M.S., Srinivasan, M.M., 1994. Expected waiting times in single-device trip-based material handling systems. European Journal of Operational Research 75, 200–216.

Bozer, Y.A., Rim, S.C., 1996. A branch and bound method for solving the bidirectional circular layout problem. Applied Mathematical Modelling 20, 342–351.

Bozer, Y.A., Srinivasan, M.M., 1989. Tanden configurations for AGV systems offer simplicity and flexibility. Industrial Engineering 21 (2), 23–27.

Bozer, Y.A., Srinivasan, M.M., 1991. Tandem configurations for automated guided vehicle systems and the analysis of single vehicle loops. IIE Transactions 23 (1), 72–82.

Bozer, Y.A., Srinivasan, M.M., 1992. Tandem AGV systems: A partitioning algorithm and performance comparison with conventional AGV systems. European Journal of Operational Research 63, 173–191.

Bozer, Y.A., Yen, C.K., 1996. Intelligent dispatching rules for trip-based material handling systems. Journal of Manufacturing Systems 15 (4), 226–239.

Bramel, J., Simchi-Levi, D., 1997. On the effectiveness of set covering formulations for the vehicle routing problem with time windows. Operations Research 45 (2), 295–301.

Castillo, I., Reyes, S.A., Peters, B.A., 2001. Modeling and analysis of tandem AGV Systems using generalized stochastic petri nets. Journal of Manufacturing Systems 20 (4), 236–249.

Chang, S.H., Egbelu, P.J., 1996. Dynamic relative positioning of AGVs in a loop layout to minimize mean system response time. International Journal of Production Research 34 (6), 1655–1673.

Chen, M., 1996. A mathematical programming model for AGVs planning and control in manufacturing systems. Computers and Industrial Engineering 30 (4), 647–658.

Chen, Y., Leong, Y.T., Cheong Ng, J.W., Demir, E.K., Nelson, B.L., Simchi-Levi, D., 1998. Dispatching automated guided vehicles in a mega container terminal. Paper presented at INFORMS Montreal 1998, Canada.

Co, G.C., Tanchoco, J.M.A., 1991. A review of research on AGVs vehicle management. Engineering Costs and Production Economics 21, 35–42.

Cordeau, J.-F., Desaulniers, G., Desrosiers, J., Solomon, M.M., Soumis, F., 2002. VRP with time windows. In: Toth, P., Vigo, D. (Eds.), The Vehicle Routing Problem. SIAM Monographs on Discrete Mathematics and Applications, pp. 157–193.

De Guzman, M.C., Prabhu, N., Tanchoco, J.M.A., 1997. Complexity of the AGV shortest path and single-loop guide path layout problems. International Journal of Production Research 35 (8), 2083–2092.

De Koster, R.B.M., Le-Anh, T., Van der Meer, J.R., 2004. Testing and classifying vehicle dispatching rules in three real-world settings. Journal of Operations Management 22, 369–386.

Dell'Amico, M., Fischetti, M., Toth, P., 1993. Heuristic algorithms for the multiple depot vehicle scheduling problem. Management Science 39 (1), 115–125.

Desrochers, M., Desrosiers, J., Solomon, M., 1992. A new optimization algorithm for the vehicle routing problem with time windows. Operations Research 40 (2), 342–354.

Desrochers, M., Lenstra, J.K., Savelsbergh, M.W.P., Soumis, F., 1988. Vehicle routing with time windows: Optimization and approximation. In: Golden, B.L., Assad, A.A. (Eds.), Vehicle Routing: Methods and Studies. Studies in Management Science and Systems, pp. 65–84.

Dhouib, K., Kadi, D.A., 1994. Expert system for AGV managing in bidirectional networks: KADS methodology based approach. International Journal of Production Economics 33, 31–43.

Dumas, Y., Desrosiers, J., Soumis, F., 1991. The pickup and delivery problem with time windows. European Journal of Operational Research 54, 7–22.

Ebben, M., 2001. Logistic control in automated transportation networks. Beta Ph.D. thesis series D-40, Twente University Press, Enschede, The Netherlands.

Ebben, M., Van der Zee, D.J., Van der Heijden, M., 2004a. Dynamic one-way traffic control in automated transportation systems. Transportation Research Part B 38, 441–458.

Ebben, M., Van der Heijden, M., Hurink, J., Schutten, M., 2004b. Modeling of capacitated transportation systems for integral scheduling. OR Spectrum 26, 263–282.

