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Real-time deadlock-free control strategy for single multi-load automated guided vehicle on a job shop manufacturing system

FUH-HWA LIU†* and PI-CHUAN HUNG†

An unmanned automated job shop manufacturing system with a single multi-load automated guided vehicle, which traverses around a single-loop guidepath, is considered in this work. This type of shop design is often used as an independent sector of some complex AGV layouts, such as tandem, segmented bi-directional single-loop and divided configurations. The type of multi-load vehicle is a good alternative against using more single-load vehicles to serve a higher transportation demand. To an unmanned automated manufacturing system, the management of finite system resources, e.g. finite input/output queuing space and transporting carriers, plays a vital role in avoiding system deadlocks and machine blockages. The proposed control strategy for a single multi-load vehicle uses global shop real-time information to achieve the objectives: avoid shop deadlocks caused by inappropriate job movement as well as satisfy the system transport requirement. The efficiency of the proposed vehicle control strategy and the other two expanded strategies under various parameter designs are verified by computer simulation.

1. Introduction

Material handling systems (MHSs) significantly influence the resource utilization, the requirement of storage, and the overall production performance in automated manufacturing systems (AMSs). Among the modern MHSs, the automated guided vehicle system (AGVS) has been studied widely in the last decade for its fast response and greater routing flexibility on job transportation. These features make AGVS a viable alternative for the job shop system, a typical environment for the manufacture of low-volume/high-variety job types.

This paper focuses on an unmanned job shop system where a finite set of job types is produced with a constant job mix. Each job type has a unique process plan, which comprises a set of distinct processing centres and respective required processing times. This type of production often results in a fluctuating transport requirement. The trend of a wider variety in job types also complicates the consequent job flow.

In the job shop considered in this paper, one critical feature is the finite input/output queuing space in front of the machine at each centre. In the shop, all centres are connected by an AGVS. Each job waits at one output queue to be picked up by the vehicle and transported to the input queues of its desired destination. As more jobs exist in the shop, the concurrent flow of multiple jobs will compete for these finite system resources. By a system resource here we mean a physical element of the

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system that is able to hold a job for transporting, operating, or storing. This phenomenon of contention often causes deadlocks. Roughly speaking, the shop deadlock results from a wrong resource allocation policy.

The controlling problems for an unmanned system differ considerably from those cited in the traditional scheduling literature due to a different set of operating conditions. In an unmanned system, a human is not available as an additional problem solver during the system operation. Hence, the occurrence of deadlock often gradually inhibits the job flow unless an automated remedial action is undertaken. In general, shop deadlock is difficult to predict in advance and will result in a very serious production loss as it happens.

It is known that a deadlock would occur if, and only if, the following four conditions hold simultaneously (Coffman *et al.* 1971).

(1) Mutual exclusion: no resource can be shared by more than one process at a time.
(2) Hold while waiting: processes hold at least one resource while waiting for additional required resources, which are currently being held by other processes, to become available.
(3) No pre-emption: processes holding resources determine when they are released.
(4) Circular wait: closed chain of processes in which each process is waiting for a resource held by the next process in the chain.

To most of the AMSs, the first three conditions are satisfied. Therefore, this paper focuses on the avoidance and resolution of a circular wait to avoid deadlocks. The approaches that are reported to handle deadlocks can be classified under three main categories.

(1) Prevention: statically establish deadlock-free operation on the basis of a set of generic rules ensuring that the above four necessary conditions for deadlocks cannot be simultaneously satisfied.
(2) Avoidance: dynamically allocate the system resources by using a suitable online control policy, which examines the feedback about the current resource allocation state, and possibly combine this with *a priori* knowledge of the job processing routes.
(3) Detection/recovery: allow deadlock to occur, then use effective mechanisms to detect and recover it.

Generally, the deadlock detection/recovery approach is overly optimistic. In addition, although the prevention and avoidance approaches often excessively restrict the use of resources and even penalize the system performance measures, they are more practical in reality. The avoidance method is normally more flexible than the prevention method. For instance, the Banker's algorithm (Dijkstra 1968) tries to prevent deadlock. The basic idea of this algorithm is that all possible future requests for resources can be satisfied with the current set of free resources at any time. However, the algorithm does not consider the order in which resources would be requested. It might prohibit free resources from being allocated to waiting jobs whenever the total future demand for the resource by the active jobs equals the resource capacity.

In this paper, all centres are arranged around a single loop and are served by a single multi-load vehicle. This type of layout configuration is simple and often used to be an independent sector of some complex AGVS layouts, such as tandem AGVS (Bozer and Srinivasan 1989, 1992), segmented bi-directional single-loop AGVS (Sinriech *et al.* 1996), and divided AGVS (Liu and Chen 1997, 1999). In these configurations, centres are divided into several closed loops. And a single dedicated vehicle, which traverses bi-directionally along the loop, is used to serve all centres within each loop. The number of divided loops and the number of centres included in one loop are affected by the capacity of the dedicated vehicle. If a job needs to be delivered to a centre, which is not located within the same loop, it will need more than one vehicle to carry it to its destination. To reduce the number of loops (i.e. the number of vehicles) required, therefore, a multi-load vehicle is a promising alternative. Multi-load AGV (MLAGV) can potentially reduce the deadhead and unproductive time of vehicles as it can load/unload more than one job along its immediate route. According to the report of Ozden (1988), when the loading capacity of the vehicle and the queue size of the centres are matched, a 50% reduction in fleet size is possible. However, it should be noted that unlike in the single-load AGV (SLAGV), the loading positions on the multi-load vehicle must move together once the vehicle is assigned whether these positions are empty or loaded. It is clear that when there is only one vehicle in the shop, the deadlock problem for the shop with finite system resources is often unavoidable. Consequently, a sophisticated vehicle methodology for controlling the arrangement of loading positions, i.e. controlling the movement of jobs in the shop, on the MLAGV is necessary.

The purpose of this paper is to propose a deadlock-free control strategy for a single multi-load vehicle on a job shop with finite queuing size. In the proposed strategy, the job flow and the allocation/arrangement of system resources are controlled under the principle of avoiding 'circular wait' states that is caused by the inappropriate movement of jobs.

After a brief review of the related literature, a hypothetical example is described in section 3. In section 4, a multi-load AGV control strategy is constructed. The performance of the proposed strategy and other two strategies are compared by computer simulation in section 5. The last section draws the conclusions.

2. Overview of related literature

The literature reviewed in this section is limited to the two issues studied in this work: multi-load AGVS (MLAGVS) and shop deadlock. In the following, each subsection considers each issue.

2.1. *Multi-load automated guided vehicle*

Despite the potential benefits and availability of MLAGVS, researches related to this topic are sparse.

Several researchers used analytical methods to model MLAGVS. Leung *et al.* (1987) proposed a mixed-integer-programming model to assign the vehicles with different loading capacities and travelling speed levels in the shop with the objective of minimizing the sum of loaded and empty travel time. At the same time, Hodgson *et al.* (1987) presented a heuristic control rule for one single/double-load vehicle using a Markov decision process. For a manufacturing system arranged around a single loop serviced by a single MLAGV, Sinriech and Palni (1998) proposed a binary integer programming model for its representation.

Simulation is often used to investigate the performance of MLAGVS. For instance, Ozden (1988) studied the interactions of several key factors (such as the fleet size, vehicle loading capacity, number of pallets and queues capacity) on the overall shop performance by a simulation model. Occena and Yokota (1993) focused on a just-in-time environment with multi-load vehicles and evaluated the effects of various vehicle loading capacities on both the transport and logistic performance. Moreover, it is known that a multi-load vehicle can carry more than one job at a time. This feature makes the efficiency of various job pickup rules used to decide which job should be picked up from the given output queue by the vehicles become important (Nayyar and Khator 1993, Lee *et al.* 1996). Under a simple 'go-when-filled' vehicle dispatching rule, Thonemann and Brandeau (1996, 1997) studied the design problems of MLAGVS on the shops where jobs need to be transported from a central depot to their destination. The finding in these studies emphasized the necessity to explore an efficient operation strategy of MLAGVs.

