Katariina Kemppainen

PRIORITY SCHEDULING REVISITED – DOMINANT RULES, OPEN PROTOCOLS, AND INTEGRATED ORDER MANAGEMENT

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Abstract

The task of job shop scheduling – determining the sequence and timing of jobs on available resources – is one of the most discussed practical problems in operations management. There are many appropriate problem definitions for job shop scheduling due to the complex and dynamic nature of the problem with a large number of variables and constraints linked to jobs and resources, such as specific due dates, processing times, handling/routing requirements, and capacities not to mention alternative performance measures including maximum and mean tardiness, mean flow time, and portion of tardy jobs. Combinatorially the problems are NP-hard except for a few static one-machine problems with linear objective functions, in which shortest processing time and earliest due date rules are known to give optimal results for mean flow time and maximum tardiness, respectively.

This thesis looks into the coordinating power of priority scheduling when customers request different response times and suppliers do their best to fulfill the customer expectations, especially if enforced with differential pricing. The objective of scheduling is assumed to be finding a trade-off between loading efficiency and delivery accuracy when costs include items such as holding costs, tardiness penalties, and expediting charges.

From an extensive review of literature on practical applications and studies in index-based scheduling heuristics it appears that no single dominant priority index rule has been suggested for dynamic job shop problems with tardiness-related criteria. Motivated by some conflicting results published on the performance of priority index rules as well as the increasing uncertainty of manufacturing environments emphasizing the need for robust heuristics and heterogeneous response time requests of customer orders, this thesis revisits priority scheduling research and applications. Scheduling rules are studied in a variety of statistically generated job shop environments in which the task is to allocate resources to the individual operations of orders that are known to decision-makers. The performance of the priority index rules is analyzed in production systems where dispatching decisions are postponed and no idle time is inserted (non-delay scheduling). The fundamental question addressed is whether it would be possible to identify a single dominant rule to be considered as the basis for a standard scheduling protocol instead of testing different rules to find some fitting ones for each particular problem instance. In addition to the consistent comparison of priority rules, this thesis examines different technical specifications and tolerances for information and communication necessary to implement scheduling rules and illustrates the sensitivity of system performance to some alternative scheduling conventions.

The search for a theoretically justified and managerially applicable priority rule which could form the core of a standard scheduling protocol for integrated order management is reported in two parts. First, insights into the rationale and tardiness behavior of all reasonable priority index rules identified from the prior research are provided by analyzing the results of large-scale simulations in a variety of relevant job shop settings. It is demonstrated that, in fact, there is not just one rule but a whole family of dominating rules. These look-ahead rules (ATC, COVERT, and CR+SPT) strike a balance between local anticipation of job tardiness, through different types of look-ahead features, and global coordination of machine utilization through rational lead time estimates. Certain conditions of the shop and the selection of performance criteria, including order-specific costs for tardiness, inventory holding, and expediting, may favor one of these look-ahead priority rules over the others, thereby suggesting a trade-off between the informational complexity of the index and the eventual impact of the inherent coordination principle. Second, tests of different cases of implementation practices provide comforting results for the practitioners worrying over the accuracy of information used in lead time estimation and order priority determination. The look-ahead rules are not very sensitive to the selection of lead time estimation methods, nor errors in cost and processing time estimates. Furthermore, the benefits of using detailed estimates of tardiness penalties and operation-specific data are confirmed. New results indicate the superiority of the look-ahead rules when compared to the use of additional order release mechanisms and consistent improvement if the look-ahead rules are applied at least at some of the machines in the shops. Another additional benefit is the predictability of the on-time progress of orders through the shop.

The contribution emerging from the systematic and thorough examination of the inherently complex scheduling problems is a remarkably simple yet novel platform for evaluating the conditions for efficient coordination of priority dispatching rules. First, the benchmarking framework summarizes the intuitive results of dispatching research for managerial applications by matching the complexity and rationale of rules with requirements of problems. Second, the preliminary specification of, and experiments with, priority scheduling protocols set the stage for the future studies and large-scale applications of dispatch priority rules. Overall, this thesis provides a deeper understanding of the mechanisms of dispatching – instead of testing yet another rule – to facilitate a fruitful dialogue between managers and scholars. The agenda for future research still includes implementation issues of standard order scheduling protocols and the specifications of new classes of scheduling problems emanating from services and supply chain management.

