ON THE USE OF AUTOMATED GUIDED VEHICLES IN FLEXIBLE MANUFACTURING SYSTEMS

Samia Maza[*] and Pierre Castagna[**]
[*] *Centre de Recherche en Automatique de Nancy, UMR 7039, CNRS-Nancy university*
2, avenue de la Forêt de Haye, 54506 Vandoeuvre lès Nancy, France
[**] *Institut de Recherche en Communications et Cybernétique de Nantes, UMR CNRS 6597*
1, rue de La Noë, BP 92101 Nantes Cedex 3, France
samia.maza@ensem.inpl-nancy.fr, pierre.castagna@univ-nantes.fr

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Abstract: In manufacturing systems, material transport plays a key role for production process efficiency. Because of their advantages over other material handling systems such as conveyors and robots, AGVs are widely used in flexible manufacturing systems. The scheduling of several AGVs in a non-conflicting manner is a complicated problem, especially when the AGV system is bi-directional. In fact, many undesirable situations may arise such as deadlocks and head-on conflicts if no efficient control policy is used to prevent them. This paper presents the key issues to be addressed to efficiently employ these devices, and deal particularly with the traffic management problem.

1 INTRODUCTION

Automatic Guided Vehicle Systems (AGVS) are one of the most exciting and dynamic areas in material handling today. But AGVS is really not so new. Fifty years ago when AGVS was invented it was then called driverless systems. Through the years, advances in electronics have led to advances in guided vehicles. Technological developments may have given AGVS more flexibility and capability, but market acceptance has really given AGVS the application variety to allow it to expand into the standard accepted material handling method it is today.

Automated guided vehicles (AGVs) are material handling devices used to transport products and goods among the workstations and storage areas of a manufacturing system. The basic functions of an AGVS are:

- Navigation and Guidance allow the vehicle to follow a predetermined route which is optimized for the material flow pattern of a given application
- Routing is the vehicle's ability to make decisions along the guidance path in order to select optimum routes to specific destinations
- Traffic Management is a system or vehicle ability to avoid collisions with other vehicles while at the same time maximizing vehicle flow and therefore load movement throughout the system.
- Load Transfer is the pickup and delivery method for an AGVS system, which may be simple or integrated with other subsystems.
- System Management is the method of system control used to dictate system operation.

The goal of this paper is to present some interesting problems related to the use of AGV systems and a short overview of papers dealing with those problems especially the routing problem. We will present our research works and results concerning the routing of bi-directional AGV Systems.

In the second section, the key issues to be adressed to efficiently use the AGVs are presented. The approaches we have developed for the conflict free routing of bi-directional AGVs will be briefly presented in the third section. The simulation study is presented in section four and the study we have made for the compact disc manufacturer is presented in section five. Section six is devoted to the conclusions.

2 DESIGN AND CONTROL OF AN AGVS

An AGV system is a set of a cooperative driver-less vehicles moving on the same manufacturing floor and coordinated by a control system.

For a successful deployment of an AGVS, the following key issues should be addressed (Reveliotis, 2000):

2.1 The Flow Path Design

The manufacturing floor is specified by a set of physical or virtual guide-paths. If the AGVs are allowed to move only according to one direction, they are called unidirectional, otherwise, i.e., if they can move into the two directions, they are said to be bi-directional. It has been shown that the bi-directional AGVS can improve considerably the performances of a manufacturing system (Egbelu and Tanchoco, 1986). The design of the guide-path is an important problem, i.e., the choice of the guide-path configuration in order to minimise the travelled distances. Many research works deal with such a problem, the others deal with the determination of the guide-path's lanes direction for unidirectional AGVSs (for example Gaskins and Tanchoco, 1987). Such a problem is generally formalised as an integer programming problem with distance as criterion to optimise. The most known configurations are the simple loop, multiple loops, tandem and conventional configurations.

