

## Active Rescheduling for Automated Guided Vehicle Systems

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### Synopsis

This paper examines the use of knowledge-based techniques to generate a framework for the active rescheduling of an automated guided vehicle system in a manufacturing environment. Our approach to active rescheduling uses “cues” drawn from events on the shop floor to trigger rescheduling. Simulation experiments are used to capture knowledge about the shop floor and various scheduling strategies. An extensible agent architecture is developed to facilitate active rescheduling.

### 1.0 Introduction

#### 1.1 Purpose of Research

The process of controlling a manufacturing system would be easy if such a system were completely predictable. Unfortunately, manufacturing processes are subject to a great many sources of variability. It is desired to achieve real-time response to dynamically changing conditions on the shop floor. Responsiveness translates to dollar savings in reduced inventory, increased quality, reduced stockouts, etc. The central item needed to achieve such responsiveness is flexibility. We believe that flexibility requires monitoring the sources of variability and incorporating their effects in achieving dynamic control of the manufacturing system, and that such control is accomplished via the dynamic modification of schedules in response to sensor-based monitoring of the shop floor.

The goal of our research is to construct an extensible framework for knowledge based scheduling that leverages the advantages of both artificial intelligence and operations research. Our particular focus is dynamic scheduling in response to shop floor events, and our initial domain has been the material handling system for highly automated electronic component production lines. The plant is viewed as a set of interacting subsystems, including receiving, production lines, material handling, maintenance, and shipping. We assume that the shop floor events are not uniquely predictable as to their time of occurrence, even where there are stochastic descriptions of the general frequency of their occurrence, and that a schedule exists to achieve goals in time by employing resources within constraints. Dynamic scheduling is performed in such a way that rescheduling of appropriate subsystems occurs in response to changing shop floor conditions. The Automated Guided Vehicle System (AGVS) is used to demonstrate the notion of active rescheduling in response to shop floor “cues”. An extension to other manufacturing subsystems is described at the end of this paper.

The following issues are addressed in the course of this research:

1. Sensor-based monitoring of shop floor state. This requires an adequate computer description of the plant and its interacting subsystems, such as material handling, process lines, receiving, shipping, maintenance, etc.
2. Assessment of the current state in such a way that the appropriate AGV control strategy can be chosen. This requires the incorporation of knowledge of empirical results suggesting which AGV strategies for both dispatch and routing work well for given shop floor conditions. In addition, the changing of strategies in mid-production must be efficiently accomplished to maintain progress toward meeting master production goals.
3. The blending of AI and OR technologies to achieve global production goals. The meeting of these goals requires the effective use of limited resources under constraints. The use of AI techniques alone, while effective for such tasks as constraint propagation and domain description, fails to incorporate the results of years of mathematical development invested in OR techniques for manufacturing. On the other hand, the use of OR techniques alone can be too limiting in assumptions and may fail to be flexible enough to reflect actual shop floor conditions. By incorporating both types of analyses, the strengths of each can overcome inherent weaknesses of the other.
4. An understanding of interacting manufacturing subsystems. It is desired to effectively control the whole system rather than optimize small portions of the system in an uncoordinated fashion. The manufacturing floor is a large system with many interacting components. The material handling subsystem is not an end unto itself. The effect of manufacturing subsystem scheduling decisions on other subsystems (e.g., maintenance, shipping, etc.) must be modeled and incorporated into the global assessment of the impact on the master production schedule.

## 1.2 Domain

The research is being performed on site at the Chrysler Acustar plant in Huntsville, Alabama. This plant is a large facility for the manufacture of electromechanical auto parts such as gear clusters and radios. A system of 27 AGVs (Litton Corp., prime contractor) services fifteen production lines which are generally dedicated to the manufacture of a particular part or family of related parts. A Material Handling Control System (MHCS) provides control for over 5000 part numbers. Eighteen of the AGVs deliver parts from the distribution center to the production lines and dunnage (empty containers, trash, and spare parts) from the lines to the distribution center. Approximately 150 AGV pickup and delivery stands (P/D stands) are points to which AGVs travel for this purpose. Unidirectional AGV track allows for the delivery of parts to the right side of a particular line and the return of dunnage along the left side of the line. AGV jobs are entered to the computer system by production line employees. AGV dispatching (assignment of jobs to vehicles) and routing (path planning) are determined according to a particular AGV strategy.

## 1.3 Definition of Active Rescheduling

The term “active rescheduling” is motivated by the work of Mike Swain [1], Dana Ballard [2], and others in active vision, whereby “cues” are identified and used to enhance performance in the recognition of objects from visual images [3]. Active vision is useful for applications (such as

recognition of partially-occluded items on a conveyor line) in which more traditional vision processing techniques (such as edge detection, orientation, and matching with objects stored in memory) are too processor-intensive to be practical in the time available for analysis.

