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SIMULATION-BASED SCHEDULING FOR DYNAMIC DISCRETE MANUFACTURING

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ABSTRACT

A simulation-based real-time scheduling mechanism for dynamic discrete manufacturing is presented in this paper. Modified mean flow time performance for different scheduling approaches is compared through off-line simulation experiments, under dynamic manufacturing environments that are subjects to disturbances such as machine breakdowns. These experimental results are used as reference indices for the real-time scheduling mechanism to select the better scheduling approaches for further evaluation based on the actual manufacturing conditions. Discrete-event simulation is used on-line to evaluate the selected approaches and the corresponding schedules to determine the best solution. The selected schedule is used until the deviation of actual performance from the estimated one exceeds a given limit, or when a major event occurs. A new simulation is then performed with the remaining operations to select a new schedule.

1 INTRODUCTION

Market globalization not only creates new business opportunities for companies but also introduces new competitors, and changes the business environment from a vendor's to a customer's market. This gives rise to a range of consequences on the production process. The most prominent is the requirement for higher productivity over the whole manufacturing period. Most manufacturing systems today are operating at near optimal productivity under normal conditions, but fail to sustain the performance under process disturbances of any kind. A recent study shows that production disturbances can reach 80% of the total loss of the overall equipment effectiveness (OEE) of even 50% mean value utilization (Ylipää 2002). To stay competitive in the global market, it is thus vital for manufacturing companies not only to cope with frequent product changes and fluctuating demand, but also to reduce disturbances or at least the impact of disturbances on the overall manufacturing performance.

To deal with the challenge, an effective scheduling system that can maintain its performance while reacting to production disruptions in a timely manner is essential. In this respect, scheduling is no longer a static optimization problem, but an ongoing reactive process. This challenge is not trivial because most scheduling problems are NP-hard, and local disturbances can affect the global performance of the system in a non-linear way (Bongaerts, Brussel, and Valckenaers 1998; Parunak 1991). Moreover, practical scheduling problems are dynamic, uncertain and often unpredictable due to the continuous arrival of new and unforeseen orders, and the occurrence of all kinds of disturbances (e.g. machine breakdowns, process and yield variations, etc.).

These manufacturing characteristics limit the effectiveness of conventional scheduling approaches, which are static and deterministic. Such efforts formulate scheduling as combinatorial optimization problem, with the schedules computed over a specific time frame assuming all problem characteristics are known in advance, without consideration of reconciling any discrepancies with the actual progress on the shop floor (Matsuura, Tsubone, and Kanezashi 1993). Reactive (and/or proactive) scheduling, which can react to dynamic and stochastic manufacturing environments, becomes a better alternative for today's manufacturing scheduling problems.

Two broad categories of reactive scheduling approaches can be identified (Matsuura, Tsubone, and Kanezashi 1993; Vieira, Herrmann, and Lin 2002): predictive-reactive scheduling (i.e. sequencing or optimization-based) and dynamic scheduling (i.e. dispatching). The predictive-reactive approach seeks to establish an order for all the open jobs and reacts to process disturbances by reordering the jobs, while the dynamic approach provides a solution by the use of dispatching rules for selection from the queue of jobs.

Predictive-reactive scheduling is a two-stage approach, the first stage generates a schedule and the second updates the schedule in response to disruptions. Schedule generation acts as a predictive mechanism for production activities, and is important to serve as the basis for planning support activities such as material procurement, etc. Schedule generation can be either nominal or robust (i.e. proactive). In the former, foreseeable disturbances are not considered whereas the latter considers them in the schedule, e.g. by inserting idle times in the schedule.

Updating the schedule can involve either partial repair of the disrupted schedule or complete rescheduling. The update can be either periodic, event-driven or hybrid (Vieira, Herrmann, and Lin 2002). A periodic policy regenerates schedule periodically. An event-driven policy performs rescheduling upon the occurrence of events. A hybrid policy, which combines both periodic and event-driven policies, reschedules the system periodically or when major events take place.