Egbelu, P.J., 1987. The use of non-simulation approaches in estimating vehicle requirements in an automated guided vehicle based transport system. Material Flow 4, 17–32.

Egbelu, P.J., 1993a. Concurrent specification of unit load sizes and automated guided vehicle fleet size in manufacturing system. International Journal of Production Economics 29, 49–64.

Egbelu, P.J., 1993b. Positioning of automated guided vehicles in a loop layout to improve response time. European Journal of Operational Research 71, 32–44.

Egbelu, P.J., Tanchoco, J.M.A., 1984. Characterization of automatic guided vehicle dispatching rules. International Journal of Production Research 22 (3), 359–374.

Egbelu, P.J., Tanchoco, J.M.A., 1986. Potentials for bi-directional guide-path for automated guided vehicle based systems. International Journal of Production Research 24 (5), 1075–1097.

Evers, J.J.M., Koppers, S.A.J., 1996. Automated guided vehicle traffic control at a container terminal. Transportation Research A 30 (1), 21–34.

Fanti, M.P., 2002. Event-based controller to avoid deadlock and collisions in zone-control AGVS. International Journal of Production Research 40 (6), 1453–1478.

Faraji, M., Batta, R., 1994. Forming cells to eliminate vehicle interference and system locking in an AGVS. International Journal of Production Research 32 (9), 2219–2241.

Farling, B.E., Mosier, C.T., Mahmoodi, F., 2001. Analysis of automated guided vehicle configuration in flexible manufacturing systems. International Journal of Production Research 39 (18), 4239–4260.

Fisher, M., 1995. Vehicle routing. In: Ball, M.O., Magnanti, C.L., Monma, C.L., Nemhauser, G.L. (Eds.), Network Routing. Elsevier, Amsterdam, pp. 1–33.

Fisher, M.L., Jörnsten, K.O., Madsen, O.B.G., 1997. Vehicle routing with time windows: Two optimization algorithms. Operations Research 45 (3), 488–492.

Fitzgerald, K.R., 1985. How to estimate the number of AGVs you need. Modern Materials Handling (October), 79.

Gademann, A.J.R.M., Van de Velde, S.L., 2000. Positioning automated guided vehicles in a loop layout. European Journal of Operational Research 127, 565–573.

Ganesharajah, T., Hall, N.G., Sriskandarajah, C., 1998. Design and operational issues in AGV-served manufacturing systems. Annals of Operations Research 76, 109–154.

Ganesharajah, T., Sriskandarajah, C., 1995. Survey of scheduling research in AGV-served manufacturing systems. Advances in Instrumentation and Control, Proceedings of the International Conference and Exhibit 50 (1), 87–94.

Gans, N., Van Ryzin, G., 1999. Dynamic vehicle dispatching: Optimal heavy traffic performance and practical insights. Operations Research 47 (5), 675–692.

Gaskins, R.J., Tanchoco, J.M.A., 1987. Flow path design for automated guided vehicle systems. International Journal of Production Research 25 (5), 667–676.

Gaskins, R.J., Tanchoco, J.M.A., Taghaboni, F., 1989. Virtual flow paths for free-ranging automated guided vehicle systems. International Journal of Production Research 27 (1), 91–100.

Gaur, D.R., Gupta, A., Krishnamurti, R., 2003. A 5/3-approximation algorithm for scheduling vehicles on a path with release and handling times. Information Processing Letters 86, 87–91.

Gendreau, M., Guertin, F., Potvin, J.Y., Taillard, É., 1999. Parallel tabu search for real-time vehicle routing and dispatching. Transportation Science 33 (4), 381–390.

Gobal, S.L., Kasilingam, R.G., 1991. A simulation model for estimating vehicle requirements in automated guided vehicle systems. Computers and Industrial Engineering 21 (1–4), 623–627.

Goetz Jr., W.G., Egbelu, P.J., 1990. Guide path design and location of load pick-up/drop-off points for an automated guided vehicle system. International Journal of Production Research 28 (5), 927–941.

Götting, H.H., 2000. Automation and Steering of Vehicles in ports. Port Technology International 10, 101–111.

Grunow, M., Günther, H.O., Lehmann, M., 2004. Dispatching multi-load AGVs in highly automated seaport container terminals. OR Spectrum 26, 211–235.

Haefner, L.E., Bieschke, M.S., 1998. ITS opportunities in port operations. Transportation Conference Proceedings, 131–134.