Active rescheduling requires a selective attention capability in shop floor reasoning and problem solving. [4] [5] The manufacturing plant is viewed as a group of interacting subsystems. We contend that subsystem interactions can be captured as schedule interactions. Scheduling is the assignment of resources to accomplish goals within constraints. To the extent that interacting subsystems compete for limited resources, require processes or material from each other as prerequisite constraints, and possess conflicting goals, the notion of using scheduling to model subsystem interactions seems reasonable.

Active rescheduling is used in two senses in our research. In the first sense, shop floor “cues” are identified and the corresponding sensors or data inputs are monitored to determine when a subsystem agent should be notified that a change in schedule and/or schedule strategy may be required. The agenda controller, which possesses a global view of shop floor activities, directs such “trigger” information to the appropriate subsystem agent(s). In response, the subsystem agent(s) determines whether a schedule change is warranted. The bulk of this paper describes such a process for the AGVS. Computer simulation studies were performed to determine under which conditions particular AGVS scheduling strategies should be employed. In the second sense, active rescheduling is employed to assist in the recognition of significant interactions among subsystem schedules. An agenda controller resolves schedule conflicts among subsystems. [3]

Scheduling personnel at Acustar were interviewed to determine which manufacturing parameters can be used as “cues” for triggering rescheduling activities. Only one or two parameters were chosen for each manufacturing subsystem. The motivation for the use of cues to trigger rescheduling is twofold:

1. The architecture of the scheduling system is such that the development and maintenance of subsystem schedules is distributed among agents, with an agent representing each manufacturing subsystem (e.g., receiving, shipping, production lines or cells, material handling, etc.). However, it is desired to keep the global production goals in mind at a higher level of focus than individual subsystems. The architecture therefore provides for a higher-level agent which is responsible for recognizing the need for schedule changes and mediating negotiation among agents to resolve schedule conflicts. Since these activities are processed by the single, higher-level agent, there will be a high volume of such transactions to be processed for a typical manufacturing plant. The notion of manufacturing cues as a quick-focus mechanism is reasonable in this regard, since it requires very little data analysis. The more detailed focus needed for the scheduling effort is then handled by the appropriate agent, once it is triggered. As in the active vision approach, this approach allows for the recognition of significant events in the manufacturing system in the limited time available for such recognition.
2. This design choice is based on the assumption that a schedule change is not desired or needed unless it results from the needs of another, competing manufacturing subsystem

schedule or unless the current schedule is no longer effective, as evidenced by the cues, or measures of effectiveness for the particular subsystem.

3. It is accepted among scheduling researchers [6] that there is a point of diminishing returns when it comes to complexity of the scheduling process versus schedule performance. If the scheduling technique becomes too complex, the scheduler tends not to produce desirable schedules.

The use of manufacturing parameters as cues to trigger a reschedule for a particular subsystem simplifies the process of deciding which subsystem may need to be rescheduled based on current shop floor conditions. Once the subsystem agent determines that a reschedule is required, the actual rescheduling process uses many more manufacturing parameters.

<b>Manufacturing Subsystem</b>	<b>“Cue” Parameters</b>
Receiving	Number of backorders/stockouts
Material Handling	AGV loading/utilization order position patterns (measure of potential congestion)
Production line 1 ... ... Production line n	Line throughput Machine throughput
Maintenance	Number of breakdowns Number of skilled personnel
Shipping	Number of orders to expedite Number of stockouts

Figure 1  
Subsystems and “cue” parameters

Figure 1 depicts the manufacturing subsystem parameters used as reschedule cues. When the parameter varies significantly, the schedule for the particular subsystem becomes suspect. The subsystem agent must determine whether a reschedule analysis is required. The number of stockouts/backorders and the number of part substitutions act as cues for revising the Receiving schedule. The Material Handling cues include AGV loading/utilization and a measure of the pattern of AGV requests (for determining the amount of potential traffic congestion). A reschedule for each of the production lines may be triggered by a significant change in line throughput or individual machine throughput. Maintenance cue parameters include number of machine breakdowns and number of skilled personnel. Shipping will be monitored via number of order expedites and stockout parameters. The scheduling/rescheduling process is distributed across the manufacturing subsystems and performed at two levels of abstraction. At the higher level, a reschedule controller monitors the current shop floor state and assesses whether a reschedule may be needed based on the current values of the cue parameters. At the lower level, a scheduling agent exists for each subsystem, which is able to perform scheduling and rescheduling appropriately. The higher-level controller allows the reasoner to maintain a view of the overall production goals (in terms of the master production schedule) in activating the lower-level scheduling agents and in resolving conflicts among them. The lower-level agents contain

knowledge of mathematical and/or heuristic scheduling techniques, application knowledge, and the ability to acquire more detailed state information for scheduling purposes.

Section 2 examines AGVS strategies based upon dispatch and routing strategies obtained from the literature and from a vendor survey. The architecture for accomplishing active rescheduling is described in Section 3, with emphasis on the material handling subsystem. Related work in dynamic scheduling is presented in Section 4. In Section 5, an extension of the research to incorporate additional subsystem agents is presented. Conclusions regarding the research are given in Section 6.