2.2 The Fleet Size and Vehicle's Capacity Determination

The AGVs can be classified according to their load capacity into two categories: single and multiple load vehicles. And one of the important problems to be addressed when designing AGVS is the determination of the AGVs number and their loading capacity. The research works which deal with such problem are numerous and can be classified into three categories:

- Analytical methods;
- Simulating methods;
- Hybrid or mixed methods.

For example in (Egbelu and Tanchoco, 1987), four analytical methods are proposed to determine the minimum fleet size to satisfy the production needs. These methods were tested for various dispatching rules. Beamon and Chen (Beamon and Chen, 1998a) reproach the traditional methods to not consider the system reliability when determining the optimal fleet size. To consider the reliability of the AGVs and the guide-path intersections, they include in their proposed approach, the vehicles and intersections failure rates in order to calculate the minimum number of AGVs needed. Beamon and Deshpande (Beamon and Deshpande, 1998b) proposed an approach to jointly optimise the fleet size the vehicle's load capacity (i.e., the load batch size). The objective is to make the better trade-off between those two criteria. Indeed, more great is the load size; shorter will be the total travelled distances, since one vehicle will make only one displacement with many loads. However, the loading and unloading time will be greater than for a single load. In the same manner, when there is a great number of AGVs, the system performances will be improved until the optimal number. Beyond this optimal number, the performances will be degraded since a great number of vehicles increases the traffic congestion and deadlocks.

- In (Castagna and Maza, 2004) we proposed a simulation approach to determine the optimal fleet size given a production horizon T, the manufacturing ranges, the production rate, and the guide-path.

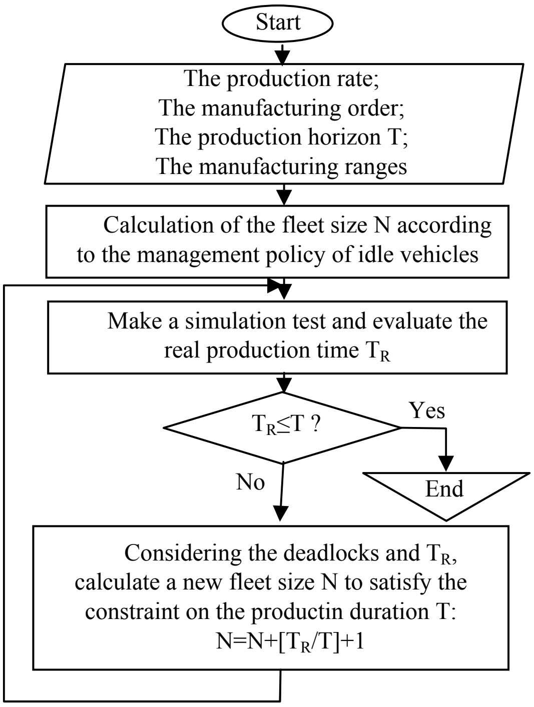

Figure 1: the fleet size calculation procedure.

The basic idea of this approach is:

In the first step, the number of AGVs needed to realise the specified number of products into the specified makespan T is calculated.

In the second step, a simulation study is conducted to test the calculated number; and to refine it by considering the achieved performances (see figure 1). Indeed, when the fleet size is calculated in the first step, deadlocks are not considered. The simulation allows the determination of the real production time T_R needed to accomplish all the transportation missions. This new makespan is used to determine the AGVs fleet size once again and is tested by simulation. The optimal fleet size is obtained when all the transportation tasks are effectively achieved in the specified production horizon T.

This study was made for various management policies of idle AGVs and was compared to the analytical approach proposed in (Egbelu and Tanchoco, 1987).

2.3 The Dispatching Problem

To achieve a product or a job, it has to be routed on several stations of the manufacturing system to undergo some transformation operations. These are those transitions which introduce the problem of vehicle's task assignment.

Indeed, when an operation is completed on one workstation, the product makes a request for a vehicle to be transported to the next station.

The dispatching problem consists in choosing one request among several ones in a standby state, and choosing one vehicle to be affected to that request. This vehicle should be able to make the resulting displacement.