Keywords: scheduling, priority index rules, job shop manufacturing, order handling, coordination, protocol, simulation, supply chain management.

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Helsinki, November 2005

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1 Introduction

The task of job shop scheduling – determining the sequence and timing of jobs on available resources – is one of the most discussed practical problems in operations management (e.g. Carroll 1965; Conway *et al.* 1967; Baker 1974; Morton and Pentico 1993; Pinedo 2002). There are many appropriate definitions for the complex and dynamic job shop problems with a large number of variables and constraints linked to jobs and resources, such as specific due dates, processing times, handling/routing requirements, and capacities not to mention alternative performance measures including maximum and mean tardiness, mean flow time, and portion of tardy jobs. Combinatorially the problems are NP-hard[1] except for a few static one-machine problems with linear objective functions in which shortest processing time and earliest due date rules are known to give optimal results for mean flow time and maximum tardiness, respectively. The objective of job shop scheduling is assumed to be finding a trade-off between loading efficiency and delivery accuracy when costs include items such as holding costs, tardiness penalties, and expediting charges. This thesis studies alternative dispatch priority rules in a variety of job shop environments, in which the task is to allocate resources to the individual operations of orders that are known to decision-makers. It should be noted that the priority rules designed for job shops do not necessarily work for dispatching in transportation and material handling (e.g. Le Ahn 2005) because the routings of vehicles or other resources, and hence the durations of operations are not known in advance.

As for the scheduling research, one stream has focused on solving closed problems of manufacturing and service operations analytically or has developed algorithmic techniques that enable finding at least close-to-optimal solutions (e.g. Fisher 1973; Lageweg *et al.* 1977; Lenstra *et al.* 1977). Numerous techniques have been developed for determining, for example, in what sequence a set of jobs, each consisting of a specific number of operations, should be processed on a number of resources to minimize their mean completion time (e.g. Conway *et al.* 1967; Baker 1974; French 1982). In fact, 'researchable' job shop scheduling problems have been standardized to provide reliable benchmarks for new methods (e.g. Muth and Thompson 1963; Lawrence 1984; Applegate and Cook 1991). Another stream of scheduling research has emphasized the importance of simple and robust methods and used

[1] Many scheduling problems are too complex to have a polynomial time algorithm and they are so-called NP-hard problems (Pinedo 1995, 20) in which NP stands for Non-deterministic Polynomial-time hard.

simulation to develop better planning principles and scheduling rules under practical constraints (e.g. Morton and Rachamadugu 1982; Vepsalainen and Morton 1987; Morton and Pentico 1993; Lawrence and Morton 1993). As a result, "the Carnegie School" has introduced advanced scheduling heuristics for manufacturing operations as well as for project management.

Even for the pragmatic priority scheduling approach, which uses simple procedures for selecting the next job to be processed on an idle resource, scheduling researchers apparently have not been able to provide satisfactory results that would have lead to extensive real-life applications. It is not a coincidence that the importance of practice-oriented scheduling research including configurable algorithms, adaptation of scheduling methods to a variety of models, rescheduling, and effective user interfaces has recently been emphasized to induce the use of developed algorithms and procedures in practice (McKay *et al.* 2002, Portougal and Robb 2000). The potential of priority rules may have been underestimated for three reasons. First, despite the long research traditions the results of priority scheduling are still prone to various interpretations. There is even conflicting evidence on the superiority of different dispatch priority rules among the results published in prestigious journals (e.g. Kutanoglu and Sabuncuoglu 1999 versus Jaymohan and Rajendran 2004). For this reason alone a revisitation to the priority scheduling research is called for. Second, uncertainties due to new orders, cancellations, material shortages, and machine breakdowns undermine the use of optimizing heuristics and sequencing algorithms. Lawrence and Sewell (1997) examined the effectiveness of dispatch priority rules and algorithmic optimizing procedures in job shop scheduling problems and found that the performance of optimizing solution methodologies quickly deteriorates due to processing time uncertainty when compared to dynamically updated heuristic schedules. They explicitly encouraged researchers to continue to identify and design rule-based scheduling heuristics for a variety of practical production settings. Third fundamental reason for rechecking the results of different prior studies is the bias in production scheduling research to deal with inherent variability in demand and customer requirements either by designing case-specific solutions or by eliminating the variability through standardization of service offerings. However, variability can also be useful (Hopp and Spearman 2000) because it allows selectivity in order processing. For instance, high priority can be given to short orders with high delay penalties and close to their due dates, which makes them clear the shop quickly, and orders with lower priority are processed as background load and may take longer to finish. Managers can then count on the predictability of the lead times quoted on this basis. Hence, priority-based scheduling can be an efficient method for managing the distributed decisions of order handling in complex production systems due to its coordinating effect.