Hall, N.G., Sriskandarajah, C., Ganesharajah, T., 2001a. Operational decisions in AGV-Served Flowshop Loops: Fleet sizing and decomposition. Annals of Operations Research 107, 189–209.

Hall, N.G., Sriskandarajah, C., Ganesharajah, T., 2001b. Operational decisions in AGV-served flowshop loops: Scheduling. Annals of Operations Research 107, 161–188.

Han, M.H., McGinnis, L.F., 1989. Control of material handling transporter in automated manufacturing. IIE Transactions 21 (2), 184–190.

Hane, C.A., Barnhart, C., Johnson, E.L., Marsten, R.E., Nemhauser, G.L., Sigismondi, G., 1995. The fleet assignment problem: Solving a large-scale integer program. Mathematical Programming 70, 211–232.

Hartmann, S., 2004. A general framework for scheduling equipment and manpower at container terminals. OR Spectrum 26, 51–74.

Ho, Y.C., 2000. A dynamic-zone strategy for vehicle-collision prevention and load balancing in an AGV system with a single-loop guide path. Computers in Industry 42, 159–176.

Hodgson, T.J., King, R.E., Monteith, S.K., Schultz, S.R., 1987. Developing control rules for an AGVS using Markov decision processes. Material Flow 4, 85–96.

Hoff, E.B., Sarker, B.R., 1998. An overview of path design and dispatching methods for automated guided vehicles. Integrated Manufacturing Systems 9 (5), 296–307.

Hsieh, L.F., Shah, D.Y., 1996. A design process for tandem automated guided vehicle systems: The concurrent design of machine layout and guided vehicle routes in tandem automated guided vehicle systems. Integrated Manufacturing Systems 7 (6), 30–38.

Hsieh, S., Kang, M.Y., 1998. Developing AGVS Petri net control models from flowpath nets. Journal of Manufacturing Systems 17 (4), 237–250.

Huang, C., 1997. Design of material transportation system for tandem automated guided vehicle systems. International Journal of Production Research 35 (4), 943–953.

Hwang, H., Moon, S., Gen, M., 2002. An integrated model for the design of end-of-aisle order picking system and the determination of unit load sizes of AGVs. Computers and Industrial Engineering 42, 249–258.

Ilić, O.R., 1994. Analysis of the number of automated guided vehicles required in flexible manufacturing systems. International Journal of Advanced Manufacturing Technology 9, 382–389.

Jeong, B.H., Randhawa, S.U., 2001. A multi-attribute dispatching rule for automated guided vehicle systems. International Journal of Production Research 39 (13), 2817–2832.

Johnson, M.E., 2001. Modelling empty vehicle traffic in AGVS design. International Journal of Production Research 39 (12), 2615–2633.

Johnson, M.E., Brandeau, M.L., 1993. An analytic model for design of a multivehicle automated guided vehicle system. Management Science 39 (12), 1477–1489.

Johnson, M.E., Brandeau, M.L., 1996. Stochastic modeling for automated material handling system design and control. Transportation Science 30, 330–350.

Johnson, M.E., Brandeau, M.L., 1999. Design of an automated shop floor material handling system with inventory considerations. Operations Research 47 (1), 65–80.

Kasilingam, R.G., Gobal, S.L., 1996. Vehicle requirements model for automated guided vehicle systems. International Journal of Advanced Manufacturing Technology 12, 276–279.

Kaspi, M., Kesselman, U., Tanchoco, J.M.A., 2002. Optimal solution for the flow path design problem of a balanced unidirectional AGV system. International Journal of Production Research 40 (2), 389–401.

Kaspi, M., Tanchoco, J.M.A., 1990. Optimal flow path design of unidirectional AGV systems. International Journal of Production Research 28 (6), 1023–1030.

Kelly, J.P., Xu, J., 1999. A set-partitioning-based heuristic for the vehicle routing problem. Journal on Computing 11 (2), 161–172.

Kim, C.W., Tanchoco, J.M.A., 1991. Conflict-free shortest-time bidirectional AGV routeing. International Journal of Production Research 29 (12), 2377–2391.

Kim, C.W., Tanchoco, J.M.A., 1993b. Operational control of a bidirectional automated guided vehicle system. International Journal of Production Research 31 (9), 2123–2138.