The dispatching problem was developed in many research papers, but their number is still smaller than the one of the papers dealing with the scheduling problem without transportation resources. For example Blazewicz et al (Blazewicz et al, 1991) propose an approach to search for a scheduling that jointly considers the jobs and vehicles. Egbelu and Tanchoco (Egbelu and Tanchoco, 1984) describe the major vehicles' dispatching rules for two special cases: (a) when there is only one transporting request and many idle vehicles, and (b) when there is only one idle AGV and many jobs requesting a vehicle.

Other dispatching cases were considered in (Albert, 1998).

2.4 The AGVs Routing and Traffic Management Problem

The aim of routing AGVs is to find an optimal (e.g. shortest possible time path) and feasible route for every single AGV.

Actually, the routing decision includes three aspects. Firstly, it should detect whether there *exists* a route which could lead the vehicle from its origin to the destination. Secondly, the route selected for an AGV must be feasible, i.e., the route must be congestion-, conflict- and deadlock-free (Taghaboni and Tanchoco, 1995), etc. Thirdly, the route must be optimal or at least partially optimal, e.g. minimize idling runs of vehicles.

Indeed, AGVS are the seat of a great number of undesirable situations, in particular when they are bi-directional. Situations like conflicts and deadlocks. Conflicts occur when for example two AGVs are attempting to travel one lane at the same direction but at different speeds, or into opposite directions. Other conflicts occur when several vehicles attempt to cross one intersection at the same time (Figure 2.)

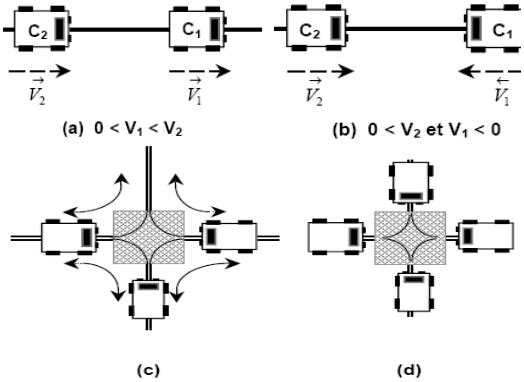

Figure 2: Example of conflicts between AGVs.

Deadlock is a well known problem in the resource allocation systems and technological areas such as computer operating systems, transportation and automated manufacturing systems (Lawley and Reveliotis, 1999).

A resource allocation system (RAS) consists of a finite set of resources that must be allocated to competing processes. The processes enter the system, request, acquire, use, and release their required resources, and then exit the system.

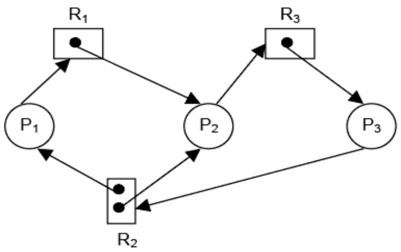

Figure 3: Example of deadlock situation in a resource allocation graph for a RAS of 3 processes and 3 resources, where R_2 is of capacity 2.

Many types of RASs are prone to deadlock, an insidious halting condition in which there exists a set of processes with every process in the set awaiting the allocation of resources held by other processes in the set (Figure 3).

Well known strategies for handling deadlock are (1) prevention, (2) detection-resolution, and (3) avoidance. Prevention restrains the request structure of processes so that deadlock is impossible. Because it limits process concurrency, prevention tends to be overly restrictive and typically achieves poor resource utilization.

Detection-resolution approaches allow deadlock to occur and then concentrate on expedient resolution. This approach achieves the greatest flexibility in resource allocation at the cost of system stoppage and resolution procedures, which may involve aborting processes or the time consuming transport and reshuffling of physical entities. Avoidance uses current state information along with knowledge of process request and release structures to restrain the way resources are allocated so that deadlock never occurs. Avoidance achieves a middle ground in terms of allocation flexibility, being more flexible than prevention but less flexible than detection. It does not incur the cost of system stoppage and resolution and thus is the preferred method when the incremental increase in allocation flexibility does not merit the cost of allowing deadlock to occur. Dijskstra was pioneer in that field and proposed a polynomial algorithm, known as the banker algorithm, to resolve a sequential resource allocation problem. A more complete discussion of fundamental deadlock concepts can be found in most books on computer operating systems, for example see (Silberschatz and Peterson, 1991).

