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PERFORMANCE EVALUATION OF AGENT-BASED MATERIAL HANDLING SYSTEMS USING SIMULATION TECHNIQUES

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ABSTRACT

The increasing influence of global economy is changing the conventional approach to managing manufacturing companies. Real-time reaction to changes in shop-floor operations, quick and quality response in satisfying customer requests, and reconfigurability in both hardware equipment and software modules, are already viewed as essential characteristics for next generation manufacturing systems. Part of a larger research that employs agent-based modeling techniques in manufacturing planning and control, this work proposes an agent-based material handling system and contrasts the centralized and decentralized scheduling approaches for allocation of material handling operations to the available resources in the system. To justify the use of the decentralized agent-based approach and assess its performance compared to conventional scheduling systems, a series of validation tests and a simulation study are carried out. As illustrated by the preliminary results obtained in the simulation study the decentralized agent-based approach can give good feasible solutions in a short amount of time.

1 INTRODUCTION

The increasing influence of global economy is changing the conventional approach to managing manufacturing companies. Real-time reaction to changes in shop-floor operations, quick and quality response in satisfying customer requests, and reconfigurability in both hardware equipment and software modules, are already viewed as essential characteristics for next generation manufacturing systems. This work is part of a larger research (Babiceanu, Chen and Sturges 2004, 2005a, 2005b) that employs agent-based modeling techniques in manufacturing planning and control for the purpose of obtaining better system performances. The main objective of the research so far, is to develop real-time feasible schedules for material handling (MH) resources working in dynamic manufacturing environments. Because of their rigid structure, the existing MH systems are difficult to adapt to the requirements set on future manufacturing. In this research, the agent-based modeling framework is utilized to develop a decentralized control system used for scheduling MH operations in manufacturing cell environments. The agent-based material handling system (AMHS) developed uses specific internal agent assignment and inter-agent coordination mechanisms, as presented in Babiceanu, Chen and Sturges (2005a).

To justify the use of agent technology for manufacturing control and assess the performance of the AMHS in comparison to conventional systems, a series of tests and a simulation study are carried out. Optimal and heuristic search algorithms that serve as the basis for the MH conventional control approach are developed for this purpose. Section 2 gives a brief description of the AMHS and its operation, and contrasts the two scheduling approaches that are the subject of the simulation study. Section 3 depicts the characteristics and the design of experiments for the simulation study, and the first results obtained after testing the simulation programs, Finally, Section 4 provides conclusions coming from the results obtained so far and future research directions. The characteristics tested in the simulation study include: the quality of the solution delivered, the real-time scheduling ability, including the real-time response to changes in production orders, and the fault-tolerance and MH hardware reconfigurability capabilities. By comparing the results given by the two alternative system configurations, the performance of the proposed agent-based approach can be evaluated.

2 AGENT-BASED MATERIAL HANDLING SYSTEM OPERATION

The proposed agent-based architecture, presented in Figure 1, is formed by the physical MH resources all of them having their own control unit, called Material Handling Agents (MHA), a central computer having a global system perspective, called Global View Agent (GVA), and a System Monitor entity having an associated Database (SMD). Software modules, in the form of Order Agents (OA), are assigned for each new order that enters into the system (Babiceanu, Chen and Sturges 2004).

2.1 Scheduling Material Handling Operations

In real-world manufacturing systems, after having developed the schedule of processing operations, to correctly find the total processing time of the orders released to the shop-floor, it is necessary to insert the MH operations between processing operations and recalculate the schedule makespan based on this new information. All the algorithms developed for the MH agent-based job evaluation, allocation and execution processes, and for the computation needs of the GVA take into consideration the precedence constraints of the jobs on each machine, the precedence constraints of the operations of each job, and the MH resource constraint, that states that, at each particular time, there should not be scheduled more MH operations than the number of available MH resources.