Kim, C.W., Tanchoco, J.M.A., Koo, P.H., 1997. Deadlock prevention in manufacturing systems with AGV systems: Banker's algorithm approach. Journal of Manufacturing Science and Engineering—Transactions of the ASME 119 (4B), 849–854.

Kim, C.W., Tanchoco, J.M.A., Koo, P.H., 1999. AGV dispatching based on workload balancing. International Journal of Production Research 37 (17), 4053–4066.

Kim, J., Klein, C.M., 1996. Location of departmental pickup and delivery points for an AGV system. International Journal of Production Research 34 (2), 407–420.

Kim, K.H., 1995. Positioning of automated guided vehicles in a loop layout to minimize the mean vehicle response time. International Journal of Production Economics 39, 201–214.

Kim, K.H., Bae, J.W., 1999. A dispatching method for automated guided vehicles to minimize delays of containership operations. International Journal of Management Science 5 (1), 1–25.

Kim, K.H., Bae, J.W., 2004. A look-ahead dispatching method for automated guided vehicles in automated port container terminals. Transportation Science 38 (2), 224–234.

Kim, K.H., Kim, J.Y., 1997. Estimating mean response time and positioning idle vehicles of automated guided vehicle systems in loop layout. Computers and Industrial Engineering 33 (3–4), 669–672.

Kim, K.H., Tanchoco, J.M.A., 1993a. Economical design of material flow paths. International Journal of Production Research 31 (6), 1387–1407.

Kim, K.S., Jae, M., 2003. An object-oriented simulation and extension for tandem AGV systems. The International Journal of Advanced Manufacturing Technology. Available from: <http://www.springerlink.com>.

Kim, S.H., Hwang, H., 1999. An adaptive dispatching algorithm for automated guided vehicles based on an evolutionary process. International Journal of Production Economics 60–61, 465–472.

King, R.E., Kim, K.S., 1995. AgvTalk: An object-oriented simulator for AGV systems. Computers and Industrial Engineering 28 (3), 575–592.

King, R.E., Wilson, C., 1991. A review of automated guided-vehicle systems design and scheduling. Production Planning and Control 2 (1), 44–51.

Kiran, A.S., Tansel, B.C., 1989. Optimal pickup point location on material handling networks. International Journal of Production Research 27 (9), 1475–1486.

Kiran, A.S., Unal, A.T., Karabati, S., 1992. A location problem on unicyclic networks: Balanced case. European Journal of Operational Research 62, 194–202.

Ko, K.C., Egbelu, P.J., 2003. Unidirectional AGV guidepath network design: A heuristic algorithm. International Journal of Production Research 41 (10), 2325–2343.

Kodali, R., 1997. Knowledge-based system for selection of an AGV and a workcentre for transport of a part in on-line scheduling of FMS. Production Planning and Control 8 (2), 114–122.

Koff, G.A., 1987. Automatic Guided Vehicle Systems: Applications, controls and planning. Material Flow 4, 3–16.

Kohl, N., Desrosiers, J., Madsen, O.B.G., Solomon, M.M., Soumis, F., 1999. 2-path cuts for the vehicle routing problem with time windows. Transportation Science 33 (1), 101–116.

Kohl, N., Madsen, O.B.G., 1997. An optimization algorithm for the vehicle routing problem with time windows based on Lagrangian relaxation. Operations Research 45 (3), 395–406.

Kolen, A.W.J., Rinnooy Kan, A.H.G., Trienekens, H.W.J.M., 1987. Vehicle routing with time windows. Operations Research 35 (2), 266–273.

Koo, P.H., Jang, J., 2002. Vehicle travel time models for AGV systems under various dispatching rules. The International Journal of Flexible Manufacturing Systems 14, 249–261.

Koo, P.H., Lee, W.S., Jang, D.W., 2004. Fleet sizing and vehicle routing for container transportation in a static environment. OR Spectrum 26, 193–209.

Kouvelis, P., Gutierrez, G.J., Chiang, W.C., 1992. Heuristic unidirectional flowpath design approaches for automated guided vehicle systems. International Journal of Production Research 30 (6), 1327–1351.

Kouvelis, P., Kim, M.W., 1992. Unidirectional loop network layout problem in automated manufacturing systems. Operations Research 40 (3), 533–550.

Krishnamurthy, N.N., Batta, R., Karwan, M.H., 1993. Developing conflict-free routes for automated guided vehicles. Operations Research 41 (6), 1077–1090.

Laporte, G., 1992. The vehicle routing problem: An overview of exact and approximate algorithms. European Journal of Operational Research 59, 345–358.