Within order handling and production planning the intimate interplay of customer importance, service offerings, and profits increases the challenge of scheduling. Key customers, identified on the basis of strategic importance, may receive the fastest service only to get the shipments too early, while deliveries are delayed for other customers. Shouldn't the customer orders be divided into normal and rush deliveries on the basis of due dates requested by customers. Plambeck (2004) proved that this type of lead time differentiation, where same product is sold to different customers at different prices based on delivery lead time, can both increase profits and reduce capacity requirements. Here, order-specific costs and delivery time requirements are assumed, and it is investigated how variability inherent in customer orders can be used to increase the efficiency and predictability of operations in production systems via selectivity.

This thesis looks into the coordinating power of priority scheduling in decision-making when customers have different response time requests and suppliers do their best to fulfill the customer expectations, especially if enforced with differential pricing (similar to Gilbert and Ballou 1999). The performance of dispatch priority rules is analyzed in production systems where dispatching is postponed and no idle time is inserted in schedules, i.e. non-delay scheduling. The fundamental question is whether it would be possible to identify a single dominant rule or a family of such rules to be considered as the basis for a standard scheduling protocol instead of testing alternative dispatching rules in order to find some fitting ones for each particular problem incidence. For customer order handling, open protocols shared by decision-makers would define the rules of order scheduling in a given situation, conventions of usage in different production or supply chain contexts as well as the technical specifications and tolerances for the necessary information and communication.

1.1 Practical Illustrations of Order Management

Today companies pursue the global objectives of high resource utilization, fast order turnaround, and outstanding customer service. At each process stage, decision-makers deal with order management and scheduling decisions which have to be coordinated over time and among resources. Problems may be caused by misinterpretation of demand signals and capacity information, misalignment of goals, and inability of decision-makers to respond swiftly to modifications in any information that specifies the system activities. While the organizational behavior should be changed first, the consideration of system-wide objectives also calls for methods that would enhance the coordination of order management and scheduling decisions possibly distributed to different functions of production systems, or supply networks alike.

Let us consider three real-life examples. In a leading paper industry company, average customer lead times improved significantly after one of the top executives simply drew a red line indicating the targeted average lead time on the company's monthly lead time reports. Thanks to this, perhaps even trivial, signal both the managers and operative staff of the company quickly understood the impact of lead times on the performance of the company and cut down the non value-adding time of customer orders resulting in shorter and less variable lead times. Another case of improving the order management process took place within a global elevator manufacturer. The company developed a tool for lead time estimation, called S-plan, which specified lead times in weeks per each stage of the supply chain. The S-plan did result in shorter lead times but degraded performance in punctuality (actual delivery times versus confirmed delivery dates) and service level (determined based on the actual delivery times and the delivery dates requested by customers). In fact, the capability of the supply chain to react to unexpected changes deteriorated because each decision-maker began to control his operations aiming to keep the stage-specific due dates enforced by the S-plan accurately. The third real-life example concerns the decisions of order dispatching and expediting in a metal manufacturing company. Lacking an appropriate planning and scheduling software, it applied a simple decision rule: manufacturing lead times were estimated by multiplying the order-specific number of operations with average stage-specific processing time. With this method, during high demand, orders piled up on the shop floor and estimated lead times were too tight. To reduce the expediting task of supervisors and to guarantee high delivery accuracy at least to the most important customers, the management launched a new order scheduling principle that gave priority to the orders of selected customers in every dispatching decision. As a result, the orders of these key customers were finished long before their planned shipment dates pushing other customers' orders backwards in the schedule. The logic of the principle was correct, but it was not aligned with due date setting, and the overriding priority was not given to orders with the highest 'bang-for-the-buck' based on the expected penalties due to late deliveries.