2.1.1 Agent-based Control Approach

The agent-based MH resource allocation process considers information exchanged among all the entities in the system. Except for the SMD module, all other software entities have internal evaluation algorithms embedded in their structure, based on which they make the allocation decisions corresponding to their functions in the agent-based architecture.

Due to the distributed decision-making existing in the system, the algorithms used for MH job evaluation and allocation are simple and not characterized by combinatorial explosiveness. Each MH resource allocation process has as output an individual schedule (IS) which is sent to the GVA by the active OAs in the system. Using its system perspective, the GVA combines all the ISs received into a system level schedule (SLS) which is then distributed to all the entities in the architecture. No complex algorithm is required for obtaining this emergent schedule. From the algorithmic point of view, a common personal computer is powerful enough to handle the needs for any entity in the proposed AMHS. These reactive scheduling mechanisms used for MH resource assignments are presented in detail in Babiceanu, Chen and Sturges (2005a), and, only require re-arrangements of jobs along one dimension based on specific steps needed to be executed. The functions of the entities working in the agent-based architecture related to the development of the global schedule are presented in both sides of Figure 1. As shown from the figure, not only are there several types of entities involved in the decision-making process, but an individual decision type is also distributed among entities of the same category.

2.1.2 Conventional Control Approach

In the conventional control, or global scheduling approach, all possible combinations of MH resource assignments lead to a tree-search type of problem, for which optimal solving algorithms are usually accompanied by combinatorial explosion. The system is working using the centralized control approach in which the GVA acts as a central computer which is making all the decisions regarding the assignment of MH operations to the existing resources in

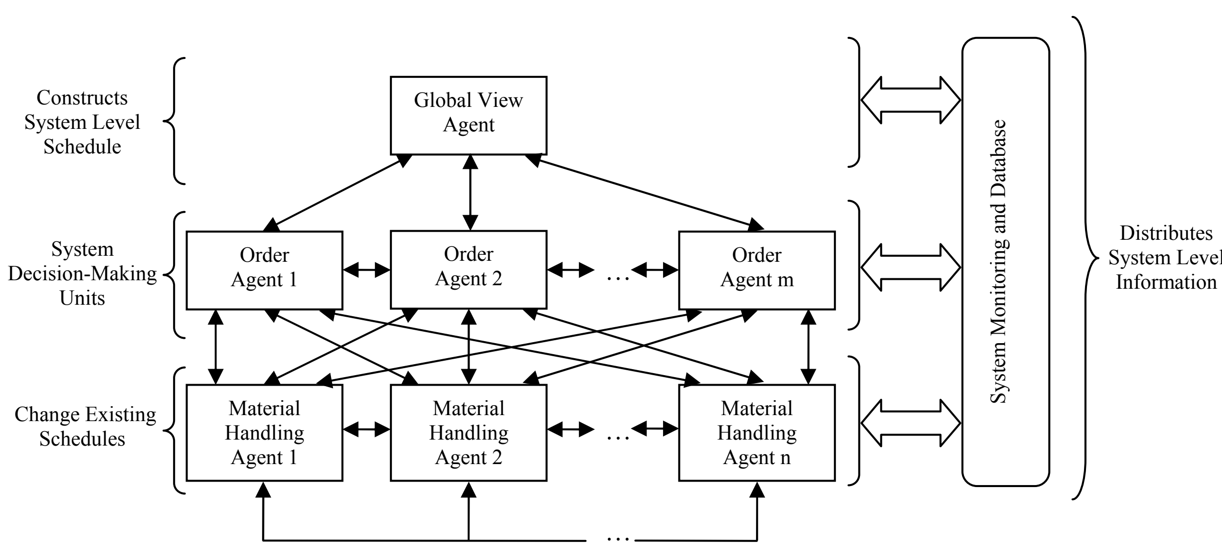

Figure 1: Agent-based Material Handling System Architecture

the system. One optimal and three heuristic algorithms are developed for the scheduling needs of the global view entity. The optimal algorithm uses the best-first search technique coming from the artificial intelligence (AI) field presented in Russell and Norvig (2003) and adapts its tree-search by using back-loops, such that it gives optimal results. Three heuristic algorithms are developed to give the GVA the possibility of finding feasible solutions in a short amount of time and compare them with the solution given by the decentralized agent-based approach.