Lee, C., Ventura, J.A., 2001. Optimal dwell point location of automated guided vehicles to minimize mean response time in a loop layout. International Journal of Production Research 39 (17), 4013–4031.

Lee, C.C., Lin, J.T., 1995. Deadlock prediction and avoidance based on Petri nets for zone-control automated guided vehicle systems. International Journal of Production Research 33 (12), 3249–3265.

Lee, J., Lee, M.K., Zhu, Z., 1996. WASA: A decision support system for workstations arrangement in single-vehicle closed-loop AGV systems. Computers and Industrial Engineering 30 (1), 41–49.

Leung, L.C., Khator, S.K., Kimbler, D.L., 1987. Assignment of AGVs with different vehicle types. Material Flow 4, 65–72.

Levitin, G., Abezgaouz, R., 2003. Optimal routing of multiple-load AGV subject of LIFO loading constraints. Computers and Operations Research 30, 397–410.

Lim, J.K., Lim, J.M., Yoshimoto, K., Kim, K.H., Takahashi, T., 2002a. A construction algorithm for designing guide paths of automated guided vehicle systems. International Journal of Production Research 40 (15), 3981–3994.

Lim, J.K., Lim, J.M., Yoshimoto, K., Kim, K.H., Takahashi, T., 2002b. Designing guide-path networks for automated guided vehicle system by using the Q-learning technique. Computers and Industrial Engineering 44, 1–17.

Lim, R., Siong, Lim, B.S., Ho, N.C., 1989. Development and implementation of an intelligent flexible manufacturing system. Journal of Mechanical Working Technology 20, 389–402.

Lin, J.T., Chang, C.C.K., Liu, W.C., 1994. A load-routeing problem in a tandem-configuration automated guided vehicle system. International Journal of Production Research 32 (2), 411–427.

Liu, F.H., Hung, P.C., 2001. Real-time deadlock-free control strategy for single multi-load automated guided vehicle on a job shop manufacturing system. International Journal of Production Research 39 (7), 1323–1342.

Lu, X., Gerchak, Y., 1998. Minimizing the expected response time of an idled server on a line. IIE Transactions 30, 401–408.

Mahadevan, B., Narendran, T.T., 1990. Design of an automated guided vehicle-based material handling system for a flexible manufacturing system. International Journal of Production Research 28 (9), 1611–1622.

Mahadevan, B., Narendran, T.T., 1993. Estimation of numberof AGVs for an FMS: An analytical model. International Journal of Production Research 31 (7), 1655–1670.

Mahadevan, B., Narendran, T.T., 1994. A hybrid modelling approach to the design of an AGV-based material handling system for an FMS. International Journal of Production Research 32 (9), 2015–2030.

Malmborg, C.J., 1990. A model for the design of zone control automated guided vehicle systems. International Journal of Production Research 28 (10), 1741–1758.

Manda, B.S., Palekar, U.S., 1997. Recent advances in the design and analysis of material handling systems. Journal of Manufacturing Science and Engineering 119, 841–848.

Mantel, R.J., Landeweerd, H.R.A., 1995. Design and operational control of an AGV system. International Journal of Production Economics 41, 257–266.

Maughan, F.G., Lewis, H.J., 2000. AGV controlled FMS. International Journal of Production Research 38 (17), 4445–4453.

Maxwell, W.L., Muckstadt, J.A., 1982. Design of automatic guided vehicle systems. IIE Transactions 14 (2), 114–124.

McHaney, R., 1995. Modelling battery constraints in discrete event automated guided vehicle systems. International Journal of Production Research 33 (11), 3023–3040.

Meersmans, P.J.M., 2002. Optimization of container handling systems. Ph.D. Thesis, Tinbergen Institute 271, Erasmus University Rotterdam.

Meersmans, P.J.M., Wagelmans, A.P.M., 2001. Effective algorithms for integrated scheduling of handling equipment at automated container terminals. ERIM Report Series Research in Management ERS-2001-36-LIS, Erasmus University Rotterdam.

Moon, S.W., Hwang, H., 1999. Determination of unit load sizes of AGV in multi-product multi-line assembly production systems. International Journal of Production Research 37 (15), 3565–3581.

Moorthy, R.L., Hock-Guan, W., Ng, W.-C., Chung-Piaw, T., 2003. Cycle deadlock prediction and avoidance for zone-controlled AGV system. International Journal of Production Economics 83, 309–324.