Tanchoco and Co (1994) provided a review of the various control problems in MLAGVS. Some control procedures were proposed in their study to dispatch vehicles. Subsequently, Bilge and Tanchoco (1997) discussed several key issues about MLAGVS and their potential benefits and made a conclusion that the transport performance of MLAGVS is less sensitive to the guidepath layout, and that the job arrival rate, which the AGVS can effectively handle, is significantly increased.

From the above discussion, it is shown that some researches are already being undertaken to study the control strategies of MLAGV. However, it is also noticed that none of these studies give a special attention to the deadlock problem inherent in the shop, which results from the finite system resources and inappropriate movement of jobs.

2.2. *Deadlock*

The deadlock problem in the area of manufacturing systems has only been considered in recent years, although the problem, in reality, has existed for many years. The main reason seems to be that deadlocks in conventional manufacturing systems were either prevented by simple flow design or detected and resolved by human intelligence. Although it has gradually become apparent after the introduction of automated control concepts, that several practical problems that arise in the control of an unmanned manufacturing system have not been studied.

Moving the jobs, which are causing vehicle blocking or whose current staying queues are full, to a temporary extra buffer may alleviate the deadlock (Egbelu and Tanchoco 1984). This approach, however, needs to consider several additional key issues, such as the location/capacity of the extra buffer, the tradeoffs among the additional transporting and cost, and the system performance. Another common approach is to control the number of jobs in the system, i.e. work-in-process, WIP (Taghaboni-Dutta and Tanchoco 1993, Kim, *et al.* 1997). That is, deadlock avoidance by controlling the shop congestion level.

Taghaboni-Dutta (1989) suggested a job dispatching method to avoid vehicles being blocked at input queues. When a job submits a transport request, the number of available spaces at its destined input queue is checked. If it is not greater than the number of jobs that are on the way to that queue, the job will not be handled until a queue space becomes available.

In the avoidance of shop deadlocks, the Petri-net scheme (Wu and Zhuang 1995, Banaszak and Krogh 1990) and graph-theoretical tools (Kim and Kim 1997) are applied extensively. However, these approaches are complex and static from the viewpoint that once they are constructed and implemented, it is not easy to modify them as the system configuration is changed.

3. Description of the job shop system under study

Figure 1 is the layout of a hypothetical example for the job shop environment described in the paper. Several related operating assumptions are listed below.

(1) Only one vehicle, which can carry up to two jobs, traverses bi-directionally on the single-loop guidepath, as shown by the bold line.
(2) Vehicle loading/unloading time is ignored in the example and the vehicle travels at a constant speed.
(3) Each processing centre has only one machine. Breakdown of the machines and the vehicle is not considered.
(4) S_i denotes the processing centre i, and I_i, O_i, M_i, respectively, denote its input queue, output queue, and processing machine, where $i = 1, 2, \ldots, 6$. For the sake of simplicity, the entrance/exit centre is denoted as the 0th centre.
(5) Each machine only processes one job at a time and cannot be interrupted during the process. Job input and output queues at processing centres are independently maintained with specified capacities and accessed on a first-come first-served basis. That is, only the job at the head of the output queue can warrant a transport request. Input and output queue capacities of each

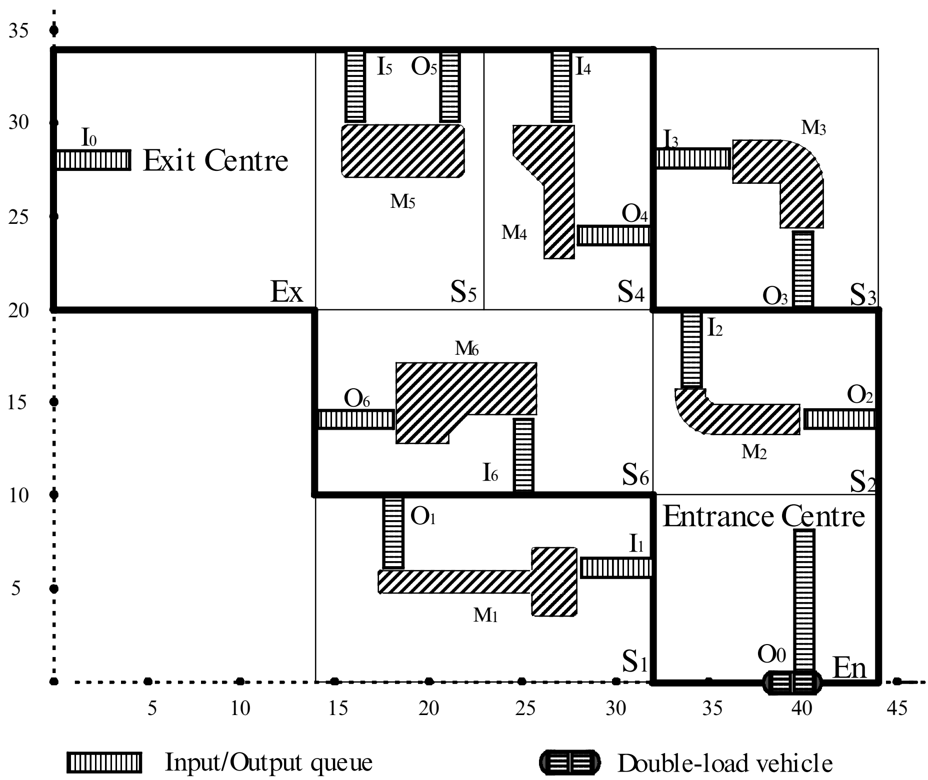

Figure 1. Layout of the hypothetical job-shop manufacturing system.

processing centre are set equal. The variable $C(b)$ is used as the capacity of queue b.
(6) When one new task is assigned, the vehicle takes the shortest path from its current location to the destination.
(7) Ten job types are processed in the system. Each job type has a prescribed process sequence, and processing times of various job types at different centres are constant.
(8) Jobs enter the system through the entrance centre according to a Poisson process with a mean λ. Various types are randomly assigned to the jobs according to the respective job mix.

4. Control strategy of multi-load AGVS in a single loop

In an unmanned shop with a single multi-load vehicle and several local input/output queues of finite capacity, two cases of circular wait events, as shown in figure 2, may occur when the vehicle tasks are assigned carelessly (Taghaboni-Dutta and Tanchoco 1993). In this figure, each (input/output) queue has three positions in which to store the waiting jobs and the vehicle loading capacity is 2. In figure 2(*a*), machine 1 is blocked by job 1, which cannot be moved to the full O_1, and a full vehicle ends up waiting to drop off two jobs to the full I_1. In this case, the centre 1 is called *chockfull* (i.e. M_1 is occupied by one job, and both O_1 and I_1 are full) and no jobs on the vehicle can be unloaded. Concurrent machine and vehicle blockages render any further assignment impossible for this vehicle unless corrective actions are taken. It is noted that, for an unmanned shop with a single vehicle, the situation in figure 2(a) is called *deadlock*. This emphasizes the importance and essentiality of a deadlock-free environment to the shop with only one vehicle.

When the vehicle controller only considers the transport request whose destined input queue is not full, the case of circular wait, as shown in figure 2(b), may occur. Job 2 at the head of the full O_1 will never be transported to its destination I_2 because centre 2 is chockfull. Likewise, job 3 on the chockfull centre 2 also cannot be transported to its destination I_1. A frequently cited solution for these two cases is to remove any one of the jobs, which generate circular wait, to an extra central buffer

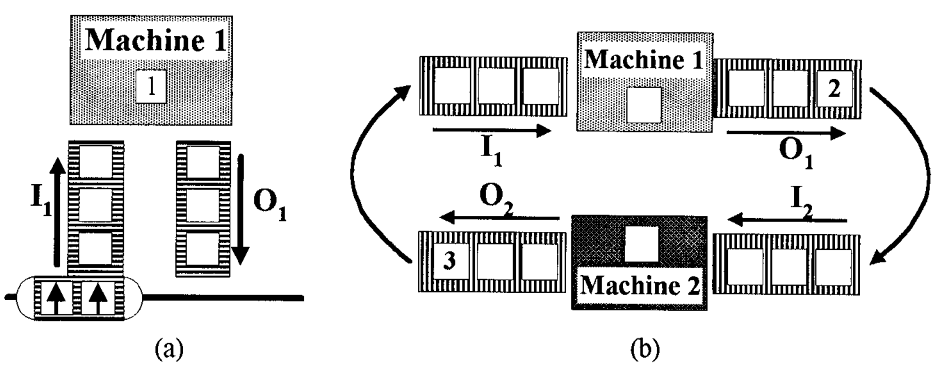

Figure 2. Two circular wait cases.