2.2 Fault-Tolerance and Material Handling Hardware Reconfigurability Capabilities

Besides accommodating any changes in the manufacturing orders, achieving fault-tolerance to potential breakdowns and modifying the hardware architecture of the system without any significant delays is at least as important to the process of achieving a true real-time response. Three different types of hardware breakdowns are studied along with the capability to add or remove resources at any time.

2.2.1 Adding and Removing Material Handling Resources

Considering that the hardware part of a new MH resource is already installed, adding the MHA to the system is simply done by sending out a new resource message based on specific communication protocols among the entities forming the decentralized architecture. After being acknowledged by the other entities, the new MH resource is then available for any new MH operation requested. The process of removing MH resources from the architecture is similar to the process of adding resources. A simple broadcast message informs all the entities that a particular MHA is down and/or not accepting any more requests, so the other OAs and MHAs in the system will update their databases with this information.

2.2.2 System Response to a Breakdown Occurrence

Since in real-world manufacturing environments breakdowns of the hardware part of manufacturing resources occur, the AMHS needs mechanisms to respond in short time to any MH resource hardware breakdown. Three different types of hardware breakdowns could occur: a MH hardware resource is idle and does not respond to a new command issued by its control unit; a MH hardware resource is in motion without carrying a part and gets blocked; and, third, a MH hardware resource which carries a part is in motion and gets blocked. A mechanism to check for MH resource breakdowns is included in the OA's job evaluation, allocation and execution algorithms (Babiceanu, Chen and Sturges 2005a).

In the first two cases, the control unit of the affected MH resource is sending a breakdown message to the SMD module, such that this information is made available in real-time to all the entities in the architecture. The job affected by the breakdown is re-announced as available for processing and the job allocation process will accommodate it to another MHA. After the maintenance service is finished, the recovered MHA is added back to the architecture by using the procedure described in the previous subsection.

The third type of breakdown is solved similarly to the first two, with the added activity of transferring the part from the broken MH resource to the one selected for that particular job after the new SLS is generated and announced to all the entities in the architecture. The part transfer is obtained using methods and tools specific to the MH resources that form the MH system, and requires the announcement of the exact position of the broken MH resource in the system.

3 AGENT-BASED MATERIAL HANDLING SYSTEM SIMULATION STUDY AND REAL-TIME RESPONSE

The operation and the results given by the AMHS under the two control policies presented above, when working in a simulated job-shop environment are the subject of the simulation study. The conditions, simulation scenarios, and characteristics tested are similar for the two approaches such that a reliable comparison is obtained. The study is performed using different configurations for the job-shop model by varying the number of MH resources and jobs among the different tests, as well as during the same test. Throughout the simulation study, diverse types of changes are considered in the system. Processing times, new arriving jobs, the breakdown and recovery times for the MH resources are all considered random, and coming from specific distributions. The characteristics tested, as presented before, are the capability of the AMHS system to respond in real-time to any new MH operation request and consistently deliver good solutions, as well as the MH hardware reconfigurability and fault-tolerance capabilities.

3.1 Design of Experiments

The simulation study is carried out using a ten-machine job shop problem where two types of real-world potential events, such as new arriving jobs and MH resource breakdowns, are simulated. The AMHS job evaluation, allocation and execution algorithms and the conventional scheduling approach are run every time the number of jobs in the system is increasing with one or more jobs, or there is a change in the number of available MH resources. Bunches of replications for each of the two approaches are performed such that a confidence interval on the difference between the expected responses of the two different systems can be built. The independence of replications is obtained by using different random numbers for each replication. The performance measure considered in the simulation study is the total completion time of all the jobs in the system. For each simulation replication, when a specified number of jobs (e.g., 1,000 jobs) are released, the system is not accepting any new jobs, and the simulation replication stops after all the jobs already released to the system are fully processed. The simulation logic for the agent-based scheduling approach is presented in a flowchart form in Figure 2.