Müller, T., 1983. Automated Guided Vehicles. IFS (Publications) Ltd./Springer-Verlag, UK/Berlin.

Nakano, M., Ohno, K., 1999. Decomposition algorithm for performance evaluation of AGV systems. Production and Operations Management 8 (2), 193–205.

Narasimhan, R., Batta, R., Karwan, M.H., 1999. Routing automated guided vehicles in the presence of interruptions. International Journal of Production Research 37 (3), 653–681.

Newton, D., 1985. Simulation model calculates how many automated guided vehicles are needed. Industrial Engineering 17 (2), 68–78.

Oboth, C., Batta, R., Karwan, M., 1999. Dynamic conflict-free routing of automated guided vehicles. International Journal of Production Research 37 (9), 2003–2030.

Ozden, M., 1988. A simulation study of multiple-load-carrying automated guided vehicles in a flexible manufacturing system. International Journal of Production Research 26 (8), 1353–1366.

Psaraftis, H.N., 1988. Dynamic vehicle routing problems. In: Golden, B.L., Assad, A.A. (Eds.), Vehicle Routing: Methods and Studies. Studies in Management Science and Systems, pp. 223–248.

Qiu, L., Hsu, W.J., 2001. A bi-directional path layout for conflict-free routing of AGVs. International Journal of Production Research 39 (1), 2177–2195.

Qiu, L., Hsu, W.J., Huang, S.Y., Wang, H., 2002. Scheduling and routing algorithms for AGVs: A survey (2002). International Journal of Production Research 40 (3), 745–760.

Rajotia, S., Shanker, K., Batra, J.L., 1998a. An heuristic for configuring a mixed uni/bidirectional flow path for an AGV system. International Journal of Production Research 36 (7), 1779–1799.

Rajotia, S., Shanker, K., Batra, J.L., 1998b. Determination of optimal AGV fleet size for an FMS. International Journal of Production Research 36 (5), 1177–1198.

Rajotia, S., Shanker, K., Batra, J.L., 1998c. A semi-dynamic time window constrained routeing strategy in an AGV system. International Journal of Production Research 36 (1), 35–50.

Reveliotis, S.A., 2000. Conflict resolution in AGV systems. IIE Transactions 32, 647–659.

Rexing, B., Barnhart, C., Kniker, T., Jarrah, A., Krishnamurthy, N., 2000. Airline fleet assignment with time windows. Transportation Science 34 (1), 1–20.

Ro, I.K., Kim, J.I., 1990. Multi-criteria operational control rules in flexible manufacturing systems (FMSs). International Journal of Production Research 28 (1), 47–63.

Ross, E.A., Mahmoodi, F., Mosier, C.T., 1996. Tandem configuration Automated Guided Vehicle systems: A comparative study. Decision Sciences 27, 81–102.

Sabuncuoglu, I., 1998. A study of scheduling rules of flexible manufacturing systems: A simulation approach. International Journal of Production Research 36 (2), 527–546.

Savelsbergh, M., Sol, M., 1998. Drive: Dynamic routing of independent vehicles. Operations Research 46 (4), 474–490.

Savelsbergh, M.W.P., Sol, M., 1995. The general pickup and delivery problem. Transportation Science 29 (1), 17–29.

Seifert, R.W., Kay, M.G., Wilson, J.R., 1998. Evaluation of AGV routeing strategies using hierarchical simulation. International Journal of Production Research 36 (7), 1961–1976.

Seo, Y., Egbelu, P.J., 1999. Integrated manufacturing planning for an AGV-based FMS. International Journal of Production Economics 60–61, 473–478.

Shah, M., Lin, L., Nagi, R., 1997. A production order-driven AGV control model with object-oriented implemenation. Computer Integrated Manufacturing Systems 10 (1), 35–48.

Sharp, G.P., Liu, F.H.F., 1990. An analytical method for configuring fixed-path, closed loop material handling systems. International Journal of Production Research 28 (4), 757–783.

Shiizuka, H., Suzuki, M., 1994. Modeling of AGV networks in flexible manufacturing systems. Computers and Industrial Engineering 27 (1–4), 81–86.

SiemensDematic, 2004. <http://www.agvsystems.com>, visited August 2004.

Singh, S.P., Tiwari, M.K., 2002. Intelligent agent framework to determine the optimal conflict-free path for an automated guided vehicles system. International Journal of Production Research 40 (16), 4195–4223.