The key lessons of the practical examples on due date management, lead time estimation, and order scheduling are the following:

- simple changes in management culture such as increasing awareness on the importance of lead time reduction can improve customer service;

- the use of standard methods such as the S-plan and 'one-day-per-stage' lead time estimation may help internal procedures but hurt customer service when applied in a rigid manner;
- strategic customer classifications allow the division of orders into different service classes but do not offer the best foundation for order management and scheduling; and
- the expediting of rush orders, i.e. the use of order priorities, should be linked to lead time quoting and service pricing.

In addition to demonstrating the intricacies of priority assignments, these examples emphasize the importance of quoting reliable lead time estimates based on order priorities on the level of operations and system stages. After all, the importance of predictable lead times and operating efficiency is ever increasing due to minimization of slack in any combination of inventory, capacity, and time.

Although the coordination of decentralized dispatching decisions with priority index rules does not necessarily require the use of hierarchical planning structures, their implementation would benefit from the major development of information systems over the last decades. Today powerful computers and advanced information systems not only facilitate the use of advanced planning and scheduling techniques but also support the collection of comprehensive data on both the progress of orders and changes in system states. As a result, the main challenges for decision-makers are the selection of most appropriate methods for order scheduling and securing the access to correct and up-to-date information. It is assumed that integrated order management powered by standard protocols of order handling could, in addition to coordinating lead times and delivery performance, help collaborating decision-makers in specifying what type of data is valuable in doing so. Borrowing from economic planning (Kydland and Prescott 1977), production schedulers relying on rational expectations could then use rules rather than discretion.

Supply chain management (SCM) strives for higher chain-wide efficiency, for example via information sharing and alignment of incentives (e.g. Mentzer *et al.* 2001; Lambert and Cooper 2000). A common conclusion of supply chain studies has been that the suppliers need to offer their customers incentives for sharing demand information, because direct cost savings of visibility primarily benefit the suppliers. Furthermore, the lack of knowledge and agreement on the use of the shared information is identified as one of the causes for limited information sharing (Kemppainen and Vepsäläinen 2003). Also the difficulty of finding the right balance and order of logistical and technological differentiation, and the informational integration through information systems, which is often costly, hinders open sharing of data

(Kemppainen and Vepsäläinen 2005). Hence, this thesis contributes to SCM by suggesting what type of order scheduling protocols specifying the relevant data to be shared are expected work in complex business environments that rely on the rational expectations of decentralized decision-makers. Priority-based order scheduling studied in this thesis does not necessarily work in all business environments, but it is considered a prospective mechanism particularly for the coordination of myopic and greedy dispatching decisions in complex job shops when the mutual interference of orders is hard to predict.

1.2 Research Problem and Objectives

This thesis examines the potential extensions of priority scheduling towards applications in the context of supply chains. More specifically, it seeks scheduling rules and technical implementations in order handling applicable across sales and production organizations as well as with suppliers and customers of the firm. Thus, it would be important to identify from the prior job shop scheduling research robust priority index rules, which could form standard, open protocols for order scheduling. The protocols standardizing the code of conduct for decision-making, communication, and technical implementation of scheduling rules in order handling can be applied within one organization or across multiple organizations.

Dynamic real-life scheduling problems quickly become NP-hard, especially with non-linear objective functions, and so the power of algorithmic optimizing procedures is disputable. The relatively rigid material resource planning systems and other collaborative planning processes, aiming to coordinate scheduling decisions in advance, have difficulties in adjusting to the stochastic environment of make-to-order companies where variables such as order due dates and quantities can have high variability and/or change frequently. Acknowledging these limitations, here the focus is on analyzing the benefits of order-specific priority indices, which are calculated using information about orders, resources, and/or a system as a whole. Priority index values utilizing the diversity of customer orders support the myopic and greedy decisions of order management and scheduling without heavy requirements on information systems in use.