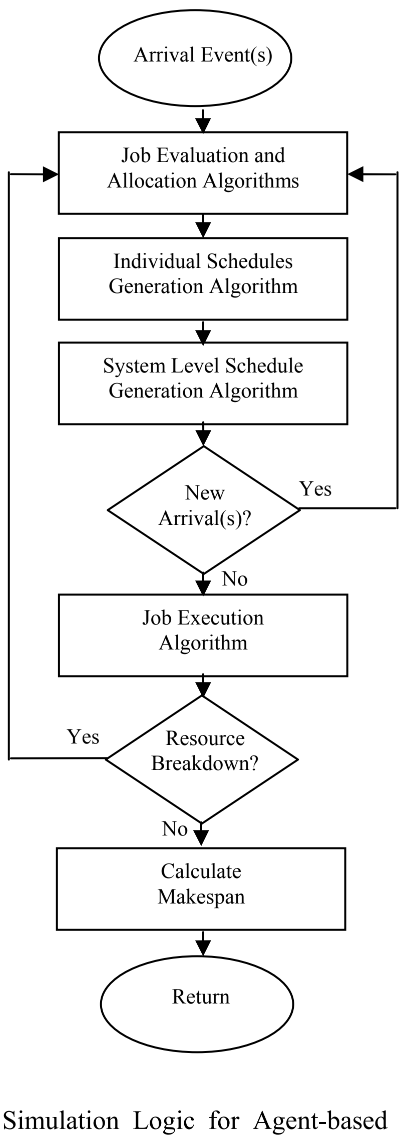

Figure 2: Simulation Logic for Agent-based Scheduling Approach

3.1.1 New Jobs

Each new coming job, denoted as an arrival event, has ten operations and the processing time for each operation is drawn from a uniform distribution *U(2, 9)*, while the time between job arrivals into the system follows an exponential distribution having a mean of ten, such that by using equation (1), jobs released at the same time can be obtained. The actual release time of the jobs are obtained by accumulating the inter-arrival times delivered by the exponential distribution.

$$t = \lfloor 10(10EXP(-10x)) \rfloor, \quad (1)$$

where t represents the inter-arrival time taken as the nearest smaller integer resulted from the distribution and x is the random number.

3.1.2 Changes in the Number of Available Material Handling Resources

Resource breakdowns are considered in the simulation study as unexpected disturbances in the manufacturing environment, where the amount of time between two failures for each resource, called mean time between failures (MTBF) is drawn from exponential distributions given by equation (2) below:

$$MTBF(t) = \lfloor 8(EXP(U(2,9))) \rfloor, \quad (2)$$

where *MTBF(t)* represents the time at which a resource breakdown occurs and *U(2, 9)* is the uniform distribution of the processing times for all jobs in the system.

For the overall behavior of the system these breakdowns are similar to removing MH resources from the system. After the breakdowns, the simulated mean time to recover for each resource, called mean time to repair (MTTR) is drawn also from exponential distributions using equation (3) below:

$$MTTR(t) = \lfloor 5(EXP(U(2,9))) \rfloor, \quad (3)$$

where *MTTR(t)* represents the time at which a resource is added back to the system, and *U(2, 9)* is the uniform distribution of the processing times for all jobs in the system.

For the overall behavior of the system, this process is equivalent to adding new MH resources and making them available for the job evaluation and allocation process. Another way to simulate breakdowns is to consider only one MTBF distribution and select randomly which MH resource is to be removed from the system. In this case only one MTTR distribution is sufficient.