(Egbelu and Tanchoco 1984, Kim *et al.* 1997). In modern manufacturing environments, however, it is often impossible to set a large central buffer to handle deadlocks in the facility for the restriction on the available shop space. Moreover, it is worth noting that sometimes the additional transportation cost and storage cost for the central buffer are measurable when the total production cost is considered.

The proposed scheme in this paper uses part of the loading positions on the multi-load vehicle as a temporary buffer for the jobs, which causes vehicle/centre blockages, when necessary. In other words, the multi-load vehicle is employed as the tool for reducing the traffic control complexity when no extra central buffer is set.

In figure 2(*b*), the circular wait can be resolved by careful vehicle dispatching. For instance, one feasible dispatching sequence for a single empty two-load vehicle is:

> Assign the vehicle to O_1 and pick up job 2 → assign the vehicle to O_2 and pick up job 3 → assign the vehicle to I_2 then unload job 2 → assign the vehicle to I_1 then unload job 3.

Similarly, the chockfull centre 1 in figure 2(*a*) can be recovered if one of the two positions on board is kept available before the vehicle arrives at the centre. Provided the vehicle still has available loading space, careful vehicle loading space allocation planning can avoid this deadlock event by deciding which job should be picked up first and which job should be temporarily delayed. According to this idea, whenever there is only one available spare position on the partially loaded vehicle, the decision for the next task of the vehicle is critical regarding the occurrence of the case in figure 2(*a*).

With the simple discussion above, some vehicle control concepts employed in the research are summarized.

(1) The transport request on one centre will be given a higher priority if this centre is chockfull in the meantime.
(2) The vehicle can pick up one job only if loading this job will not create vehicle blockage.
(3) To ensure the finite system resources are utilized efficiently, the job, which has completed all required operations and is waiting to move to the exit centre, will be considered first to receive the transporting service for releasing the system resource it holds.

The proposed control strategy desires to use the real-time global information of the shop and a look-ahead check to make an appropriate arrangement for the finite system resources. Through this arrangement, the job flow among the shop is under a control that can prohibit the occurrence of shop deadlocks without using extra storage space as well as yield a satisfactory shop transport performance.

4.1. *Control strategy of MLAGV*

In the subsections below, different protocols for choosing the next task of the vehicle on various loading states are prescribed separately. In these protocols, the required shop processing information includes the vehicle loading states, waiting status on each queue, processing status of each machine, destinations of all jobs on board, etc. It is reasonable to assume that the mentioned information is real-time and acquirable from the shop for the vehicle controller in an AMS. In order to let the multi-load vehicle load and unload additional jobs en route, the positions on the vehicle are not reserved as the vehicle is assigned a pickup task. Therefore, these en-route actions may sometimes result in the scheduled vehicle task being disrupted. For reducing the unproductive travelling time of the vehicle and avoiding unexpected deadlocks, task reassignment is allowed whenever the vehicle controller finds this condition. Hereafter, the word 'vehicle' means 'multi-load vehicle' unless otherwise specified.

4.1.1. *Dispatching full vehicle*

The approach of dispatching the full vehicle will affect the time duration, which the vehicle spends waiting to unload the job(s) on board. It is possible that an input queue may be full at the time of the decision and one space may be available while the vehicle reaches this queue. For the AMS, with a single full loaded vehicle, some factors can be used to look ahead at the status of one input queue when the vehicle arrives at it, if the queue is assigned as the destination. For instance, these factors can include the travelling distance required by each job on board to its destination, from the vehicle current location Ω, the current waiting length at the destined input queue of each job on the vehicle, and the current processing status on each related machine. Using this idea, the waiting time spent by the vehicle for dropping off one job on some centre can be anticipated and reduced. Accordingly, the rule for dispatching a full vehicle at the decision point is stated as follows.

Rule: FVD

Step 1. If the destined centres of all jobs on the vehicle are chockfull at the decision point, a warning of shop deadlock is submitted. Otherwise, go to step 2.

Step 2. Look ahead the shortest time interval required for one space to become available on the destined input queue of each job on the vehicle from the decision point if this job is assigned as the next dropoff task of the full vehicle. For the job on the zth position of the vehicle, this interval τ_z is defined as:

$$\tau_z = \begin{cases} T_r(x(z)) & \text{if } I_{x(z)} \text{ is full but } S_{x(z)} \text{ is not chockfull at the decision point,} \\ \infty & \text{if } S_{x(z)} \text{ is chockfull at the decision point,} \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

where $x(z)$ is the destined centre of the job on the zth position of the vehicle, and $T_r(i)$ is the remaining processing time of the job on M_i.

Step 3. Choose the input queue of the centre $x(z^*)$, which satisfies the following expression, as the destination of the next vehicle delivery trip.

$$f_{x(z*)} = \mathrm{Max}\{[\mathrm{M}^+/D(\Omega, I_{x(z)})]^\alpha | \tau_z < D(\Omega, I_{x(z)}) \text{ and } S_{x(z)} \text{ is not chockfull, } \forall z\} \tag{2}$$

where, M^+ is the total length of the single-loop guidepath, and

$$\alpha = \begin{cases} 1.5 & \text{if } x(z) \text{ is the exit centre,} \\ 1 & \text{otherwise.} \end{cases} \tag{3}$$

If no destination can be decided, dispatch the vehicle to drop off the job whose next destined centre is not chockfull and has a minimum remaining processing time.

4.1.2. *Dispatching partially loaded vehicle*

At the moment the vehicle completes a delivery/pickup task and becomes partially loaded at its current location Ω, the vehicle will be assigned a new task, either pickup or delivery. In the case that Ω is an output queue and there is one immediate outstanding transport request waiting at this location, the vehicle will load this job if the vehicle controller ensures loading this job will not cause shop deadlock. Similarly, in the case that Ω is an input queue and this input queue is eligible for receiving one job from the vehicle, then it performs unloading activity. Here, an input queue is defined as *eligible* for the non-empty vehicle if it is the destination of any one job on this vehicle and carries at least one vacancy. Otherwise, decide the next task of the vehicle by the following partially loaded vehicle dispatching (PLVD) rule. In this rule, two categories of transport requests will be used to help the vehicle to decide its next task. (1) Blocking request: the request sent from a chockfull centre; and (2) finished request: the request has completed all prescribed operations and is waiting to move to the exit centre at one full output queue.

The basic ideas of this rule are to avoid the occurrence of shop deadlocks depending on the loading status of the vehicle, to mitigate the occurrence of chockfull centres, and use the looked-ahead earliest begin time to select the next vehicle destination from various pickup and dropoff candidates.

Rule: PLVD

Step 1. If there is only one remaining vacancy on the vehicle and all destined centres of the jobs on the vehicle are chockfull, identify O_{i^*} as the output queue such that

$$D(\Omega, O_{i^*}) = \mathrm{Min}\{D(\Omega,\ O_{x(z)}),\ \text{for each loaded position } z \text{ on the vehicle}\}. \tag{4}$$

If O_{i^*} could be identified, assign it as the destination of next vehicle pickup trip. Otherwise, go to step 2.

Step 2. If any immediate outstanding transport request exists in the shop, go to step 3. Otherwise, go to step 6.