In an attempt to construct an effective reactive scheduling system, various approaches have been proposed and evaluated by the research community. In dynamic scheduling research, an extensive list of dispatching rules is proposed and studied, ranging from simple rules to complex combinations of rules (Naroska and Schwiegelshohn 2002, Panwalkar and Iskander 1977, Perkins and Kumar 1989). In predictive-reactive scheduling literature, several research domains can be identified. First, rescheduling policy is studied (Church and Uzsoy 1992, Holloway and Nelson 1974). Second, optimization-based rescheduling (i.e. either periodic, event-driven or hybrid) is compared to real-time heuristics or dispatching rules (Chang, Sullivan, Bagchi, and Wilson 1985; Sabuncuoglu and Bayiz 2000; Wan 1995; Yamamoto and Nof 1985). Third, both new scheduling and rescheduling methods are proposed (Akturk and Gorgulu 1999; Dorn, Kerr, and Thalhammer 1995; Jain and Elmaraghy 1997; Matsuura, Tsubone, and Kanezashi 1993; Wu and Li 1995).

In general, a number of conclusions can be drawn from the reactive scheduling literature. The performance of optimization methods and dispatching based heuristics converges when there is considerable uncertainty and variability in the system (Lawrence and Sewell 1997; Sabuncuoglu and Karabuk 1997; Sabuncuoglu and Bayiz 2000). The optimization-based methods perform better than real-time dispatching rules when workload across the machines is not uniform i.e. there are bottlenecks (Sabuncuoglu and Bayiz 2000). The general consensus in reactive scheduling is that the performance of a scheduling method is problem-dependent (Sabuncuoglu and Bayiz 2000; Wan 1995), and that a scheduling/rescheduling approach can improve performance compared with fixed sequencing and dispatching procedures (Yamamoto and Nof 1985).

Towards this end, there are some efforts in developing scheduling techniques that can adapt to the scheduling problems. Matsuura, Tsubone, and Kanezashi (1993) proposed a scheduling approach that switches sequencing to dispatching according to the manufacturing condition. In the approach, sequencing is favored when manufacturing conditions remain similar to the original one (i.e., minimal variability) and dispatching is preferred when departure from the original situation cannot be ignored. Kim and Kim (1994) presented a scheduling mechanism that selects the best dispatching rule by evaluating a set of candidate rules using simulation. The selected rule is used until the difference between the actual system performance and the estimated performance exceeds a given limit. A new simulation is then performed to select a new rule. This cycle of simulate-select-evaluate is iterated repeatedly.

Our work extends research in this area, and a simulation-based scheduling mechanism, which dynamically adapts to the changing manufacturing condition, is proposed. In the approach, discrete-event simulation is used both off-line and on-line. Simulation is used off-line to build reference indices based on the performance of different scheduling approaches under varying shop floor conditions. Simulation is then used on-line to evaluate the schedules generated by the better scheduling approaches (i.e. based on both simulated and historical performance) for the actual manufacturing conditions to identify the best to use. The schedule is used until the deviation of actual performance from the estimated performance goes beyond a predefined limit, or when a major event occurs. A new scheduling approach and its schedule will then be selected using on-line simulation.

The rest of the paper is organized as follows. We will first discuss on typical production disturbances in discrete manufacturing environments, their characteristics, disturbance metrics, and reactive scheduling approaches that can react to disturbances. This is followed by a description of the proposed simulation-based scheduling mechanism. Finally, we will conclude in Section 4.

2 PRODUCTION CHANGES AND DISTURBANCES IN DISCRETE MANUFACTURING

A production change is an intentionally alteration to the production conditions whereas a disturbance is an unanticipated change to the production conditions (Brueckner 1998). Production changes are usually planned much in advance of time and thus beyond the scope of reactive scheduling research. Disturbances in the manufacturing environments can be related to capacity, orders or measurement of data (see Table 1).

Some similarities can be found among these disturbances in terms of their impacts on scheduling. For example, machine failures would have similar effect as (i.e. longer) deviation of actual processing time from the estimated one. Unavailability of tools or operators will eventually result in non-operational machines, which require the tools or operators to run. Delayed, shortage or defective of supplies may later cause delayed or cancelled orders. Change in due date of orders, and urgent orders may affect scheduling in a similar manner to the effect of change in job priority.

2.1 Characteristics of Production Disturbances

Studies show that the following characteristics of disturbances can impact manufacturing performance:

- **Type of disturbance** – The type of events for which the system is subject to, and this has been described earlier.
- **Size of disturbance** – The magnitude of a disturbance, for example machine breakdown duration can be short or long, or deviation of actual processing time from the estimated processing time can be small or large.
- **Interval of disturbance** – The duration (i.e. mean and variance) between two disturbances, which can be expressed in terms of frequency (i.e. inversely proportional) of disturbances.
- **Incidence of disturbance** – The time of occurrence, which can occur either earlier or late in a schedule.
- **Early notification of disturbance –** The extent of time for which the system is "notified" earlier than the actual time of event. For example, an urgent order can only be released into the shop floor hours later.