3.1.3 Simulation Scenarios and Output Analysis

The bunches of replications in the simulation study are run such that for a particular bunch of replications only one factor is modified, the others are kept from the same distribution. For example, if modifying the arrival rate, the MTBF and MTTR are consistently drawn from the same distribution. This technique is applied to both decentralized agent-based approach and conventional scheduling approach.

The paired-t approach (Law and Kelton, 2000) is used to build a confidence interval on the difference between the expected responses of the agent-based and the global scheduling approach, results obtained by using the optimal algorithm. For both approaches, after each replication the completion time of the last job to be processed in the system is monitored. Since the paired-t method requires that observations drawn from each simulated approach be normally distributed and independent within that approach, bunches of replications are simulated and their mean is taken in consideration when constructing the confidence intervals. The paired-t confidence interval method does require also that the number of observations obtained from one simulated system be equal to the number of observations obtained from the second simulated system, so an equal number of bunches composed of an equal number of replications are considered for both systems. The following notations are used:

- System S_1 is represented by the agent-based approach
- System S_2 is represented by the global scheduling approach
- $j_1 = 1, \ldots, n_1 = n,$ is the number of bunches of replications for system S_1
- $j_2 = 1, \ldots, n_2 = n,$ is the number of bunches of replications for system S_1
- $k_1 = k,$ is the number of replications in a bunch for system S_1
- $k_2 = k,$ is the number of replications in a bunch for system S_2
- $Z_{1ji}, j = 1, \ldots, n, i = 1, \ldots, k,$ are the individual points obtained after the replications in a bunch for system S_1
- $Z_{2ji}, j = 1, \ldots, n, i = 1, \ldots, k,$ are the individual points obtained after the replications in a bunch for system S_2.

Since the number of bunches of application for the two systems needs to be equal (i.e., $n_1 = n_2$) to apply the paired-t comparison approach then, the mean for the replications in a bunch for systems S_1 and S_2 is given by the following two equations, respectively:

$$X_{1j} = \frac{\sum_{i=1}^{k} Z_{1i}}{k}$$

and

$$X_{2j} = \frac{\sum_{i=1}^{k} Z_{2i}}{k}.$$

Then:

- X_{1j}, $j = 1, \ldots, n$ are the IID observations coming from system S_1
- X_{2j}, $j = 1, \ldots, n$ are the IID observations coming from system S_2.

By pairing X_{1j}, and X_{2j} for each observation j of the two approaches, and considering their difference,

$$X_{(1-2)j} = X_{1j} - X_{2j},$$

a new random variable that denotes the difference between the j^th^ observations in the two simulated approaches can be defined.

The $X_{(1-2)j}$'s are IID random variables and their point estimators are defined below. The sample mean is

$$\overline{X}_{(1-2)} = \frac{\sum_{j=1}^{n} X_{(1-2)j}}{n},$$

and the sample standard deviation is calculated using the following equation:

$$S_{(1-2)} = \sqrt{\frac{\sum_{j=1}^{n} \left[X_{(1-2)j} - \overline{X}_{(1-2)j}\right]^2}{n-1}}.$$

An unbiased estimator of $Var\left[\overline{X}_{(1-2)}\right]$ needed to form a $100(1 - \alpha)\%$ confidence interval on the expected response in the difference between the two systems is given by the following equation:

$$Var\left[\overline{X}_{(1-2)}\right] = \frac{\sum_{j=1}^{n} \left[X_{(1-2)j} - \overline{X}_{(1-2)j}\right]^2}{n(n-1)}.$$

The confidence interval on the expected difference between the responses of the two systems can then be defined as:

$$\overline{X}_{(1-2)} \pm t_{n-1,1-\alpha/2}\sqrt{Var\left[\overline{X}_{(1-2)}\right]}.$$