Step 3. Let O_{i^*} as the nearest output queue, which has one immediate outstanding transport request which belongs to blocking or finished request as the destination of the next vehicle pickup task. If O_{i^*} could be identified, go to step 5. Otherwise, go to step 4.

Step 4. For each non-empty output queue O_i, check its current waiting length $c(O_i)$. Then, define its waiting-line ratio $r(O_i)$ as:

$$r(O_i) = c(O_i)/C(O_i) + u(i) + \beta. \tag{5}$$

$$\text{Where } u(i) = \begin{cases} 1 & \text{if } M_i \text{ is occupied by one job,} \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

$$\beta = \begin{cases} 0.5 & \text{if there is outstanding finished request on } O_i, \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

Then, choose O_{i^*} as the output queue such that

$$R(O_{i^*}) = \text{Max}\{r(O_i) \times d(O_i)/\bar{d} \mid \forall O_i, c(O_i) > 0\}. \tag{8}$$

where $d(O_i)$ is the time that the request on O_i has spent on waiting for the vehicle, and

$$\bar{d} = \text{Max}\{d(O_i) \mid \forall O_i, c(O_i) > 0\}. \tag{9}$$

Go to step 5.

Step 5. Among all jobs on the vehicle, identify $f_{x(z*)}$ by equation (2). If $f_{x(z*)}$ can be identified and $f_{x(z*)} > \{\text{M}^+/D(\Omega, O_{i^*})\}$, assign $I_{x(z*)}$ as the destination of the next vehicle trip. Otherwise, assign O_{i^*} instead.

Step 6. Choose the output queue O_{i^*} such that

$$D(\Omega, O_{i^*}) = \{D(\Omega, O_i) \mid \forall O_i, u(i) = 1, T_r(i) < D(\Omega, O_i)\}. \tag{10}$$

If O_{i^*} can be found, go to step 7. Otherwise, go to step 8.

Step 7. If $D(\Omega, O_{i^*}) \leq \text{D}(\Omega, I_{x(z)})$ for each non-empty position z on the vehicle, assign O_{i^*} as the destination of the next vehicle pickup trip. Otherwise, go to the next step.

Step 8. Among all jobs on the vehicle, identify $f_{x(z*)}$ by equation (2). If $z*$ cannot be identified, reset $z*$ as the position z on the vehicle such that

$$\bar{f}_{x(z*)} = \text{Max}\{\text{M}^+/T_r(x(z),\ \text{for each loaded position } z \text{ on the vehicle}\}. \tag{11}$$

Go to the next step.

Step 9. If $\bar{f}_{x(z*)} > \{M^+/D(\Omega, O_{i^*})]$, assign $I_{x(z*)}$ as the destination of next vehicle trip. Otherwise, assign O_{i^*} instead.

4.1.3. *Dispatching empty vehicle*

Whenever the vehicle completes a prescribed delivery task and becomes empty, if there is any immediate outstanding transport request in the shop, the destination for the next vehicle pickup task needs to be decided. In the case that Ω is an output queue and an immediate outstanding transport request is waiting on this queue, the vehicle is assigned to it. Otherwise, decide the destination of the next vehicle pickup task by the following empty vehicle dispatching (EVD) rule. In this rule, the first target is the chockfull centre in the shop and the second one is the request whose current centre has the most jobs waiting for transfer.

Rule: EVD

Step 1. Identify O_{i^*} as the destination of the next vehicle pickup trip by step 3 of rule PLVD. If O_{i^*} cannot be identified, go to the next step.

Step 2. For each non-empty output queue O_i, calculate its waiting-line ratio by equation (5). Choose O_{i^*}, which satisfies equation (8), as the destination of the next vehicle pickup task.

4.2. *Accommodate additional jobs en route*

The vehicle with the remaining loading space is allowed to load/unload additional jobs along the route to its intended destination assigned by the PLVD, EVD or FVD rule. When the vehicle meets one eligible input queue on its current route, then the respective job(s) is unloaded. Likewise, if the vehicle encounters one output queue with an immediate outstanding transport request, the following procedure is used to decide whether to grant this request or not.

Procedure: loading one job en route

Case 1. *The vehicle is dispatched to I_{i^*} by rule PLVD*

Step 1. Grant this request. Then, if another immediate outstanding transport request is generated on the current queue and the vehicle has remaining loading space, repeat step 1. Otherwise, go to step 2.

Step 2. The vehicle keeps moving toward I_{i^*} along its current route.

Case 2. *The vehicle is dispatched to O_{i^*} by rule EVD or PLVD*

Step 1. If only one remaining space is available on the vehicle, go to step 3. Otherwise, grant this request and go to step 2.

Step 2. If another immediate outstanding transport request is then generated on the current queue, go to step 1. Otherwise, go to step 4.

Step 3. Attend this request if this job, or any one job that has already ridden on the vehicle, will be dropped off to its desired input queue, which needs to be located on the vehicle current path to O_{i^*}, immediately as the vehicle arrives at that queue. Otherwise, go to step 4.

Step 4. The vehicle keeps moving toward O_{i^*} along its current route.

Instead of attending arbitrarily any request that the vehicle meets en route, this procedure helps to avoid the deadlock caused by a careless pickup activity, and enhances the vehicle utilization concurrently.

4.3. *Awaiting location of the idle vehicle*

Unless the shop is overloaded, the occurrence of vehicle idleness is inevitable. One dispatching issue that deserves attention is regarding the parking of the empty vehicle when it becomes idle. An empty vehicle is said as idle when it is functional but no immediate outstanding transport request exists in the shop. To an efficient AGVS, it is necessary to reduce the vehicle-empty travelling time from its current awaiting location to the queue where one transport request is generated. In this work, the determination of the awaiting location for the idle vehicle in a loop layout is addressed simply by looking ahead to the location and instant of generating one new transport request in the shop. It is noted that, if an immediate transport request is generated while the idle vehicle is on the route to the assigned awaiting location, the vehicle will cancel its current trip and attend that request.

Procedure: Awaiting Location Assignment (ALA)

Step 1. If all machines are currently idle, dispatch the vehicle to O_0. Then, wait there until a new job is ready to enter the shop. Otherwise, go to the step 2.

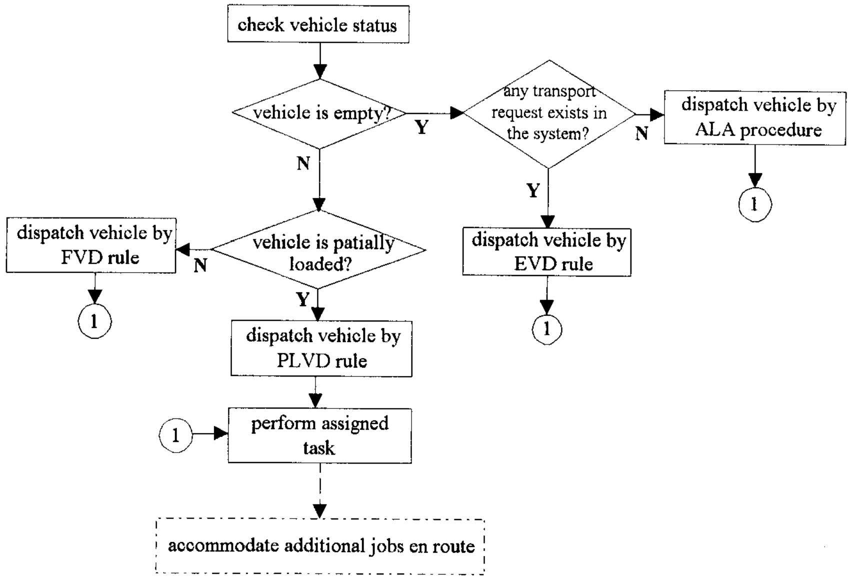

Figure 3. Relationship diagram between rules and procedures proposed in this work.