This thesis analyzes where and how the index-based scheduling heuristics can be applied, first, to better anticipate the flow of customer orders of different sizes and with different levels of priority through production systems, and second, to coordinate the postponed and localized decisions of order management and scheduling in systems with distributed decision-making. This type of order handling protocol, as called in this study, refers to system-wide integrated order management in which scheduling rules are used stage-wise for estimating the urgencies of customer orders for dispatching. In addition to loading customer orders to machines on the shop floor, priority indices can be used in aggregate statistics for coordinating purposes in order acceptance, pricing, and communication. This thesis emphasizes the use of shared rules instead of allowing decision-makers to use discretion, independently or collaboratively, based on information not necessarily visible to all decision-makers. The economic rationale of the rules applied should be agreeable, pertaining to the relative costs of orders, similar to marginal delay costs in Dolan (1978), so as to allow distributed decision-makers to rely on rational expectations and eventually on some form of pricing of priorities (Vepsalainen 1984).

The objectives of this thesis are as follows:

1. To characterize the state-of-the-art of priority scheduling based on the literature on practical applications and studies in index-based scheduling heuristics designed for order dispatching, due date assignment, order acceptance, and order release.
2. To identify robust and well-performing priority index rules or families of such rules, if any, for order management by comparing the candidate rules selected from the prior research, using conventional simulation experiments in relevant, statistically generated test settings.
3. To examine different technical specifications and tolerances for information and communication necessary to implement scheduling rules, and to illustrate the sensitivity of system performance to the different conventions of usage in order handling.

Manufacturers have not widely implemented and used priority scheduling suggested for order handling in the scheduling literature, as will be discussed in more detail later. The modest use of index-based scheduling heuristics suggests that scheduling research lacks managerial perspective that would focus on the economic rationale of order management decisions, and the ever increasing number of techniques offered by researchers makes the selection of the most appropriate method difficult even for educated managers. To ease the selection and the use of the methods of order management and scheduling, first real-life experiences are discussed according to published research. Second, the results of scheduling literature investigating index-based scheduling heuristics designed for the decisions of order acceptance, order release, due date assignment, and dispatching since the 1950s are reviewed and summarized. Based on the extensive number of mainly simulation-based studies considered in the thorough literature review the most prominent methods are identified for further analysis with our new benchmarking framework determining the performance of dispatch priority rules.

The first experimental part of this thesis examines the performance of scheduling rules selected from the prior research in job shops. The purpose of the large-scale simulations is, first, to set straight the rankings of established dispatch priority rules especially in the weighted job shop problems, and second, to identify promising candidates from the established rules for open order protocols instead of designing new rules. The comparisons of the alternative scheduling rules are primarily done based on the normalized versions of performance measures, which standardize the results of experiments using information on the problem size and job characteristics.

The second experimental part is a constructive analysis that discusses the evaluation and design of open protocols in order handling. The simulations focus on the logic and behavior of selected priority rules by testing the specifications and tolerances of scheduling rules as well as their conventions of usage in order handling. The tests reported assess also in terms of the new benchmarking framework the sensitivity of priority index rules to the quality, scope, and level of information as well as to the specifications of lead time estimation methods. Response models and conventions for integrating decisions across the process of order handling are also addressed by examining illustrative combinations of dispatch priority rules and order release mechanisms. Also the properties of the identified best performing priority index rules which make them attractive for decision-makers are discussed. These results, all in all, are relevant not only for practitioners, who potentially can improve company performance by using order protocols formed on the basis of dispatch priority rules, but also for researchers who for long seem to have focused on the technical aspects of order scheduling.