These few last years, many research works were conducted to avoid deadlocks in automated manufacturing systems, for example (Pia Fanti, 1997) and (Reveliotis, 1996).

An AGV system can be considered as a resource allocation system, where the processes are the AGVs and the resources are intersections and lanes of the guide path. The problem of deadlock and conflict free routing in AGVS will be developed in the next section.

3 CONFLICT FREE ROUTING OF BI-DIRECTIONAL AGVS

In our research work, we were especially interested in conflict-free routing of bi-directional AGVS.

Several routing approaches were proposed in the literature and can be classified into two categories:

(1) Predictive or planning methods: here the conflicts are predicted off-line and vehicles' paths are planned to avoid these conflicts and to minimise a performance criterion see for example (Krishnamurthy et al, 1993) and (Oboth et al, 1998).

(2) Reactive or dynamic methods: here, an AGV path is not planned and routing decisions are made in a real time manner according to system's state. Such methods are always qualified as zone dynamic control methods, since the guide path is divided into non overlapping zones considered as non-sharable resources; see for example (Reveliotis, 2000), and (Branislav, 2002).

The advantage of the first category of methods is that the system's performances (like the makespan or travel time of AGVs) are a priori considered and optimised. However, unlike the reactive methods, the planning approaches are sensitive to perturbations since the scheduling is made in a deterministic way. Dynamic methods are very robust but do not consider the performances optimisation beyond a short horizon.

In order to have the advantages of the types of methods, we proposed a new approach in (Maza ad Castagna, 2005a, 2005b) based on a planning method proposed in (Kim and Tanchoco, 1991).

This planning method is based on an algorithm called *cfstp* (i.e. conflict free shortest time procedure), which calculates for each AGV, having a transporting mission the fastest route, considering the traffic status, to reach its destination without conflicts. To this end, intersections and characteristic point of the guide path are modelled by square areas, called nodes, which are considered as non sharable resources. When an AGV moves on this guide path, it reserves some nodes for a while (see figure 4). This duration is called reserved time window (noted r_n for node n), where the node is exclusively reserved by that vehicle. Other time intervals where nodes are free are called free time windows (noted f_m for node m).

The *cfstp* calculates the shortest path on a directed time windows graph, in which the vertices represent the free time windows and the links model the reachability between these time windows. The ability to reach a time window from another one is established by calling another algorithm called *the reachability test procedure*. For two free time windows f_n^p and f_m^q associated respectively to the nodes n and m, this last procedure makes the following reachability tests between them:

(1) Check for space feasibility, i.e., the existence of a physical link relating m to n.
(2) Check for time feasibility, i.e., the node m is reachable from the node n within its free time window f_m^q.
(3) Check for potential conflicts.

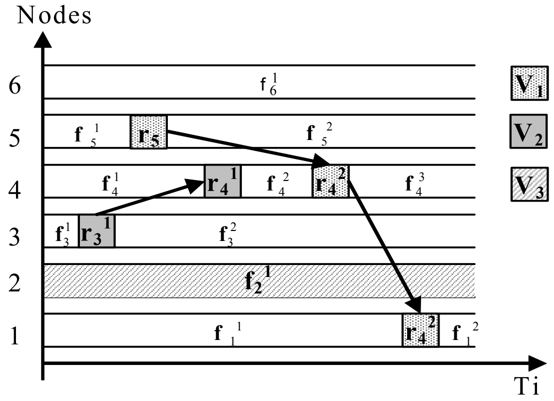

Figure 4: Example of time-windows table.

— r_i^j is the j^th reserved time window of node i
— f_l^k is the k^th free time window of node l.