Step 2. Let O_{i^*} be the nearest output queue that satisfies the following expression:

$$T_r(i^*) \leq D(\Omega, O_{i^*}), \ \forall O_i, u(i) = 1. \tag{12}$$

If O_{i^*} can be specified, then assign O_{i^*} as the awaiting location of the idle vehicle. Otherwise, go to step 3.

Step 3. Select O_{i^*} such that

$$T_r(i^*) = \text{Min}\{T_r(i) \mid \forall S_i, u(i) = 1\}. \tag{13}$$

If O_{i^*} can be identified and $T_r(i^*) \leq D(\Omega, O_0)$, assign it as the awaiting location of the idle vehicle. Otherwise, go to the next step.

Step 4. Calculate the probability P that, from the current time, there is at least one job that will be ready to enter the shop on O_0 during $T_r(i^*)$. If P is greater than a prescribed threshold value θ, assign O_0 as the awaiting location of the idle vehicle. Otherwise, assign O_{i^*} instead.

To summarize the rules and procedures described in the section, the figure 3 shows the overall relationships between them.

5. Alternative strategies

The main concept of the proposed multi-load vehicle control strategy in section 4 is to avoid shop deadlock by appropriately allocating the finite system resources based on the task assignment of the vehicle instead of setting any extra storage and controlling the shop WIP level. To verify the performance of the proposed strategy, the other two frequently cited concepts of avoiding deadlocks are investigated.

- **Limiting the maximum shop WIP level to a constant:** based on Kim *et al.* (1997), the minimum number of jobs that can cause a shop deadlock is the sum of the capacities of two centres with the smallest capacities when no central buffer is used. Based on this concept, the maximum shop WIP in one alternative strategy is kept at the number defined as the minimum sum of the total holding capacities of any two processing centres, minus one. Because the holding capacity of one processing centre i is equal to the sum of $C(I_i)$, $C(O_i)$, and its machine capacity (i.e. 1 in this paper), the threshold value can therefore be written as:

$$\mathrm{Min}\{C(I_i) + C(O_i) + C(I_j) + C(O_j)\} + 1, \text{ for any two processing centres } i,j. \tag{14}$$

This restriction may reduce the resource utilization and so suffer shop throughput when the queue capacity is small, but it can guarantee that deadlocks will never occur.

- **Setting an extra central buffer:** this is a widely used approach for deadlock avoidance in literature (Okogbaa and Huang 1992). In this work, a central buffer with infinite capacity is settled in the neighbourhood of the exit centre. This infinite capacity setting provides an opportunity to examine the maximum extra buffer space required for guaranteeing a deadlock-free operation. The job — which creates vehicle blocking or both its current staying output queue and destined input queue are full — will be moved to the central buffer. However, if one space becomes available on the destined input queue while the job is on the way to the central buffer, the vehicle controller will cancel the current trip of the vehicle and reassign the vehicle. By this design, the time required for one space on the vehicle becoming available can be shortened.

Based on the concepts above, the other two alternative strategies are constructed to investigate the efficiency of the proposed strategy. For easily differentiating, the proposed strategy, the strategy with limited shop WIP level, and the strategy with a central buffer are denoted as strategies I, II and III, respectively. Unlike strategy I, the latter two strategies only make use of partial shop information, e.g. the waiting-line length on each output queue, travelling distance, and destination of each transport request. In strategies II and III, a transport request is deliverable if its destined input queue is not full at the current decision time. For deciding the next vehicle task, the following procedure will be used.

Step 1. If the vehicle is not full, compute the waiting-line rate of each output queue that has one immediate outstanding deliverable transport request. Unlike strategy I, the waiting-line rate $r(O_i)$ for an output queue O_i is defined as $c(O_i)/C(O_i)$. Then, select O_{i^*} by applying the revised $r(O_i)$ to equation (8).

Step 2. If the vehicle is not empty, identify $I_{x(z*)}$ such that

$$D(\Omega, I_{x(z*)}) = \mathrm{Min}\{D(\Omega, I_{x(z)}), \text{for each loaded position } z \text{ on the vehicle}\}. \tag{15}$$

Step 3. If both O_{i^*} and $I_{x(z*)}$ can be identified, select either one of them by the nearest-first criterion as the destination of the next vehicle trip. Otherwise, choose the one that can be identified.

In the next section, strategy I is compared with strategies II and III for assessing its efficiency by simulation analyses.

6. Simulation experiments and results

A set of experiments is designed to investigate the effectiveness of the proposed vehicle control strategy. The hypothetical job-shop manufacturing system presented in section 3 is modelled by the visual simulation package AutoMod (1998) and is run on a Pentium II PC.

6.1. *Design of experiment*

Four design parameters are considered in the experiments: P/T ratio, mean job arrival rate λ (jobs per hour, jh^{-1}), local input/output queue capacity C, and vehicle control strategies S.

Given a set of job types, the ratio of their total scheduled processing time to their total essential minimum transferring time is called the P/T ratio and is used as an index to represent the criticality of processing capacity. To study the influence of various P/T ratios on the performance of three strategies, three different ratio levels: 4, 5 and 6 are considered. Through the combination of various P/T ratios and job arrival rates, the system workload level can be diversified.

The column λ of the nested tables 1, 2 and 3 lists four mean job arrival rates: 10, 15, 20 and 22 jh^{-1}. Column C lists five input/output queue capacities, namely, 1, 2, 3, 4 and 5. Finally, three control strategies I, II and III are arranged in column S. Hence, a total of 180 ($= 3 \times 4 \times 5 \times 3$) simulation models are needed. In addition, given one P/T ratio, 40 sets of process plans are generated for each group of ten job types according to the following procedure to reduce the effect of some specific process plans and to hold statistical normalization.

Step 1. Each job type is assigned three or four processes by the same probability. Then, the processing centres are randomly specified one by one to each process sequence. No job will be processed at the same centre twice or more.

Step 2. As one process sequence is generated, the total minimal transferring time required by this job type can be computed.

Step 3. The total scheduled processing time for this job type equals the multiplication of the given P/T ratio and its total minimum transferring time. Then, for each job type, the following sub-steps are used to decide the processing time on each scheduled centre.

Step 3.1. Generate three (four) random numbers within the range $[1/3 \pm 0.1]$ ($[1/4 \pm 0.1]$) according to a uniform distribution.

Step 3.2. Normalize those numbers such that their sum equals one.

Step 3.3. Multiply the total scheduled processing time with each normalized number.

Incidentally, the threshold value θ in strategy I is set at 0.8 in these experiments.

Each simulation experiment is run for 26 simulation hours. To eliminate the initial transient bias, the output during the first two simulation hours is discarded in all runs. To each simulation model, the mean and standard deviation (std.) of the 40 problems are computed for several performance criteria.

In this study, the performance criteria investigated during each simulation run include:

- PI_1: the shop throughput,
- PI_2: the average riding time (seconds) of one job on the vehicle per trip,