## **2.0 AGVS Strategies**

### **2.1 Types**

Existing AGVS strategies for both dispatch and routing were obtained from the literature and a survey of United States AGV vendors. Appendix I contains the results in table form. The first group of strategies is for accomplishing AGV dispatching: the assigning of jobs to vehicles or vehicles to jobs. The second group of strategies is for AGV routing: the planning of paths.

There are two types of AGV dispatch strategies. The first strategy type is vehicle-initiated dispatching, in which a task is selected from a set of requests for AGV service. Such strategies include: Earliest Pickup (EP), Extracted Rule Erlang (ERE), Modified First Come First Serve (MFCFS), Rule, Shortest Travel Time/Distance Rule, and Maximum Outgoing Queue Size Rule. The first strategy, EP, minimizes pickup time by calculating when an AGV can pick up a part at a particular station [7], ERE is a heuristic rule that predicts future demands utilizing the tracked stages of arrivals at each station, and positions the AGVs accordingly [7]. The third strategy, MFCFS, attempts to sequentially assign vehicles to jobs in chronological order as requests are received from the stands [8]. The goal of Rule is to maximize job throughput. [9] The Shortest Travel Time/Distance Rule dispatches the vehicle to the work center that is closest to the vehicle by time or distance [8]. The final strategy, Maximum Outgoing Queue Size Rule, dispatches a vehicle to the work center that has the maximum outgoing queue size [8].

The second type of AGV dispatch strategy is workstation-initiated dispatching, in which a vehicle is selected from a set of idle vehicles to be assigned the next task in the queue of tasks. Such strategies are chosen based on the AGV system type in use. For example, some strategies work better on uni-directional tracks than on bi-directional tracks. The location of pickup and delivery (P/D) stands does not matter in some dispatch strategies, whereas others incorporate the notion of distance. The workstation-initiated dispatch strategies seen most often in manufacturing are Vehicle Look For Work (VLFW), First In-First Out (FIFO), Nearest Vehicle (NV), Farthest Vehicle (FV), priorities, and combinations thereof.

Newton [10] defines VLFW as the strategy where a vehicle consistently makes a pickup close to its last deposit point, and FIFO as the strategy where the vehicle always serves the oldest move request first. He also defines a hybrid FIFO/VLFW strategy referred to as critical request. A critical request is a request that has waited beyond a threshold of time for service, at which time it is assigned to be the next job to be serviced by the first available AGV.

In manufacturing, Vehicle Look For Work is used primarily when the floor is divided into zones with uni-directional tracks. Zones can be defined as lines, sections of the floor, or loops. Some AGV systems require that only a defined number of AGVs can travel in a zone at one time, while others require that an AGV work exclusively in one zone. Bartholdi and Platzman [11] expanded VLFW and Mahadevan and Narendran's work [12] with loops, and assigned a vehicle to a specific loop to look for work. The AGV, using the VLFW strategy, travels the zone looking for a job. The AGV will process the first job that it comes to, and the destination of the job becomes the starting point in looking for another job.

One common scheduling strategy used by AGV vendors in manufacturing is a combination of VLFW, zones, and priorities. The VLFW strategy is employed, except that the AGV will accept the job in its zone that has the highest priority. One such AGV system sends a list of all P/D stands in a zone to the AGV that has just entered the zone. The list contains the station numbers listed in decreasing order according to station priority, the critical times for the station, and the job status. The list of pending jobs is examined to determine whether a job has become critical. If no jobs are critical then, starting at the top of the list, the AGV looks for work. The AGV will take the job at the station with the highest priority in its zone. The zone of the destination of the job becomes the AGV's new zone and the process is repeated. If a job becomes critical and no AGV is in its zone, the AGVs in the surrounding zone must report their job status and location. A vehicle with appropriate status and location is immediately assigned to the job. If a vehicle cannot find a job in its zone, it proceeds to the next zone and looks for work. If no work is found, the AGV utilizes this time for a maintenance check or battery charge.

Another strategy used by vendors employs the concepts of priorities and age rates. Age rates are rates used to increase the stand's priority every set interval of time during which the stand is not serviced. The priority increase amount is not the same for every station; it varies depending on the importance of the stand and its product. The age rate can be zero. This strategy insures that the most important jobs are handled first, and that all jobs are eventually serviced. This strategy is used when vehicles are not assigned to specific zones.

Nearest Vehicle and Farthest Vehicle strategies are defined by Egbelu and Tanchoco [8]. In the systems that utilize the NV and FV strategies the entire shop floor is usually referred to as a single zone. Jobs are handled most often in a FIFO manner by the vehicle that is nearest to the station. If this choice of vehicle will result in blockage, then the farthest vehicle, calculated by distance, is chosen for the job. The NV strategy can be used in combination with the concept of stand priorities. The Nearest Vehicle strategy can be modified to refer to nearest in travel time rather than distance. Since the nearest vehicle according to distance is not always the vehicle that can service the job most quickly, this strategy is sometimes preferred over NV distance.