There are other characteristics of disturbances such as gradual introduction of disturbance (e.g. in a ramp-up way), propagation of disturbance i.e. disruption that triggers other disruptions, etc., which, in a way, can be transformed into one or a combination of the primary characteristics mentioned earlier.

A disturbance can affect production process, causing deviation from steady operating conditions, and can have the greatest effect on the critical (i.e. bottleneck) resources in production systems. Disturbances can result in shortfall (e.g. machine breakdowns) or surplus (e.g. shorter processing times) of capacity, and/or increase (e.g. urgent orders) or decrease (e.g. cancelled orders) of workload. To enable rapid response to disturbances and to reduce the impact of disturbances on the production system, capacity (or time) and/or work (or material) buffer can be introduced into the systems

Table 1: Typical Disturbances in Discrete Manufacturing

Disturbance class	**Examples of disturbances**	**References**
Related to capacity	Machine failures	Church and Uzsoy 1992; Jain and Elmaraghy 1997; Kim and Kim 1994; Li, Shyu, and Adiga 1993; Sabuncuoglu and Karabuk 1997; Yamamoto and Nof 1985
	Unavailability of tools	Stoop and Wiers 1996, Suresh and Chaudhari 1993
	Operator absenteeism	Church and Uzsoy 1992
Related to orders	Delayed, shortage or defective of materials or supplies	Abumaizar and Svestka 1997; Li, Shyu, and Adiga 1993
	Quality problems and rework	Church and Uzsoy 1992; Li, Shyu, and Adiga 1993
	Urgent (or rush, or hot) orders	Abumaizar and Svestka 1997; Jain and Elmaraghy 1997; Kim and Kim 1994; Li, Shyu, and Adiga 1993
	Change in job priority	Jain and Elmaraghy 1997
	Job (or order) cancellation	Abumaizar and Svestka 1997; Jain and Elmaraghy 1997; Li, Shyu, and Adiga 1993
	Due date change (i.e. delay or advance)	Li, Shyu, and Adiga 1993
	Specification change (i.e. insertion of deletion of operations in existing jobs)	Matsuura, Tsubone, and Kanezashi 1993
Related to measurement of data	Differences between estimated and actual times, e.g. processing steps and repair times	Li, Shyu, and Adiga 1993; Stoop and Wiers 1996
	Differences between estimated and actual yield (quality miss)	Suresh and Chaudhari 1993

(Matson and McFarlane 1998). This buffer however, can degrade system performance particularly if the level of disturbances is less than expected.

To assess the degree of disturbances in a manufacturing system, the following approximate disturbance measure for a specific schedule period (i.e. based on rolling horizon) is proposed:

$$\partial = \sum_{i=1}^{n} k_i \times f_S\left(t_i^{\,E} - t_i^{\,S}\right) \times f_I\,(t_i^{\,S} - t_S) \times f_N\,(t_i^{\,S} - t_i^{\,N})$$

where

n = Number of disturbances within a specific schedule period, from t_S to t_E,

$t_i^{\,S}$ = Start time of disturbance, i,

$t_i^{\,E}$ = End time of disturbance, i,

t_S = Start time of schedule,

t_E = End time of schedule,

$t_i^{\,N}$ = Notification time of disturbance, i,

k_i = Disturbance factor, which depends on the type of disturbance, i,

f_S = Size function, which relates the effect of disturbance to its magnitude,

f_I = Incidence function ($0 \le f_I \le 1$), which relates the effect of disturbance to its time of occurrence in the schedule. A function with decreasing value with time,

f_N = Notification function ($0 \le f_N \le 1$), which relates the effect of disturbance to its time of notification. A function with decreasing value with time.

In our model, we use the following factor and functions:

$k_i = 1$, $f_S(x) = x$,

$$f_I(x) = 1 - \frac{t_i^{\,S} - t_S}{t_E - t_S}, \quad f_N(x) = 1 - \frac{t_i^{\,S} - t_i^{\,N}}{t_E - t_S}.$$

2.2 Manufacturing Environments

In addition to the characteristics of disturbances, other factors relating to production conditions, can also affect scheduling performance:

- **Size of shop floor** – The size of the problem, and can be expressed as approximate number of job operations and resources present in the shop floor. This factor will affect the computational load and thus the scheduling responsiveness.
- **Type of shop floor** – The type of shop floor can be flow shop, job shop, flexible manufacturing system, etc.
- **Type of workload** – The workload distribution of shop floor. The shop floor can be under-loaded or overloaded, and uniformly or non-uniformly loaded (i.e. bottleneck).