Sinriech, D., 1995. Network design models for discrete material flow systems: A literature review. International Journal of Advanced Manufacturing Technology 10, 277–291.

Sinriech, D., Kotlarski, J., 2002. A dynamic scheduling algorithm for a multiple-load-carrier system. International Journal of Production Research 40 (5), 1065–1080.

Sinriech, D., Palni, L., 1998. Scheduling pickup and deliveries in a multiple-load discrete carrier environment. IIE Transactions 30, 1035–1047.

Sinriech, D., Tanchoco, J.M.A., 1991. Intersection graph method for AGV flow path design. International Journal of Production Research 29 (9), 1725–1732.

Sinriech, D., Tanchoco, J.M.A., 1992a. Impact of empty vehicle flow on performance of single-loop AGV systems. International Journal of Production Research 30 (10), 2237–2252.

Sinriech, D., Tanchoco, J.M.A., 1992b. An economic model for determining AGV fleet size. International Journal of Production Research 30 (6), 1255–1268.

Sinriech, D., Tanchoco, J.M.A., 1993. Solution methods for the mathematical models of single-loop AGV systems. International Journal of Production Research 31 (3), 705–725.

Sinriech, D., Tanchoco, J.M.A., 1995. An introduction to the segmented flow approach for discrete material flow systems. International Journal of Production Research 33 (12), 3381–3410.

Sinriech, D., Tanchoco, J.M.A., 1997. Design procedures and implementation of the segmented flow topology (SFT) for discrete material flow systems. IIE Transactions 29, 323–335.

Sinriech, D., Tanchoco, J.M.A., Herer, Y.T., 1996. The segmented bidirectional single-loop topology for material flow systems. IIE Transactions 28 (1), 40–54.

Solomon, M.M., 1987. Algorithms for the vehicle routing and scheduling problems with time window constraints. Operations Research 35 (2), 254–265.

Solomon, M.M., Baker, E.K., Schaffer, J.R., 1988. Vehicle routing and scheduling problems with time window constraints: Efficient implementations of solution improvement procedures. In: Golden, B.L., Assad, A.A. (Eds.), Vehicle Routing: Methods and Studies. Studies in Management Science and Systems, pp. 85–104.

Solomon, M.M., Desrosiers, J., 1988. Time window constrained routing and scheduling problems. Transportation Science 22 (1), 1–13.

Soukhal, A., Oulamara, A., Martineau, P., 2005. Complexity of flow shop scheduling problems with transportation constraints. European Journal of Operational Research 161 (1), 32–41.

Soylu, M., Özdemirel, N.E., Kayaligil, S., 2000. A self-organizing neural network approach for the single AGV routing problem. European Journal of Operational Research 121, 124–137.

Srinivasan, M.M., Bozer, Y.A., Cho, M., 1994. Trip-based material handling systems: Throughput capacity analysis. IIE Transactions 26 (1), 70–89.

Sun, X.C., Tchernev, N., 1996. Impact of empty vehicle flow on optimal flow path design for unidirectional AGV systems. International Journal of Production Research 34 (10), 2827–2852.

Taghaboni, F., Tanchoco, J.M.A., 1988. A LISP-based controller for free-ranging automated guided vehicle systems. International Journal of Production Research 26 (2), 173–188.

Taghaboni-Dutta, F., Tanchoco, J.M.A., 1995. Comparison of dynamic routeing techniques for automated guided vehicle system. International Journal of Production Research 33 (10), 2653–2669.

Tan, K.K., Tang, K.Z., 2001. Vehicle dispatching system based on Taguchi-tuned fuzzy rules. European Journal of Operational Research 128, 545–557.

Tanchoco, J.M.A., Egbelu, P.J., Taghaboni, F., 1987. Determination of the total number of vehicles in an AGV-based material transport system. Material Flow 4, 33–51.

Tanchoco, J.M.A., Sinriech, D., 1992. OSL-optimal single-loop guide paths for AGVS. International Journal of Production Research 30 (3), 665–681.

Tsai, Y.T., Wang, K.S., 1999. The development of modular-based design in considering technology complexity. European Journal of Operational Research 119, 692–703.

Ulusoy, G., Bilge, Ü., 1993. Simultaneous scheduling of machines and automated guided vehicles. International Journal of Production Research 31 (12), 2857–2873.