Several strategies exist for AGV routing. Beasley [13] devised a strategy in which two heuristic solution methods were used to address the fixed routes problem with daily repetition:

1. An adapted savings algorithm, the Clarke and Wright algorithm, was used to construct a route based upon a savings measure. If the route produces an infeasible link, it is rejected, else it is added to the solution set.

2. An adapted  $r$ -optimal algorithm is employed which behaves in a similar manner to the adapted savings algorithm, except that it examines a set of routes, rather than single links, and checks for feasibility.

Kaspi and Tanchoco [14] devised flexible flow lines in which vehicles follow “virtual” flow paths. The direction of the flow paths must be able to change as the need arises. A branch and bound technique was employed that utilizes depth-first search and backtracking.

Sinriech and Tanchoco [15] developed an Intersection Graph Method for solving the AGV Flow Path Optimization Model developed by Kaspi and Tanchoco [14]. The objective of the model is to direct the arcs in a unidirected graph with intersection nodes, which represents the flow path network so that the total vehicle travel distance is minimized.

Kim and Tanchoco [16] worked on the conflict-free shortest-time AGV routing problem: to find a path for an AGV which allows the vehicle to arrive at the destination as early as possible without disrupting other active travel schedules. The proposed algorithm maintains a list of free time windows or time intervals at each node and routes the vehicle through the free time windows.

Desrochers, et al. [17] defined the Vehicle Routing Problem with Time Windows (VRPTW), in which a number of vehicles are located at a single depot and must serve a number of geographically dispersed customers. Dynamic programming and branch and bound techniques were used to minimize the total travel costs.

Egbelu [18] solved the problem of selecting the home positions of vehicles in a single loop-type AGV network using heuristic algorithms and mathematical representations. The objective is to minimize the vehicle dead travel time (during which the AGV is empty).

Desrochers, et al. [19] viewed the VRPTW as a generalization of the vehicle routing problem where the service of a customer can begin within the time window or interval. The linear programming (LP) relaxation of the set partitioning formulation of the VRPTW is solved by column generation. Feasible columns are added as needed by solving a shortest path problem with time windows and capacity constraints using dynamic programming. The LP solution uses a branch and bound algorithm to solve the integer set partitioning formulation.

Fisher and Jaikumar [20] developed a heuristic to determine which of the demands will be satisfied by each vehicle and what route each vehicle will follow in servicing its assigned demand in order to minimize total delivery cost. The heuristic technique assigns a vehicle to a customer by solving a generalized assignment problem with an objective function that approximates delivery cost.

Goetschalckx and Jacobs-Blecha [21] were concerned with the Vehicle Routing Problem With Backhauls, a pickup and delivery problem where all deliveries on each route must be made before any pickups can be made. A two-phased solution methodology was proposed. In the first phase, a high-quality initial feasible solution is generated based on space-filling curves. In

the second phase, this solution is improved based on optimization of the subproblems identified in a mathematical model of the problem.

Dispatch Strategies	Routing Strategies		
	Shortest Path	Generalized Assignment	Min-Max
First In-First Out	•	•	•
Least Utilized Vehicle	•	•	•
Longest Idle Time	•	•	•
Nearest Vehicle	•	•	•
Random Vehicle	•	•	•
Earliest Pickup	•	•	•
Random Work Station	•	•	•
Shortest Travel/Distance	•	•	•
Vehicle Looks for Work	•	•	•

Figure 2  
Dispatch and routing strategies considered

Figure 2 illustrates the AGVS strategies that were considered for our research. Some of the strategies described above were not included because of their complexity, which renders them ineffective in a real-time scheduling system, which responds to dynamic shop floor changes. Other strategies were not included because they could not be applied to the Acustar AGVS.

## 2.2 Simulation Experiments to Study AGVS Strategies

A large stochastic, discrete-event simulation was developed in the AutoMod™ simulation language (AutoSimulations, Inc.) on a SPARCstation 10™ machine (Sun Microsystems, Inc.). [22] [23] An experiment was developed for each AGVS strategy (a combination of one dispatch strategy and one routing strategy, as depicted in Figure 2). The purpose of the simulation experiments was to study the effects of AGV strategies under a variety of plant conditions on two measures of effectiveness: average AGV utilization and average time to fill an AGV order (average time to arrive). Results of the simulation experiments were used as a knowledge source for the application of strategies in the AGVS agent, described in Section 3 of this paper. Thus, a “source” for knowledge acquisition for the intelligent AGVS scheduling agent was the series of simulation experiments.