To assess the shop floor environments, the following approximate model measure for a schedule period is proposed:

$$\eta = k_S \times k_W \times \phi, \qquad \phi = \left(\sum_{i=1}^{n} N_i + m \right)$$

where

ϕ = Shop floor model size,

m = Number of machines during the schedule period,

n = Number of orders (or jobs),

N_i = Number of operations for order, i,

k_S = Model type factor, which depends on the type of shop floor,

k_W = Workload factor, which depends on the workload distribution of the shop floor.

To enable impact evaluation of disturbances across different manufacturing environments, e.g. different types of shop floor, etc., disturbance measure, ∂ can be divided by the model measure, η (i.e. ∂ / η). The values of the factors such as k_S (e.g. for flow shop and job shop) could be estimated using simulation by performing two sets of experiments with all conditions unchanged except for the model type. In our scheduling mechanism, we set $k_S = k_W = 1$ since the shop floors are the same in both simulated and actual, and different sets of results are kept for different workload factors.

2.3 Scheduling and Rescheduling Approaches

The different perspectives of manufacturing environments lead to different solving methodologies for scheduling. The various reactive scheduling approaches, their advantages, disadvantages and shop floor prerequisites for effective application are presented in Table 2. Predictive scheduling can either be used standalone by complete rescheduling in periodic, event-driven or hybrid mode, or combined with reactive rescheduling. Reactive schedule update is commonly used together with either nominal or robust schedule generation, which is used to create an initial schedule.

Table 2: Different Approaches to Reactive Scheduling

Approach	**Examples**	**Advantages**	**Disadvantages**	**Shop floor conditions for effective application**
Predictive nominal	Tabu search, shifting bottleneck procedure (Jain and Meeran 1999)	Near optimal schedule quality, can be globally optimized for each run	Computationally intensive, schedule robustness is normally not considered	Should be very stable with absolutely minimal disruptions
Predictive robust	Deferred commitment (Byeon, Wu, and Storer 1998), idle time insertion (Mehta and Uzsoy 1998)	Good schedule quality, can incorporate robustness to absorb disruptions	Computationally intensive, schedule quality may be degraded due to introduced time and/or material buffer	Should be stable with minor and infrequent disruptions
Reactive	Right shift rescheduling, RSR (Leon, Wu, and Storer 1994), affected operation rescheduling, AOR (Abumaizar and Svestka 1997)	Normally low in computational effort, react to disruptions with stability consideration	Schedule quality is degraded	Can have multiple disruptions
Dynamic	Dispatching rules such as FIFO, SPT, etc. (Church and Uzsoy 1992)	Low computational effort, effect of disruptions in minimal	Poor schedule quality, highly problem dependent	Can be highly dynamic and stochastic

3 SIMULATION-BASED REACTIVE SCHEDULING MECHANISM

The scheduling mechanism consists of two distinct stages: off-line simulation evaluation and on-line reactive scheduling. The roles of these stages are outlined in the following subsections.

3.1 Off-Line Simulation Evaluation

Off-line simulation is used to establish initial reference indices for the performance of different scheduling approaches. Multiple replications of stochastic simulation with increasing degree of disturbances under different manufacturing environments are performed to obtain estimated performance for the scheduling approaches (Figure 1). The different scheduling approaches are evaluated separately using the same set of simulation replications, and the approaches are triggered on each occurrence of disturbances in the simulation. The obtained performance statistics (mean and variance) for each value of disturbance measure ∂, include:

- Modified flow time

$$F_m = \frac{1}{n}\sum_{i=1}^{n}\frac{F_i}{P_i} = \frac{1}{n}\sum_{i=1}^{n}\frac{\left(C_i - R_i\right)}{P_i}$$

where

n = Number of completion jobs,
F_i = Flow time ($= C_i - R_i$) of job i,
C_i = Completion time of job i,
R_i = Time of entry of job i,
P_i = Total theoretical processing time of job i.