When a mission is possible, the *cfstp* delivers for its assigned AGV a set of nodes to be visited and the arrival and exit times to those nodes to avoid conflicts and minimise the travel time. As said before, such method is sensitive to perturbations.

There are two types of contingencies: temporary and permanent. We consider only the first type, such as a slowing down in front of a fixed or a moving obstacle, or a temporary stop on a lane or a node to charge the battery, etc. In that case, the scheduled arrival and exit times will not be respected and consequently, there is no security guarantee for the AGVs since collisions can occur.

To ensure the reliability of an AGVS in the presence of interruptions while maintaining the scheduled trajectories, a control architecture was proposed in (Maza and Castagna, 2001, 2005a).

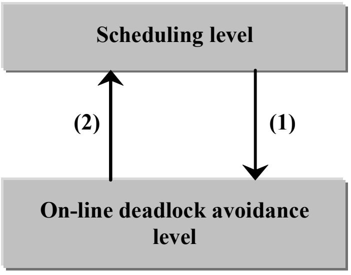

Figure 5: The AGV control architecture.

(1) the scheduling level delivers for each node i, an ordered list, O_i, of AGVs having to cross it in a growing order of their arrival dates.
(2) the deadlock avoidance level operates in presence of contingencies by respecting the predicted node's crossing order (*RVWA*) or by re-ordering the AGVs (*RVRAA* or *RVDA*). It informs the 1st level about the current changes.

Indeed, a second level of real-time control was added to the AGVs scheduling level which uses the *cfstp*, in order to avoid deadlocks and conflicts when needed (see Figure 5). First, the AGVs are scheduled on the nodes of the guide-path in a non conflicting manner while optimising the mission's duration. Then, the scheduled entry times to each node are used to establish for each AGV, its own priority to cross these nodes.

Three polynomial algorithms were proposed. The first one based on static priorities, called *RVWA* (or *Robust Vehicle Waiting Algorithm*). *RVWA* is based on a theorem that says that if each AGV respects its node crossing order, the property of non-conflict is conserved.

The second algorithm based on dynamic priorities, called *RVRAA* (or *Robust Vehicle Routing Ahead Algorithm*) allows the rescheduling of the AGVs on some nodes in order to improve the *RVWA* which always induces unnecessary waiting of vehicles to respect their crossing priorities (Maza and Castagna, 2005a). The basic idea of *RVRAA* is to give the AGV V which calls the algorithm the greatest priority on some specified path [N,M], where N is the node where V calls *RVRAA*, and M is the node where V has the highest priority.

The third algorithm called *RVDA* (or *Robust Vehicle Delaying Algorithm*), also based on dynamic priorities, penalises the AGV which is late, say U, in front of some other AGVs on a path [N,M]. N is the node where the algorithm is called, and M is a node which is calculated by the algorithm to insure that the system will never reach an unsafe state (Maza and Castagna, 2005b). An AGV state is called *unsafe* if it can conduct the AGV system to a deadlock state, i.e., it satisfies the necessary condition for the occurrence of conflicts.

These three algorithms were tested and compared in a simulation study which is developed in the next section.

We have developed another approach for the reactive conflict-free routing of the AGVs based on multi-agent systems (Breton et al, 2006). The main idea of this approach is to consider an AGV as a reactive agent, whose goal is to reach a predefined destination node without conflict with the moving AGVs. In order to design the AGV-agent, the

Cassiopea Multi-Agent System (MAS) design methodology is used (Collinot and Droguoul, 1996).