A CAD diagram of the plant with AGV track and P/D stands was imported to AutoMod™. The following description of the simulation is taken from [24] Simulation state variables included the following:

1. AGV status: idle/busy,
2. AGV queue length at the distribution center,
3. order pickup time,
4. order dropoff time,

5. time of order generation,
6. P/D stand status: empty/loaded, and
7. production line status: running/down.

Extensive input data analysis was performed using actual historical data from peak production periods at Chrysler Acustar. Statistical distributions were determined for the following sources of randomness:

1. time between order creation for deliveries and pickups,
2. time between AGV breakdowns,
3. time to repair an AGV,
4. time between line breakdowns,
5. time to repair a line, and
6. time between part backorders.

The experiments included six factors that were varied between each of two levels. (Actual values for the factor levels cannot be published, since they are proprietary to Chrysler Acustar.) Each factor represents data in addition to the cue parameter trigger, which the AGVS agent may acquire and employ to determine that a change in strategy is necessary. The factors are:

1. volume of order distribution (randomly dispersed across the plant),
2. volume of orders in a selected area (creates congestion problems),
3. volume of backorders,
4. AGV failures,
5. line failures (may be from a single machine out of service), and
6. finished product priority (e.g., volume of “expedite” orders).

A Resolution IV experiment was performed, since two-factor interaction effects were determined to be negligible. Figure 3 represents the 99% confidence intervals for the effects of each factor change on the mean time to arrive and the mean AGV utilization for the first strategy: first-come-first-served dispatching and shortest-path routing.

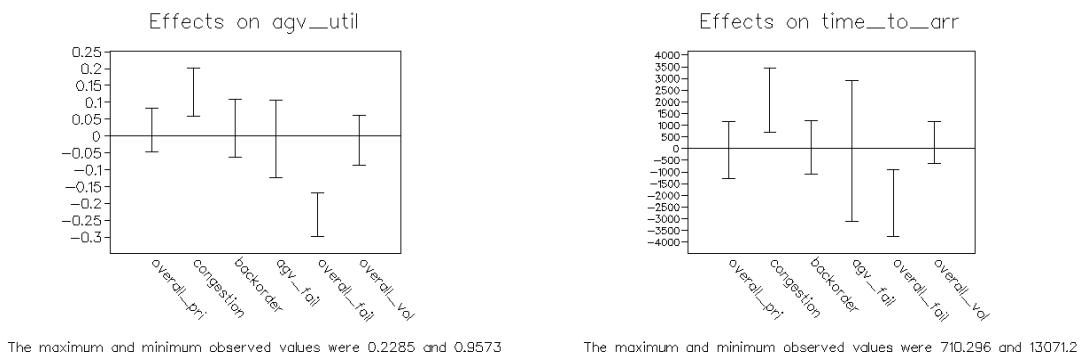


Figure 3  
Initial Model (First-In, First-Out dispatching, Shortest Path routing)

Figure 3 shows that, of the factors tested, changes in levels of the factors “congestion” and “overall\_fail” had a significant impact on the two measures of effectiveness, AGV utilization and time to complete a job. An increase in the level of congestion caused a corresponding increase in AGV utilization and an increase in the mean time to arrive. An increase in the level of production line failures caused a corresponding decrease in the AGV utilization and a decrease in the mean time to arrive.

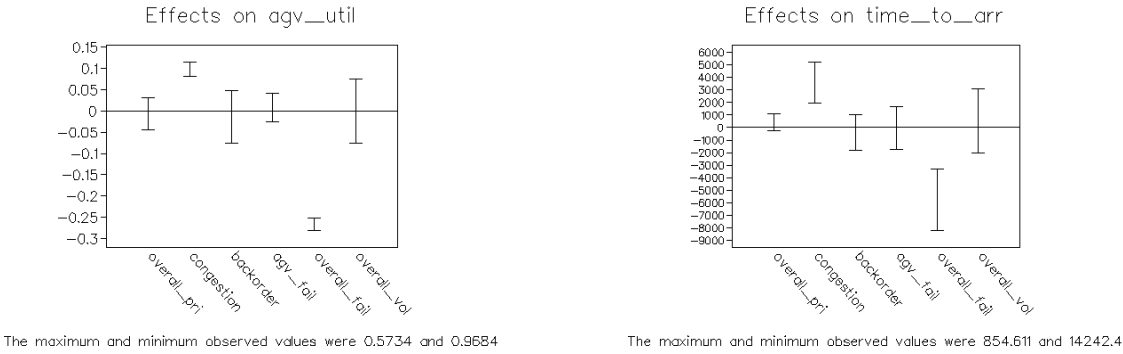


Figure 4  
Second Model (Shortest Travel Time dispatching, Shortest Path routing)

Figure 4 depicts the 99% confidence intervals for each of the six factors effects on the mean AGV utilization and the mean time to arrive. The results are similar to those of the first strategy.