- Scheduling response time

The simulation results enable relationships (i.e. line plots) to be established between modified flow time and disturbance measure ∂ under different shop floor conditions (i.e. under-, over-, uniformly, non-uniformly loaded). These relationships, as well as response time, can then be used in on-line scheduling to identify the scheduling approaches that may perform well (i.e. in terms of the modified flow time) in the actual manufacturing environments, based on the required response time and values of disturbance measure ∂.

3.2 On-Line Reactive Scheduling

At this stage, scheduling mechanism will run continuously and react to the actual production disturbances while performance statistics (i.e. modified flow time and response time), based on the actual disturbance measure, are being updated for each scheduling approach (i.e. when it is selected). The on-line scheduling mechanism consists of four major components: Real-time monitoring and control, scheduling mechanism, simulation evaluation, and scheduling controller. An overview of the system concept is illustrated in Figure 2. The functions of each component are:

3.2.1 Real-Time Monitoring and Control (RTMC)

This component receives events from the shop floor, and periodically monitors performance of the shop floor. It also

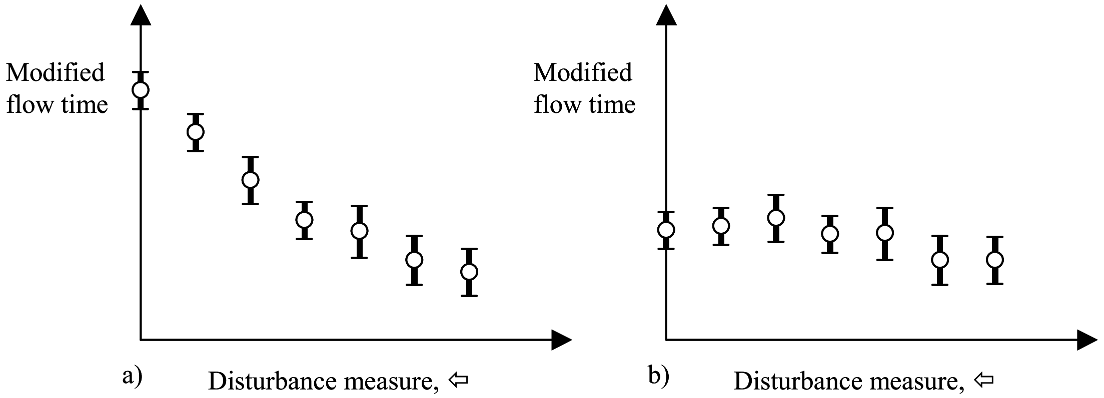

Figure 1: Typical Performance Plots for Two Different Scheduling Approaches Under Uniform Loading (a) Right Shift Scheduling (b) First In First Out