λ	C	S	PI1		PI2		PI3		PI4		PI5	
			Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
10	1	I	242	16.94	62.43	5.66	0.36	0.03	25.48	19.02	71.09	21.78
		II	238	14.79	56.17	2.95	0.35	0.03	10.93	5.29	66.53	31.20
		III	242(4*)	16.89(1.5**)	58.02	3.05	0.36	0.03	59.88	43.57	79.07	26.33
	2	I	241	17.10	56.17	3.92	0.38	0.03	0.68	1.42	18.71	36.16
		II	242	17.07	56.00	2.93	0.36	0.03	0.58	0.90	31.96	61.71
		III	241(2)	17.03(0.87)	55.24	2.87	0.36	0.03	1.55	2.23	27.10	39.42
	3	I	242	17.15	54.66	3.43	0.36	0.03	0.00	0.00	0.00	0.00
		II	241	17.24	55.89	3.08	0.36	0.03	0.05	0.22	3.26	19.13
		III	241(1)	17.22(0.63)	55.20	2.95	0.36	0.03	0.05	0.32	2.08	13.14
	4	I	242	16.95	54.20	2.95	0.36	0.03	0.00	0.00	0.00	0.00
		II	241	17.24	55.59	2.93	0.36	0.03	0.00	0.00	0.00	0.00
		III	241(1)	17.00(0.48)	55.14	2.96	0.36	0.03	0.00	0.00	0.00	0.00
	5	I	242	17.02	54.04	2.92	0.36	0.03	0.00	0.00	0.00	0.00
		II	241	17.23	55.58	2.95	0.36	0.03	0.00	0.00	0.00	0.00
		III	241(1)	17.13(0.22)	55.10	2.93	0.36	0.03	0.00	0.00	0.00	0.00
15	1	I	334	13.46	73.90	4.98	0.49	0.03	144.03	33.51	105.22	11.82
		II	269	15.29	57.90	2.71	0.40	0.01	15.40	6.35	62.25	14.99
		III	321(11)	20.26(10.24)	65.99	2.94	0.48	0.03	332.95	68.09	126.13	22.05
	2	I	350	15.05	66.63	4.22	0.52	0.04	23.35	15.79	77.42	24.29
		II	341	13.82	62.60	2.84	0.50	0.03	3.03	2.81	73.12	77.43
		III	348(4)	15.46(1.98)	62.73	3.23	0.52	0.04	70.50	46.78	87.69	22.22
	3	I	353	15.63	63.62	3.42	0.52	0.04	4.55	5.10	51.03	46.15
		II	351	15.04	62.95	2.95	0.52	0.04	1.25	1.51	43.99	64.14
		III	351(2)	15.18(1.00)	62.41	3.18	0.52	0.04	19.83	24.22	78.38	54.33
	4	I	353	15.68	62.49	3.03	0.53	0.04	0.80	1.91	16.42	33.27
		II	352	15.27	62.83	2.80	0.52	0.04	1.33	2.26	22.50	36.88
		III	352(1)	15.18(0.89)	62.23	2.92	0.52	0.04	9.03	18.50	44.49	41.08
	5	I	354	16.01	61.87	3.04	0.53	0.04	0.43	1.39	11.18	30.58
		II	351	15.36	62.91	2.91	0.52	0.04	2.18	5.65	24.12	38.04
		III	353(1)	15.62(0.93)	62.19	2.95	0.53	0.04	3.50	11.03	23.15	35.44
20	1	I	340	16.36	74.68	4.52	0.50	0.02	157.00	30.17	107.92	11.30
		II	269	14.34	57.74	2.61	0.40	0.01	15.60	5.98	63.84	21.23
		III	322(11)	21.80(9.14)	66.42	2.69	0.48	0.03	362.95	44.43	129.69	18.87
	2	I	369	17.62	68.67	3.58	0.54	0.03	41.53	16.55	81.32	18.38
		II	350	17.05	63.16	2.73	0.52	0.02	3.78	2.20	66.73	41.89
		III	365(5)	19.59(4.67)	64.39	2.58	0.54	0.03	115.70	48.13	99.83	21.11
	3	I	380	17.14	66.00	3.31	0.56	0.03	12.40	10.08	68.79	24.27
		II	373	15.88	64.65	2.36	0.55	0.03	3.90	3.54	58.98	52.96
		III	377(3)	17.82(2.34)	64.36	2.38	0.56	0.03	56.83	41.70	90.10	22.66
	4	I	385	15.83	64.70	2.79	0.57	0.03	5.93	5.89	61.16	39.07
		II	380	14.60	64.79	1.92	0.56	0.03	4.50	5.59	48.70	40.33
		III	380(2)	17.77(1.46)	64.61	2.21	0.56	0.03	39.30	41.39	77.11	29.36
	5	I	387	15.49	64.37	2.67	0.58	0.03	3.68	6.41	30.06	34.91
		II	380	13.58	65.14	2.18	0.56	0.03	6.63	9.09	48.08	40.84
		III	380(2)	16.03(1.23)	64.61	2.36	0.57	0.03	30.90	39.41	78.35	27.60
22	1	I	341	16.68	74.31	4.81	0.50	0.02	155.95	25.46	106.66	8.97
		II	270	14.18	57.56	2.67	0.40	0.01	15.38	6.29	63.02	24.57
		III	325(9)	20.66(5.90)	66.28	2.78	0.48	0.03	358.80	50.32	129.50	15.25
	2	I	369	18.02	68.76	3.55	0.55	0.03	43.95	17.76	82.41	18.85
		II	351	16.67	63.10	2.42	0.52	0.02	3.48	2.94	71.29	66.50
		III	365(4)	19.70(2.64)	64.46	2.63	0.54	0.03	115.78	45.86	100.85	17.86
	3	I	382	16.06	65.99	3.11	0.56	0.03	13.63	10.72	70.59	28.25
		II	375	15.39	64.38	2.29	0.55	0.03	3.08	3.05	50.79	57.23
		III	377(3)	16.76(1.45)	64.39	2.31	0.56	0.03	53.85	37.45	85.92	22.69
	4	I	388	16.96	64.61	2.84	0.57	0.03	5.70	7.35	48.82	39.14
		II	380	13.94	64.87	2.15	0.56	0.03	4.73	5.02	68.75	96.94
		III	382(2)	16.91(1.29)	64.63	2.26	0.56	0.03	35.28	35.03	80.13	22.15
	5	I	390	15.49	64.15	2.77	0.58	0.03	4.20	6.62	33.68	41.36
		II	382	14.57	65.13	2.38	0.56	0.03	7.65	10.25	51.34	42.76
		III	383(2)	16.39(1.49)	64.79	2.14	0.57	0.03	28.90	38.65	68.58	35.10

*: the mean of the maximal size of the reserved storage required;