**2.3 Experiment Results as Agent Knowledge**

The AGV strategy simulation experiments were a source of knowledge for the subsequent knowledge acquisition effort. The AGV scheduling agent requires knowledge about each strategy, specifying the shop floor conditions under which it is an appropriate choice for AGV scheduling. [25] Figure 5 depicts this knowledge for the first two strategies: first-in-first-out and shortest travel time. (Note that these results are for a single factor level change at a time, while holding all other factors at their “normal” levels. Experimentation requirements were excessive for testing all possible combinations of factor levels.)

FACTORS	BEST STRATEGY			OTHER FACTORS
	Utilization	Arrival Time	Overall Best	
Line Prioritization	FIFO	FIFO	FIFO	No additional factors needed.
Congestion*	STT	FIFO	FIFO	Arrival time factors were more significant than utilize. factors.
Backorders	FIFO	STT	STT	Utilization factors were about the same, while bounds for arrival time were tighter.
AGV Breakdowns	STT	STT	STT	No additional factors needed.
Line Breakdowns*	STT	STT	STT	No additional factors needed.
Order Volume	STT	FIFO	FIFO	Utilization has no significant differences between strategies. Arrival time lower for FIFO.

FIFO = First-In, First-Out STT = Shortest Travel Time

\* = Significant factors

Figure 5

Factors and strategies

### 3.0 Active Rescheduling

#### 3.1 AGVS Agent

Based on incoming “cue” information, the AGVS agent must decide whether or not a change in strategy is required. (“Rescheduling” is a misnomer for this particular subsystem, since dispatching occurs in a reactive fashion, based on receipt of orders for part deliveries and pickups from the production lines.) The agent is passed a message regarding the cue parameter change. For example, the message may be the following, “congestion high at distribution-center/east-plant intersection”. The agent acquires additional data in order to determine if a schedule and/or schedule strategy change is warranted. For the AGVS agent, the AGV job queue and associated paths are examined. Additionally, current shop-floor values for each of the six experiment factors are obtained to aid in determining whether a strategy change is warranted.

Figure 6 depicts a scheduling agent. The agent contains knowledge of one or more heuristic algorithms or mathematical techniques for the performance of scheduling analyses related to the particular manufacturing subsystem. It also contains knowledge of what must hold to be true at the time of schedule development in the domain in order to be able to commit to the production of a reasonable schedule. In other words, the agent contains knowledge of the bounding assumptions that must be fulfilled to perform each kind of analysis it can use to produce a schedule. The AGVS agent contains knowledge of available strategies, such as first-in-first-out and shortest travel time.

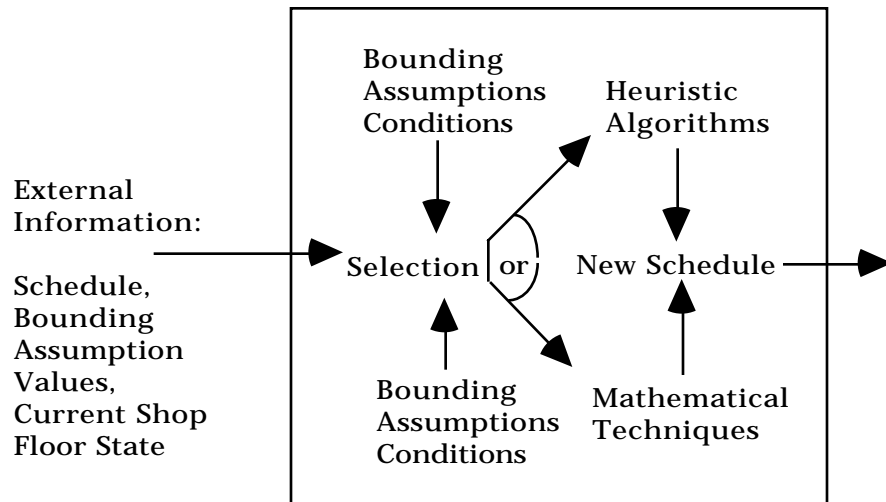


Figure 6  
Information flow in a scheduling agent

The scheduling agent makes use of the current shop floor state information (and can solicit additional information) to determine which scheduling technique's bounding assumptions can be met at the time of reschedule. The AGVS agent is designed to improve overall performance of the material handling system by enhancing AGV utilization and reducing the average time to complete a job. This task is accomplished by dynamically adjusting the AGV strategy to best meet the needs of the changing shop floor state. Once the agenda controller triggers AGVS agent activity, the agent decides if a strategy change is warranted.

If a strategy change is required, the shop data is passed to a discrimination network, which contains the simulation experiment results. Each leaf of the network contains a particular AGV strategy. Tests at intermediate levels in the network are based on values of shop floor state variables. The discrimination network makes use of subconditions to select a path through the tree, thus pruning the space during search. The intermediate-level tests represent filters to prune invalid strategies (as determined by the lack of satisfaction of bounding conditions) and inappropriate strategies (as determined by simulation experiment results).