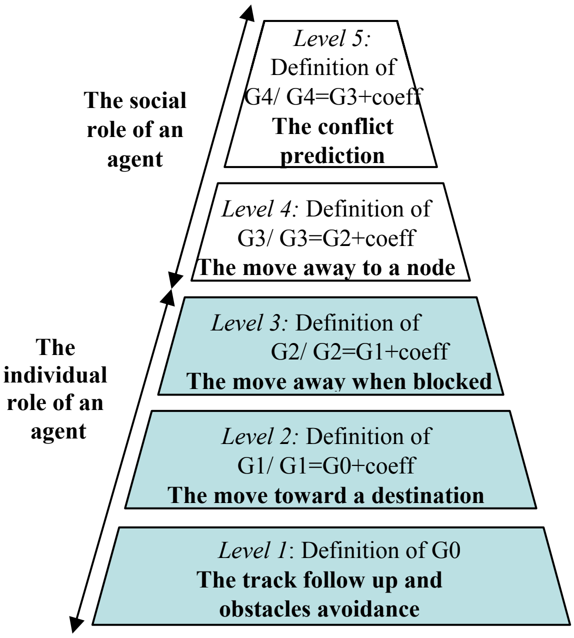

Figure 6: The application of the Cassiopea methodology to design an AGV-agent of a deadlock-free AGV system.

This methodology defines an agent in five incremental layers, considering the agent's different roles. This incremental construction has the advantage of satisfying the principle of parsimony, i.e., the definition of the agent can be stopped as soon as the system completes its desired function.

The steps followed to design an AGV-agent are given in figure 6. A gradient G_j is calculated in each step j to meet some specification (for example a track follow-up). An AGV-agent will move to minimise this gradient, i.e. according to the direction where the gradient is minimal. This approach was also compared in a simulation study to the predictive approach described before. For more details see (Breton et al, 2006).

4 SIMULATION OF BI-DIRECTIONAL AGV SYSTEMS

To test the various approaches described before, we have used the ARENA software to develop a new template panel, which allows us to model the routing of bi-directional AGVs. This function is actually not included in ARENA package. Our template also allows the modelling of real AGVSs, subject to contingencies. This template panel is well described in (Maza and Castagna, 2005a).

To check for the efficiency of our algorithms *RVWA*, *RVRAA* and *RVDA*, we made some simulation tests using our template. The AGVS under study is composed of bi-directional mesh-like guide-path of 45 nodes and 60 links and a fleet of 8 AGVs. Each simulation essay is a sequence of at least 10 replications. In one replication, each AGV has to realise a set of 100 missions randomly generated. To approach reality, random failures of AGVs are generated in the simulation model. They are characterised by two parameters: the failure rate τ and the mean time between failures MTBF.

Different simulations were done with various system parameters in order to compare these algorithms and bring out the situations where the use of one algorithm is more appropriate than another (Maza and Castagna, 2005b).

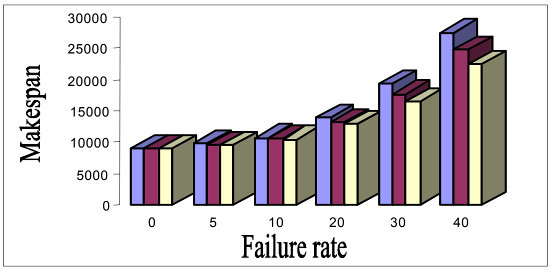

Figure 7: The makespan evolution according to the failure rate (τ=0, 5%, 10%, 20%, 30%, 40%).

For example, by varying the failure rate and fixing other parameters, it can be concluded that more the failure rate is important, better will be the makespan achieved by the algorithms *RVRAA* and *RVDA* and that the *RVDA* gives the best results (Figure 7. This can be explained by the fact that the *RVDA* algorithm is more permissive than the two other algorithms. More simulation results are available in (Maza and Castagna, 2005b).

5 AN INDUSTRIAL APPLICATION

We briefly present here an example of a simulation study we have done for an industrialist MPO who wanted to implement an AGV system. The goal of this study was the prediction of the stores evolution according to various AGVs management policies. For more than fifty years now, MPO has been an expert in the manufacture and replication of pre-recorded media. Every year, 600 millions discs and

150 millions printings elements come out of the MPO's plants.