3.2 Real-Time Response

A comparison between the time needed to obtain a feasible solution using the agent-based control approach and the time to deliver the optimal solution is provided for each replication. The global optimal algorithm embedded in the internal structure of the GVA is used for this comparison. Time counters embedded in the C++ code of the both approaches tested are used to record the time needed to obtain the feasible agent-based approach and optimal solutions in each case in which the complexity of the problem permits. The real-time scheduling ability and the real-time response to changes in production orders are evaluated by monitoring the CPU time when running the decentralized system simulation approach. True fault-tolerance is obtained when all the jobs affected by a breakdown can be reallocated in real-time to the remaining resources, and the agent-based re-scheduling process still gives an objective function value of good quality. MH hardware reconfigurability, or the capability of the AMHS to add or remove MH resources at any time during operation, is evaluated by the output of the re-scheduling process like above, and by monitoring the CPU time necessary for the system to perform the re-scheduling process.

3.3 Experimental Results

All the algorithms developed for job evaluation, allocation, and execution for both control approaches presented above, as well as the simulation study steps are coded in C++ and run on a personal computer. Using the procedure to generate scheduling problems described in Beasley (2005) a series of job-shop problems were created and used as pilot runs to verify the validity of the algorithms developed. The results obtained, presented in Table 1 show that the solutions delivered when using the agent-based approach are very close to the optimal results, the maximum percentage difference being 6.15%, and in one of the considered job-shop problems the agent-based approach reached the optimal solution.

In the preliminary runs of the simulation programs, ten replications for the both approaches are considered. The simulation is stopped after 100 jobs are completely processed. The results obtained after the trial simulation runs show that the agent-based approach can deliver results of good quality, very close to the optimal ones, the maximum percentage difference being 3.65%, with an average of 1.20%. The big difference between the two approaches comes when considering the time needed to deliver solutions, and in this case the agent-based approach outperformed the optimal algorithm. Whereas the agent-based approach can give solutions in about half minute, the optimal algorithm could take in certain instances a considerable amount of time measured in several minutes.

Table 1: Comparison of the Makespan Values Obtained Using the Two Approaches

Jobs	**MC**	**MH**	**Agent-Based Approach**		**Conventional Approach**	
#	#	#	C_{max}	CPU Time	C_{max}	CPU Time
10	5	2	766	7.6	766	22.4
10	10	2	894	9.2	880	21.1
10	10	3	1216	10.5	1198	38.6
10	10	4	138	7.4	130	25.9
12	10	4	1114	9.4	1107	34.5
15	5	2	988	8.0	965	35.3
15	10	3	938	9.9	928	39.7
20	5	2	1389	10.3	1360	42.9
20	10	4	971	11.5	945	44.5
30	10	3	878	12.3	852	48.2

Compared to the heuristic algorithms developed for global scheduling, the agent-based approach performed slightly better in terms of the quality of the solution. The CPU time needed to deliver the solutions, always measured in seconds for the three heuristic algorithms, is comparable in this case for the two approaches.

4 CONCLUSIONS AND FUTURE WORK

As illustrated by the results obtained from running the preliminary tests for the simulation study the algorithms developed for the MH agent-based approach can give good feasible solutions in a short amount of time. The fundamental difference between the decentralized agent-based control and traditional manufacturing control comes from the distributed decision-making (multiple small decision spaces) existing in decentralized systems as opposed to the centralized or hierarchical control (single large decision space) in the case of conventional scheduling systems. The distributed decision-making for the job assignment problem translates in simple algorithms having reduced computational complexity that can be solved practically in real-time for any potential real-world situation.

Remaining work will concentrate in performing the actual simulation study as described in the previous section. The paired-t approach will be used for comparison when both types of disturbances, new coming orders and resource breakdowns, are considered. Since each of the MH resources considered in the simulation study may fail, the MH operation flexibility is constrained by the status of the resources at any given time, resulting in the need for dynamic decision-making. Reactive architectures, such as the agent-based architecture developed in this research, are expected to provide better response to disturbances, and as a result, better performance in stochastic environments.

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