A schedule change may also be required. In this case, the proposed change, along with the conditions that must be fulfilled to implement the change, is posted to the agenda. Schedule change conditions take the form of the need for a resource which is currently committed to another subsystem agent, the need for "services" required from another agent, or the need for a schedule change on the part of another agent. All such conditions represent agent interactions. Their satisfaction must be orchestrated by the agenda controller, which possesses a global view of their impact. Examples of such conditions for the AGVS agent include the need for backordered parts from receiving, the need for maintenance, or the need to delay delivery to a particular production line.

### 3.2 Agenda Controller

The AGVS agent is one of many agents which, taken together, collaborate to accomplish the global production goals. Each agent represents a particular manufacturing subsystem. The global goals are represented by the master production schedule, which establishes the amount, type, and time deadline for the production of finished goods. The agenda controller exists for the purpose of allowing one or more subsystem agents to compromise its local goals for the higher goal of achieving the master production schedule. For example, production may be temporarily suspended on a particular low-priority line in order to dedicate machines from the line to expedite the production of a critical item on an adjacent line. AGVs may be rerouted as well to expedite the process. The schedules of the low-priority line and the AGVS are sacrificed for the good of meeting master production requirements.

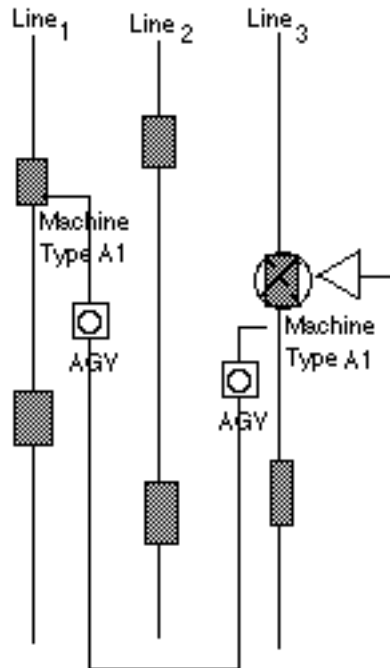


Figure 7

AGVs used between lines with “twin” machines

The active agenda controller performs the higher-level control function that provides a way for changes on the shop floor to affect the rescheduling process among manufacturing subsystems. The agenda consists of suspended schedule processes. Each process:

1. is authored by an agent representing a single manufacturing subsystem,
2. contains a proposed schedule revision along with the bounding assumptions used to create the revision,
3. contains conditions which must be satisfied in order to implement the schedule revision,
4. will be implemented as a new schedule by the agent related to the manufacturing subsystem when it is resumed.

The agenda controller orders processes on the agenda according to the priorities established by the master production schedule. The controller attempts to satisfy the conditions for a process reschedule. In attempting to satisfy a particular condition, new agenda items may be spawned. The controller must also adjust the remaining agenda processes according to the satisfaction of particular conditions. In other words, the satisfaction of a condition may render other agenda processes to be obsolete.

Agenda control is active because it does not follow a prescribed strategy according to information stored within the processes on the agenda. Rather, it reacts to external information about the physical system under consideration (i.e., the manufacturing plant) and the need to propagate the effects of schedule changes among subsystems. The active agenda controller is data driven, but the data consists of state information about the “real world” as well as the state of the processes on the agenda. Figure 8 depicts the agenda with its active controller.