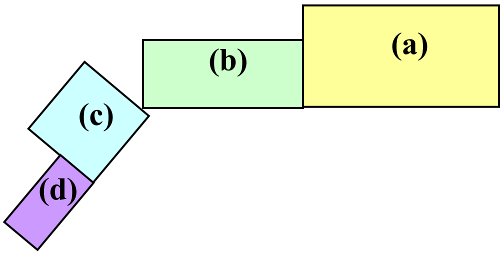

Figure 8: The MPO Production facilities.

This simulation project took place in the production plant of Averton (France). The production plant is composed of four workshops (Figure 8):

The pressing shop: the CDs and DVDs are obtained by injection of fluidized polycarbonate in a press mold. Then, a fine layer of aluminum is deposited in a vacuum, by pulverization, onto the surface of the disc (Figure 8 (a)).

The printing shop: two printing principles are utilized. The first one is silkscreen printing. This technique consists of printing by means of a cloth frame, which favors the flat decorations. The second one is offset printing, by means of linked rolls which is suitable for photos and illustrations in several hues (Figure 8 (b)).

The packaging shop: the discs are packaged in their boxes (Figure 8 (c)).

The storage zone: the store is utilized both to store raw materials and to store the CDs waiting for package (Figure 8 (d)).

All the transports of goods between the workshops are realized using an AGV system.

The particularity of this system is that one AGV is used for towing one or more non-powered carriers as a train. The AGVs are moving along a unidirectional loop guided path (Figure 9).

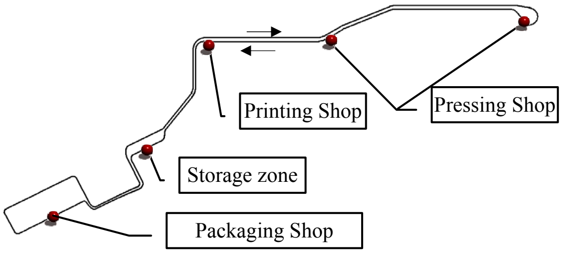

Figure 9: The transportation loop with the stations.

The simulation study is made with a couple of objectives. The first one is to determine the rule to be applied to load the carriers. We consider the two following rules:

R1: the products resulting from different production orders can be mixed on the same carrier.

R2: one carrier holds only products of the same production order.

The second objective is to locate and to size the waiting areas of the carriers. Indeed, it is necessary to place one or more garages near each workshop where the carriers can wait for a tow.

The simulator we developed shows how the 600 carriers are distributed between the different storage areas according the applied production rules. The evolution of the total number of the waiting carriers in each storage area according to time is shown on Figure 10.

6 CONCLUSION

In this paper, we presented some important problems to be considered when employing AGV systems. Some of these problems concern the design aspect, the others the piloting or control aspect. In our research work, we were concerned with the control aspect, particularly with the conflict-free routing of bi-directional AGVSs.

This paper recalls the principle of the approaches we developed for reactive routing of bi-directional AGVs and gives some simulation results. We also briefly presented a simulation study we have done to help an industrialist to make decisions at the design stage of their AGV system and also at the piloting stage. Since this application is confidential, we could not give more information on it.

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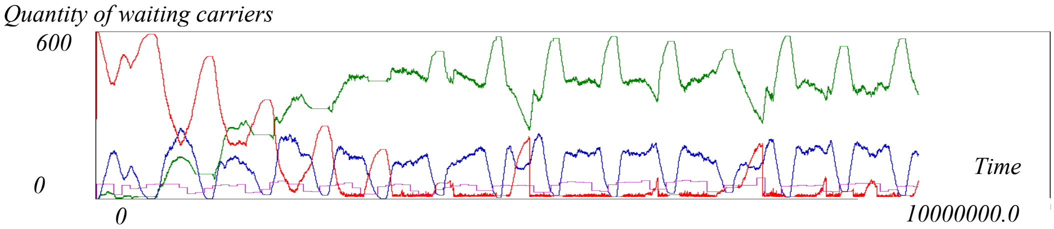

Figure 10: Example of time evolution of the carriers' number in each waiting area.

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