**: the standard deviation of the maximal capacity of the reserved storage required.

Table 1. The simulation results when P/T ratio is set to 4.0

λ	C	S	PI_1		PI_2		PI_3		PI_4		PI_5	
			Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
10	1	I	241	16.32	72.65	9.45	0.45	0.04	27.65	19.17	109.17	35.37
		II	227	12.10	55.97	3.00	0.42	0.02	6.58	3.39	99.68	48.99
		III	241(*6*)	16.17(*3.57*)	58.73	3.11	0.45	0.04	51.08	41.66	85.50	26.31
	2	I	241	16.36	61.00	7.81	0.45	0.04	1.15	2.76	36.86	88.19
		II	241	16.56	57.11	3.39	0.45	0.04	0.95	1.75	40.98	72.58
		III	241(*3*)	16.57(*1.71*)	55.98	3.15	0.45	0.04	2.53	5.75	39.17	62.77
	3	I	241	16.82	56.93	6.64	0.45	0.04	0.13	0.79	4.12	26.05
		II	241	16.73	56.33	3.86	0.45	0.04	0.30	1.20	26.54	115.14
		III	241(*2*)	16.87(*1.38*)	55.32	2.80	0.45	0.04	0.25	0.74	16.49	46.97
	4	I	241	16.56	55.21	5.45	0.48	0.04	0.00	0.00	0.00	0.00
		II	241	16.86	56.06	3.51	0.45	0.04	0.20	0.79	20.83	86.13
		III	241(*1*)	16.74(*1.20*)	55.06	3.09	0.45	0.04	0.03	0.16	1.29	8.17
	5	I	241	16.70	54.78	4.71	0.45	0.04	0.00	0.00	0.00	0.00
		II	241	16.81	55.88	3.41	0.45	0.04	0.00	0.00	0.00	0.00
		III	241(*1*)	16.81(*0.87*)	54.90	2.94	0.45	0.04	0.03	0.16	1.08	6.82
15	1	I	308	18.19	87.45	6.53	0.57	0.03	111.45	16.71	137.54	20.94
		II	238	13.80	56.42	2.90	0.44	0.01	7.55	3.43	103.30	41.30
		III	300(*24*)	23.04(*20.77*)	66.73	2.61	0.56	0.04	277.83	49.25	138.51	19.37
	2	I	327	19.12	78.42	7.62	0.61	0.04	19.85	12.00	102.67	38.98
		II	315	17.83	62.57	2.74	0.58	0.03	2.83	3.51	100.16	78.56
		III	330(*10*)	22.67(*13.05*)	64.83	3.55	0.62	0.04	68.33	41.79	119.22	42.40
	3	I	336	18.68	73.08	8.31	0.62	0.04	3.53	4.04	56.52	52.02
		II	335	18.19	64.53	3.21	0.62	0.04	2.28	4.00	122.52	122.61
		III	338(*7*)	20.18(*7.78*)	63.98	3.46	0.63	0.05	27.43	31.75	114.68	74.07
	4	I	340	20.09	70.86	8.54	0.63	0.05	1.30	2.44	29.80	44.46
		II	340	18.96	65.17	3.49	0.63	0.05	2.93	7.17	112.74	197.82
		III	340(*6*)	20.13(*7.04*)	63.53	3.57	0.64	0.05	14.85	20.94	81.16	76.29
	5	I	341	20.34	69.56	8.51	0.63	0.05	0.13	0.46	5.54	19.82
		II	340	19.37	65.30	4.00	0.64	0.05	2.10	5.70	101.73	185.87
		III	340(*6*)	20.57(*7.07*)	63.44	3.65	0.64	0.05	8.08	15.14	87.42	103.97
20	1	I	307	18.11	88.33	6.70	0.57	0.03	116.05	18.25	133.38	16.92
		II	238	13.46	56.34	2.76	0.44	0.01	6.85	3.31	95.71	41.87
		III	300(*31*)	28.28(*43.99*)	66.84	2.86	0.57	0.03	287.45	48.30	139.84	27.02
	2	I	333	24.20	80.48	7.28	0.61	0.04	24.88	10.48	104.20	30.92
		II	316	19.40	62.74	2.69	0.58	0.03	3.03	2.92	120.45	79.34
		III	338(*10*)	26.42(*14.94*)	66.01	3.13	0.63	0.04	98.15	49.77	132.72	36.21
	3	I	345	25.28	76.50	7.38	0.64	0.05	6.00	4.98	93.76	49.23
		II	343	23.09	65.54	2.30	0.63	0.04	3.15	4.79	132.86	134.62
		III	350(*10*)	27.33(*14.94*)	65.58	3.02	0.65	0.05	52.35	39.01	131.81	44.17
	4	I	352	27.65	74.23	7.80	0.65	0.05	1.50	2.05	37.55	47.55
		II	353	25.46	66.71	2.68	0.65	0.05	3.68	7.83	154.94	154.66
		III	354(*10*)	29.14(*16.10*)	65.50	2.94	0.66	0.05	33.73	35.36	128.86	60.08
	5	I	356	28.83	73.07	8.16	0.66	0.05	1.38	2.76	27.64	42.18
		II	357	26.08	66.96	2.52	0.66	0.05	3.88	8.79	141.28	157.38
		III	356(*9*)	28.92(*12.96*)	65.60	2.79	0.67	0.05	29.35	35.38	127.82	73.15
22	1	I	310	20.04	87.36	7.17	0.57	0.03	114.58	15.29	133.66	14.61
		II	238	13.90	56.50	2.54	0.44	0.01	6.85	3.74	98.12	46.24
		III	302(*28*)	24.98(*27.97*)	66.85	2.59	0.57	0.03	287.58	44.39	135.73	20.45
	2	I	334	23.80	80.13	7.11	0.62	0.04	23.20	10.38	101.34	39.31
		II	317	18.95	62.70	2.53	0.58	0.03	2.75	2.77	99.42	84.44
		III	341(*9*)	25.26(*14.13*)	65.66	2.90	0.63	0.04	92.58	36.08	127.98	35.07
	3	I	348	26.67	76.06	7.73	0.64	0.05	5.00	4.62	83.26	61.10
		II	345	23.81	65.74	2.70	0.63	0.04	2.80	4.54	152.84	122.40
		III	352(*6*)	27.01(*12.08*)	65.54	2.95	0.65	0.05	49.40	37.26	131.47	46.84
	4	I	355	28.30	74.17	8.02	0.65	0.05	2.58	3.88	55.31	58.92
		II	355	25.63	66.70	2.79	0.65	0.05	2.45	5.02	142.69	171.37
		III	358(*6*)	27.90(*11.66*)	65.54	2.85	0.66	0.05	32.85	32.96	127.26	64.38
	5	I	359	28.95	72.87	8.36	0.66	0.05	1.20	2.15	20.16	35.25
		II	360	26.99	67.07	2.97	0.66	0.05	2.53	5.78	104.08	168.96
		III	360(*7*)	30.42(*15.04*)	65.40	3.08	0.67	0.05	23.70	32.48	113.31	80.17

Table 2. The simulation results when P/T ratio is set to 5.0.