Ulusoy, G., Sivrikaya-Serifoglu, F., Bilge, Ü., 1997. A genetic algorithm approach to the simultaneous scheduling of machines and automated guided vehicles. Computers and Operations Research 24 (4), 335–351.

Van der Heijden, M., Ebben, M., Gademann, N., Van Harten, A., 2002b. Scheduling vehicles in automated transportation systems. OR Spectrum 24, 31–58.

Van der Heijden, M.C., Van Harten, A., Ebben, M.J.R., Saanen, Y.A., Valentin, E.C., Verbraeck, A., 2002a. Using simulation to design an automated underground system for transporting freight around Schiphol airport. Interfaces 32 (4), 1–19.

Van der Meer, J.R., 2000. Operational control of internal transport. ERIM Ph.D. Series Research in Management Vol. 1.

Veeravalli, B., Rajesh, G., Viswanadham, N., 2002. Design and analysis of optimal material distribution policies in flexible manufacturing systems using a single AGV. International Journal of Production Research 40 (12), 2937–2954.

Venkataramanan, M.A., Wilson, K.A., 1991. A branch-and-bound algorithm for flow-path design of automated guided vehicle systems. Naval Research Logistics 38, 431–445.

Ventura, J.A., Lee, C., 2001. A study of the tandem loop with multiple vehicles configuration for automated guided vehicle systems. Journal of Manufacturing Systems 20 (3), 153–165.

Vis, I.F.A., De Koster, R., Roodbergen, K.J., Peeters, L.W.P., 2001. Determination of the number of AGVs required at a semi-automated container terminal. Journal of the Operational Research Society 52, 409–417.

Vis, I.F.A., De Koster, R., Savelsbergh, M.W.P., in press. Minimum vehicle fleet size under time window constraints at a container terminal. Transportation Science.

Vis, I.F.A., Harika, I., 2004. Comparison of vehicle types at an automated container terminal. OR Spectrum 26, 117–143.

Wallace, A., 2001. Application of AI to AGV control–agent control of AGVs. International Journal of Production Research 39 (4), 709–726.

Watanabe, M., Furukawa, M., Kakazu, Y., 2001. Intelligent AGV driving toward an autonomous decentralized manufacturing system. Robotics and Computer Integrated Manufacturing 17, 57–64.

Wijesoma, W.S., Kodagoda, K.R.S., Teoh, E.K., 2002. Stable fuzzy state space controller for lateral control of an AGV. Journal of VLSI Signal Processing 32, 189–201.

Wu, K.H., Hsing, Chen, C.H., Ko, J.M., 1999. Path planning and prototype design of an AGV. Mathematical and computer modelling 30, 147–167.

Wu, N., Zeng, W., 2002. Deadlock avoidance in an automated guidance vehicle system using a coloured Petri net model. International Journal of Production Research 40 (1), 223–238.

Wysk, R.A., Egbelu, P.J., Zhou, C., Ghosh, B.K., 1987. Use of spread sheet analysis for evaluating AGV systems. Material Flow 4, 53–64.

Xu, F., Van Brussel, H., Nuttin, M., Moreas, R., 2003. Concepts for dynamic obstacle avoidance and their extended application in underground navigation. Robotics and Autonomous Systems 42, 1–15.

Yamashita, H., 2001. Analysis of dispatching rules of AGV systems with multiple vehicles. IIE Transactions 33, 889–895.

Yang, C.H., Choi, Y.S., Ha, T.Y., 2004. Simulation-based performance evaluation of transport vehicles at automated container terminals. OR Spectrum 26, 149–170.

Yeh, M.S., Yeh, W.C., 1998. Deadlock prediction and avoidance for zone-control AGVS. International Journal of Production Research 36 (10), 2879–2889.

Yim, D.S., Linn, R.J., 1993. Push and pull rules for dispatching automated guided vehicles in a flexible manufacturing system. International Journal of Production Research 31 (1), 43–57.

Yu, W., Egbelu, P.J., 2001. Design of variable path tandem layout for automated guided vehicle systems. Journal of Manufacturing Systems 20 (5), 305–319.

Zaremba, M.B., Obuchowicz, A., Banaszak, Z.A., Jedrzejek, K.J., 1997. A max-algebra approach to the robust distributed control of repetitive AGV systems. International Journal of Production Research 35 (10), 2667–2687.

Zeng, L., Wang, H.P., Jin, S., 1991. Conflict detection of automated guided vehicles: A petri net approach. International Journal of Production Research 29 (5), 865–879.