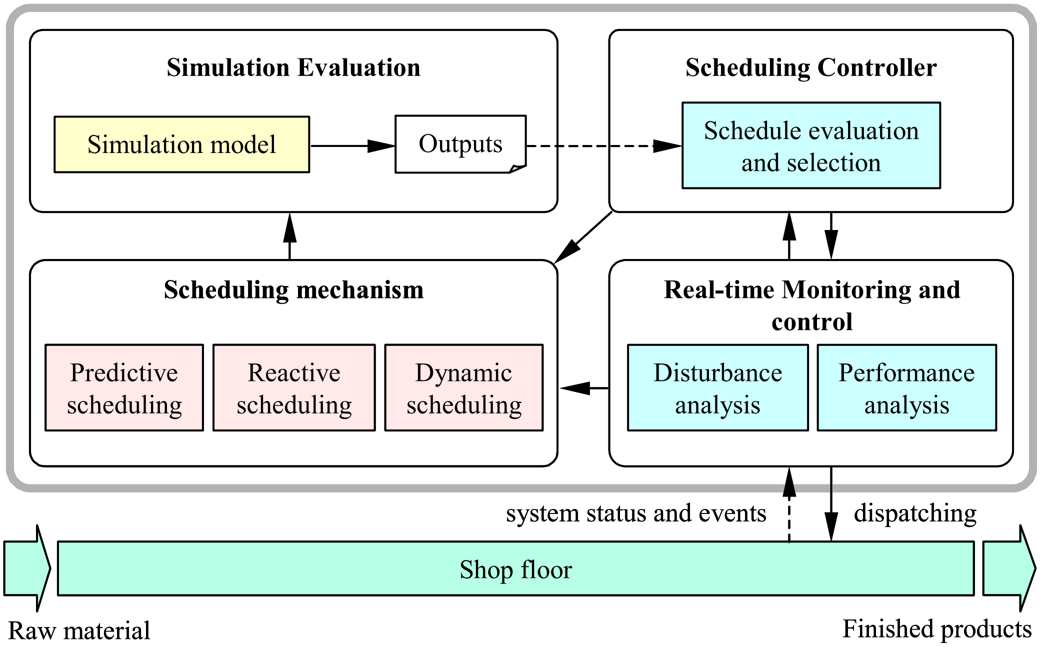

Figure 2: Reactive Scheduling Mechanism

sends all scheduling controller information to the shop floor and dispatches jobs to machine accordingly.

Two sub-components can be identified in RTMC: Disturbance analysis (DA) and performance analysis (PA). The former checks all incoming events, invokes rescheduling on major disturbances (criteria defined by users), and keeps track of disturbance statistics such as the interval, magnitude, etc. of each disturbance type at factory and/or machine level depending on the type of disturbances. These statistics are used to indicate the amount of capacity and/or work buffer that needs to be incorporated into schedule for some of the scheduling approaches (e.g. idle time insertion). Further, the data can also be used to show the reliability of each machine, and jobs can thus be scheduled to avoid the unreliable machines.

PA sub-component monitors the difference between actual and estimated performance values. Once the difference exceeds a predetermined limit at a point of monitoring, a new rescheduling is performed with the remaining operations under the current shop floor conditions.

3.2.2 Scheduling Mechanism (SM)

This component has a set of scheduling approaches that can be used for rescheduling. Each approach has statistical data on simulated and/or historical performance for different level of disturbance, and a user assigned preference indices. New scheduling approaches can be added in if past performance (i.e. usually through simulation) is obtained. The better scheduling approaches, based on the actual shop floor conditions, preference indices and response times, will be triggered to generate new schedules. In the cases dynamic scheduling approaches (see Table 2), discrete event simulation is used to generate schedule. The length of scheduling window of all scheduling approaches is fixed at three times the average total processing time. The number of scheduling approaches triggered will depend mainly on the required response time and computing resources. Compiled statistics from DA can be used to further enhance the robustness of the schedules.

3.2.3 Simulation Evaluation (SE)

This component includes a simulation model constructed based on the physical shop floor status from the factory database. When the scheduling controller passes control to SE, a series of simulation runs are initialized with the generated schedules (i.e. generated by the selected scheduling approaches) under the same stochastic conditions (i.e. with disturbances incorporated based on the statistics from DA). The length of simulation is set to be equal to the length of scheduling window. The results of the simulation will be passed back to the controller.

The outputs (i.e. modified flow time after incorporating disturbances) from the simulation are used by scheduling controller to selects the best schedule. The selected schedule becomes an input to RTMC, which dispatches jobs according to the schedule to the shop floor.

3.2.4 Scheduling Controller (SC)

SM, SE and information flow in the system is controlled by SC. SC selects the better scheduling approaches for further simulation evaluation based on the actual manufacturing conditions, and subsequently selects the best approach to be used on the shop floor. This selection process is performed at the beginning of a rolling scheduling horizon, when the system performance is not as expected, or when there is a major disturbance. The selection is also performed when the system state is back to normal (e.g. at the time of machine operating after repaired). When a minor disturbance occurs, the controller will delay the subsequent operations (i.e. similar to RSR approach).

SC also keeps track of the estimated performance value (i.e. modified flow time) of the selected scheduling approach. This value is an output from SE, and is used to compare with the monitored performance value of the actual shop floor.

4 CONCLUSIONS

A simulation-based reactive scheduling mechanism is presented in this paper. This scheduling mechanism employs discrete event simulation both off-line and on-line to evaluate a set of reactive scheduling approaches. The basic idea of the mechanism is to engage discrete event simulation to combine different scheduling approaches based on the past performance. The mechanism can therefore adapt itself by reacting to production disturbances and selects the best available reactive scheduling approach based on the actual shop floor status. In the long run, this process will result in a combination of different scheduling approaches based on their performance in each short time period. Intuitively, by alternating scheduling approaches in such a manner, the approaches will tend to compensate for the undesirable effects that each approach produces, and thus yield a schedule that is more reactive to the system dynamics.

In this paper, discrete event simulation has been shown to be an indispensable tool for detailed scheduling under a highly dynamic and unpredictable manufacturing system.

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