λ	C	S	PI1		PI2		PI3		PI4		PI5	
			Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
		I	237	15.59	90.72	14.84	0.53	0.04	39.13	27.08	146.60	41.12
	1	II	207	12.95	55.12	3.03	0.46	0.01	5.65	2.90	121.72	55.46
		III	238(*11*)	16.82(*8.94*)	60.26	3.02	0.53	0.05	41.43	38.38	104.22	31.11
		I	238	15.67	73.92	14.84	0.53	0.05	3.08	5.46	69.07	85.10
	2	II	239	15.77	58.63	4.11	0.53	0.05	1.75	2.82	91.07	108.70
10		III	239(*6*)	16.19(*5.86*)	57.24	3.80	0.53	0.05	3.10	6.25	51.96	76.79
		I	238	15.96	65.41	13.99	0.53	0.05	0.35	1.08	24.31	82.89
	3	II	239	16.10	58.25	4.83	0.53	0.05	1.30	2.72	93.61	140.20
		III	239(*4*)	15.98(*5.54*)	55.88	3.46	0.53	0.05	0.48	1.20	19.35	52.48
		I	239	16.03	61.51	12.98	0.53	0.05	0.05	0.32	2.49	15.78
	4	II	239	16.15	57.55	5.12	0.53	0.05	0.93	3.02	40.80	122.99
		III	239(*3*)	15.91(*4.97*)	55.47	3.41	0.53	0.05	0.18	0.68	12.56	52.94
		I	239	15.96	59.20	12.21	0.53	0.05	0.10	0.63	3.46	21.90
	5	II	239	15.99	57.20	5.10	0.53	0.05	0.48	1.74	33.50	115.41
		III	239(*3*)	16.01(*4.46*)	55.29	3.32	0.53	0.05	0.15	0.58	5.76	30.03
		I	274	20.35	104.93	9.26	0.61	0.03	96.55	14.95	168.56	30.61
	1	II	211	13.76	55.48	2.91	0.47	0.01	4.85	2.34	104.88	52.54
		III	271(*68*)	26.78(*38.30*)	66.64	2.41	0.64	0.04	191.65	46.76	143.22	20.92
		I	291	24.52	96.76	10.41	0.65	0.04	19.48	8.27	144.76	43.78
	2	II	279	19.49	62.69	3.08	0.62	0.03	3.45	3.43	169.58	144.11
		III	301(*35*)	26.97(*29.41*)	66.17	3.54	0.69	0.04	57.55	34.34	164.98	43.52
		I	298	26.83	92.17	12.24	0.67	0.05	4.88	4.22	112.33	68.69
15	3	II	300	25.73	66.14	3.61	0.66	0.05	4.28	6.02	221.62	205.01
		III	306(*32*)	29.10(*27.01*)	65.90	3.54	0.70	0.05	35.58	27.35	165.32	63.25
		I	302	29.05	89.37	13.37	0.68	0.06	1.50	2.13	50.29	77.92
	4	II	305	29.24	68.20	4.66	0.68	0.06	4.30	6.71	203.20	161.60
		III	307(*30*)	29.00(*27.52*)	65.40	3.68	0.70	0.05	24.68	23.09	179.48	77.24
		I	304	30.22	87.41	14.32	0.68	0.06	0.68	1.38	33.38	75.94
	5	II	307	30.24	69.08	4.63	0.68	0.06	4.08	6.34	254.00	241.75
		III	306(*28*)	29.83(*27.47*)	65.26	3.88	0.71	0.05	21.28	22.33	162.38	105.52
		I	272	20.00	106.22	9.28	0.60	0.03	96.08	12.82	173.20	29.48
	1	II	210	13.37	55.57	2.92	0.46	0.01	5.48	2.73	110.69	37.22
		III	267(*86*)	30.37(*55.95*)	66.71	2.71	0.64	0.04	199.80	50.11	147.43	21.71
		I	289	26.62	98.83	11.10	0.64	0.05	22.33	10.22	139.67	38.16
	2	II	278	19.89	62.48	2.72	0.61	0.03	3.70	3.47	192.03	122.59
		III	301(*45*)	32.01(*44.96*)	66.99	3.35	0.69	0.05	80.83	43.94	181.35	45.09
		I	299	29.79	94.22	12.05	0.66	0.06	6.88	5.40	132.09	115.52
20	3	II	300	27.73	66.49	3.38	0.66	0.05	5.25	6.98	208.27	142.79
		III	307(*42*)	34.88(*46.09*)	66.96	3.27	0.71	0.05	53.00	39.16	192.98	60.72
		I	304	32.62	92.14	12.97	0.68	0.06	2.48	3.16	74.74	96.09
	4	II	308	31.76	69.52	1.02	0.68	0.06	5.85	8.17	258.62	226.00
		III	310(*40*)	35.32(*45.09*)	66.87	3.13	0.72	0.05	45.78	40.75	205.20	71.73
		I	307	34.05	91.07	13.22	0.68	0.07	1.18	1.97	38.06	58.23
	5	II	310	33.87	69.84	3.73	0.69	0.07	6.20	9.65	270.93	157.33
		III	310(*41*)	37.74(*47.61*)	66.79	0.51	0.72	0.06	41.85	38.07	218.96	75.36
		I	275	19.93	105.09	9.14	0.61	0.04	93.33	10.65	171.39	32.87
	1	II	211	13.43	55.24	2.73	0.47	0.01	4.78	2.90	103.97	55.69
		III	270(*83*)	30.85(*54.85*)	66.84	2.36	0.65	0.04	200.03	46.32	149.98	23.58
		I	294	27.33	96.76	10.80	0.65	0.05	19.98	9.47	135.86	37.17
	2	II	279	19.94	62.36	3.31	0.62	0.04	3.63	3.01	166.46	111.72
		III	303(*43*)	31.51(*43.31*)	66.93	2.95	0.69	0.05	78.85	36.98	169.10	43.80
		I	303	29.57	92.87	11.48	0.67	0.06	5.48	4.41	117.67	69.76
22	3	II	302	27.94	66.56	3.75	0.67	0.06	4.20	5.25	231.23	171.50
		III	311(*39*)	33.85(*43.34*)	66.99	3.21	0.71	0.05	55.45	38.47	184.63	55.24
		I	308	31.84	91.04	12.05	0.68	0.06	1.70	2.84	61.90	82.74
	4	II	310	32.27	68.97	3.90	0.69	0.06	4.65	6.68	257.39	169.11
		III	313(*40*)	34.69(*46.36*)	67.22	3.24	0.72	0.05	41.38	30.76	186.65	72.43
		I	310	33.71	90.03	12.55	0.69	0.07	0.85	1.53	41.29	75.29
	5	II	313	33.87	70.47	3.81	0.69	0.07	5.50	9.06	281.97	185.70
		III	313(*39*)	36.42(*45.43*)	67.26	3.38	0.72	0.05	40.00	35.33	202.98	76.56

Table 3. The simulation results when P/T ratio is set to 6.0.

- PI_3: the average machine utilization,
- PI_4: the frequency of machine blockage occurring, and
- PI_5: the average duration (seconds) of each machine blockage event.

In PI_4 and PI_5, the machine blockage is an event where a machine cannot immediately release the job just completed since the output queue in front of the machine is full. This is one of the four essential conditions for deadlock occurring: hold while waiting. This event leads to the fact that this machine cannot be temporarily available for other waiting jobs. The mean values of these criteria are the main subjects in the analysis phase. In addition, the std. levels will show the performance variation on each group of 40 problems. Generally, from the viewpoint of management, a good control strategy will yield high throughput, low riding time, high machine utilization, low machine blockage frequency, and low machine blockage duration.

6.2. *Output analysis*

The results for three different P/T ratio levels are summarized in tables 1, 2 and 3, separately. In these tables, it is observed that strategy I is a promising vehicle control strategy when compared with the other two strategies. It is noticed that given a P/T ratio, the throughput of strategy I is less sensitive to the queue capacity when $\lambda = 10$. For the cases with larger λ levels, strategy I also yields satisfactory throughput levels without limiting the maximal shop WIP level and using any extra storage.

In strategy I, using part of the vehicle loading positions as a temporary buffer leads to a higher PI_2 level than the other two strategies for most experiment models. However, the concept of considering the current waiting-line as well as the status of those jobs that are processing gives a higher priority to recovering impending machine blockages. To some manufacturing systems, a machine blockage is unallowable as it may result in serious production losses and unexpected equipment breakdowns. In strategy II, for the sake of limiting the maximum shop WIP level, the occurrence of machine blockage is kept at a low level. However, for the shops where queues have only one capacity, the suffered throughput is noteworthy.

In strategy III, the shop is designed to recover from the deadlocks by using a central buffer. Examining the results in tables 1, 2 and 3, the throughput under this strategy does not have a significant difference compared with the other two strategies for the cases of $C \geq 2$. But for attaining a deadlock-free environment, a large central buffer is required for the shop with a high transport demand. The additional transporting activities between the central buffer and centres also prolong the vehicle response time for some outstanding requests in the shop. This is evident from the levels of PI4 and PI5, which are almost the highest among the three strategies, for strategy III in the three tables. While using this approach, it is suggested that the shop performance will be deteriorated if the location and the capacity of the extra central buffer are not appropriately planned and there is no proper method to control the job movements between the buffer and centres.

From the simulation experiments, it seems that no single strategy can dominate the other two. However, it is suggested that under the cases where the shop queuing capacity is more critical than the processing/transporting capacities, strategy I can achieve a higher throughput level than the other two strategies. On the other hand, if the processing/transporting capacity becomes the main bottleneck in the shop, i.e. they are the main factors to affect the shop performance, strategy I also is efficient to the decrement of machine blockage events. On the other hand, if the related cost from setting a WIP storage buffer is not the main consideration of the management, strategy II may be preferred. Otherwise, strategy I is a better alternative.

The simulation results obtained in the experimental stage can be used as a guideline and reference for further investigation about various strategies. For instance, the limited number of maximum shop WIP under strategy II is decided in a static way according to equation (14). However, a threshold value that can capture the effect of the process plan for the job types, which are produced in the shop, is desired by more dynamic approaches. Likewise, some problems exist for the method of setting an extra buffer. In addition to the location of the central buffer, the maximum number of jobs that can simultaneously be stored in the central buffer also affects the efficiency of strategy III. Further research for these problems will be essential and necessary.

7. Conclusions

A control strategy for a single multi-load vehicle traversing along a single-loop guidepath is presented to avoid deadlocks in an unmanned job shop system with finite local queue capacity. We conclude that by using the complete and global system information, the deadlock caused by inappropriate job movement can effectively be avoided without restricting the shop WIP level and setting an extra central buffer.

Although only a single multi-load vehicle is used in the studied environment, the obtained results can be taken as a useful guideline for the development of a control strategy for systems with more than one multi-load vehicle. On the other hand, the model of the single-loop guidepath with a single vehicle can be easily employed on some complex AGV systems mentioned in the introduction.

The control strategy developed in the study is just a rule-based heuristic, so an overall control process, perhaps, would not be optimal. Various modern approaches, such as Tabu Search (Glover 1989, 1990) and Generic Algorithms (Goldberg 1989), which have ever been used to deal with the real-time control problems, are suggested to resolve the studied problem here.

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