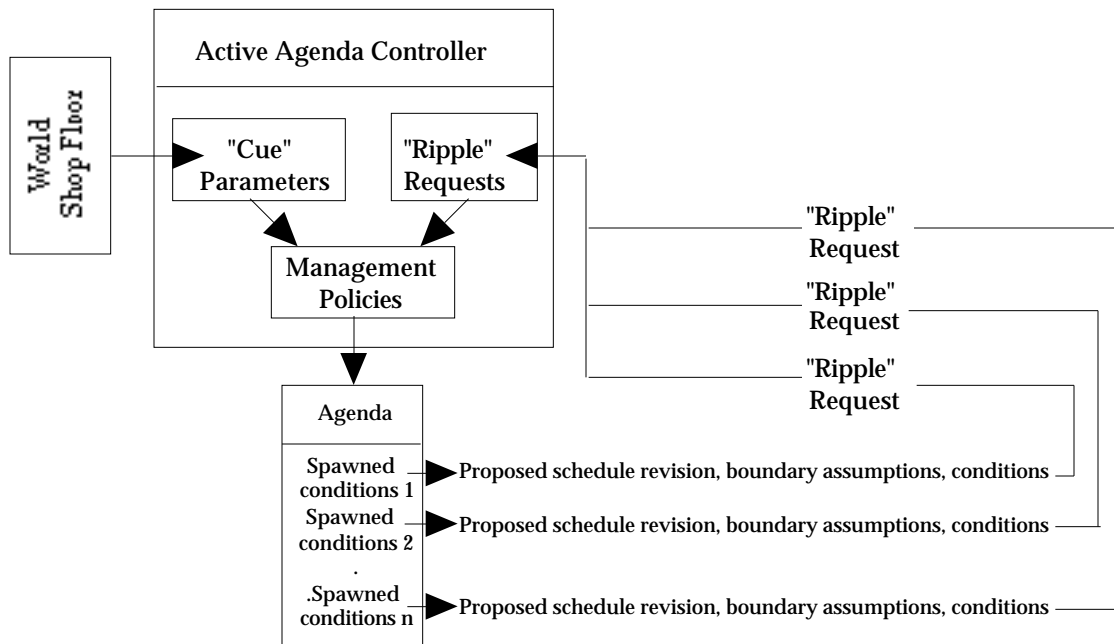


Figure 8  
Agenda and controller

The agenda controller orchestrates the process of monitoring changes in the shop floor state and triggering schedule changes by passing messages to agents regarding cue parameter values and by attempting to satisfy reschedule conditions. An agent may not be able to satisfy a particular reschedule condition that is required by another agent and posted on the agenda. In this case, the agent informs the agenda controller that it is unable to commit to satisfaction of the condition. (For example, resources may not be available to accomplish the schedule change.) The agenda representation is used to trigger reschedules by one of two means:

1. a change in cue manufacturing parameters which represent a contingency that must be considered, and

2. a “ripple effect” to other manufacturing subsystems caused by the need to satisfy reschedule conditions.

Each of these types of triggers is incorporated into the active agenda control process.

#### **4.0 Related Work**

Several researchers are examining the issue of dynamic scheduling for manufacturing and for other domains. Zweben, et al. [26] have performed research in rescheduling with iterative repair for the scheduling of shuttle operations. Xiong, et al [27] performed work in intelligent backtracking techniques for job shop scheduling. Shaw and Whinston [28] examined FMS scheduling via a goal-directed inferencing method, in which the primary form of interaction among subproblems was the sharing of machine resources. Pan, et al. [29] describe the development of an intelligent material handling system, which is integrated with other CIM functions. Wu and Wysk [30] have developed an inference structure for control and scheduling in manufacturing, which provides both forward and goal-directed inference, simulation capabilities, and the incorporation of other modes of analysis within the framework. Ringer [31] employs time-phased abstractions for combining predictive and reactive scheduling. Hadavi, et al. [32] have developed a recursive architecture for real-time distributed scheduling. Drummond [33] is researching contingent scheduling: the representation of explicit disjunction in schedules for proactive error management.

Recent work in reactive scheduling has been performed. Possible approaches to schedule revision with changing conditions, including OR dispatching and AI interval scheduling, is being studied by Smith and Morton [34]. Fox discusses the requirements for a dynamic scheduling system in [35]. Beck’s system, TOSCA, which manages job-shop scheduling constraints, is being extended to include rescheduling [36]. Diaz, et al [37] developed a system which uses customer order information to schedule and reschedule production in a steel plant. Burke and Prosser’s [38] DAS system performs predictive and reactive scheduling via negotiation between autonomous agents.

#### **5.0 Extensions to Include Additional Manufacturing Subsystem Agents**

Current research is directed toward the creation of scheduling agents to represent other manufacturing subsystems, including receiving, shipping, production lines, and maintenance. The additional agents will allow empirical testing to validate performance regarding the dynamic tradeoff of local subsystem goals in order to support and maintain global goals as determined by the master production schedule.

The approach for the development of each agent follows that described herein for the AGVS agent. Available heuristic and mathematical scheduling techniques are collected. Bounding conditions for each technique are determined. Shop floor factors that are related to the schedule are determined. Knowledge is acquired concerning the appropriateness of particular scheduling techniques under varying factor levels. (This knowledge was acquired via simulation experimentation for the AGVS agent.)

More stringent scheduling issues enter the picture for the development of the additional agents. Unlike the AGVS “schedule”, other subsystems tend to have schedules that extend further in time from the present moment. This feature of the schedules of additional subsystems allows for more proactive scheduling activities and renders the rescheduling process more complex.

## 6.0 Conclusion

Once the additional scheduling agents have been developed and incorporated into the active rescheduling architecture the completed system will be able to monitor shop floor conditions in real time and respond with appropriate schedule adjustments. The system will be able to both adjust current schedules and alter the technique used for creating schedules. Propagation of the effects of local schedule changes (through condition satisfaction) and notification of significant “cue” changes will be handled by the active agenda controller.

Benefits of this research include the following:

1. an increased responsiveness to volatile shop floor conditions,
2. incorporation of both mathematical and heuristic manufacturing analysis techniques within a semi-formal descriptive language and a distributed system of agents,
3. cooperation in dynamic scheduling with the modeling of schedule interactions,
4. agent commitment to the satisfaction of assumptions before scheduling occurs,
5. resource commitment to particular critical situations in time via selective attention,
6. the identification and use of manufacturing parameters as “cues” to trigger rescheduling analyses, and
7. dynamic adjustment of subsystem scheduling strategies to satisfy global production goals.

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