1.3 Positioning and Methods of Research

The focus of this thesis is on non-delay scheduling of heterogeneous customer orders in dynamic job shops. It analyzes alternative methods designed for localized and postponed decisions, and seeks general principles for coordinating order management and scheduling in make-to-order production primarily. It builds upon the knowledge of both production planning and scheduling since the coordination approach studied here has not yet received wide attention. The theoretical foundation for this thesis is priority scheduling research, in particular, on job shop problems. It follows that the research methods as well as the experimental designs adhere to the traditions of priority scheduling research as closely as possible. New types of problems illustrating for instance outsourced production operations are left for future research. Technical problems of distributed control of operations such as the design of communication protocols, agent models, or other IT-based solutions for information sharing are not within the scope of this thesis either.

Decisions linked to order acceptance, due date setting, order release, and dispatching in dynamic manufacturing systems producing to customer orders using the lot-for-lot principle are examined. Hence, earlier results on managing high/low priority orders in make-to-stock production are not considered (e.g. Veinott 1965; Nahmias and Demmy 1981). Nor does this study discuss static scheduling problems that typically seek to minimize the total makespan of jobs or production planning activities employing algorithmic techniques in preparing schedules for specific planning periods (e.g. Gupta and Kyparisis 1987). Excluded are also the implications of priority-based order scheduling on material management and workforce planning as well as the challenges of sequence-dependent setup times. As the research addresses the logical principles of priority scheduling, any pilot studies testing the challenges and opportunities of integrated order management in practice are left for future research.

Preliminary inquiries in manufacturing companies indicated a lack of systematic use of priority rules in order management. Hence, there has been little evidence for conducting in-depth case studies for proposing hypotheses addressing the selection of production scheduling methods for different manufacturing environments. However, since case studies are suited for research that seeks new perspectives on an overresearched topic (Swamidass 1991), a small-scale survey of order management and scheduling practices is reported indicating limited use and awareness of existing methods and techniques even within well-performing large manufacturing units. Thus, this study contents to discuss the status of order management and scheduling according to published research. Due to the lack of adequate real-life benchmarks the comparative analyses of this thesis use synthetic data determined on the basis of an extensive review of published studies. A systematic and thorough search of priority scheduling research was conducted in spring 2004. Details about the collected material as well as the review method are presented in Chapter 3.

The experimental parts of this thesis use event-based simulation, along the traditions of the above mentioned Carnegie School, to gain insights into the rankings, scheduling logic, and economic rationale of selected dispatch priority rules. The experiments, conducted in large-scale job shop problems familiar from prior research, seek better understanding of the informational efficiency of dispatch priority rules, and so do not aim to contribute to the algorithmic development of scheduling methods. The focus is on the steady-state performance of alternative systems, first, to provide comparison with the results of previous publications, and second because earlier results have shown that the size of the problem incidences – thousands of jobs in a large job shop versus some dozens of jobs in a small flow shop – does not significantly impact the results of rule comparisons (Vepsalainen 1984). Commercial simulation software that would have enabled efficient configuration of the standard job shop problems and use and testing of the scheduling rules was not found. Furthermore, there was no suitable open source software available. For these reasons, new simulation software was specified by the researcher for the purposes of this thesis, and it was programmed by a professional software developer. Descriptions of the software as well as the research method are available in Chapter 4.

1.4 Structure of the Thesis

Chapter 2 defines the problem of production scheduling and describes the stages of order handling in manufacturing. Moreover, it elaborates the alternative types of scheduling rules, especially dispatch priority rules, by discussing empirical evidence based on published research and a small-scale exploratory study in Finnish manufacturing. This chapter also suggests new classifications for identifying the most appropriate approach for order scheduling and for comparing alternative dispatch priority rules. It concludes with a discussion of the coordination effects of dispatch priority rules relevant to both production systems and networks formed of multiple organizations. A benchmarking framework is introduced for evaluating priority scheduling methods for managerial purposes. Chapter 3 is a prologue to the two experimental parts of this thesis. It summarizes the main findings from the literature review that surveyed index-based scheduling heuristics. Besides discussing competing methods and their differences, dominance charts for each of the key order management decisions (order acceptance, order release, due date assignment, and dispatching) according to the results of analyzed prior research are developed. Further, the test settings used in the comparative analyses of dispatch priority rules are explained. Building upon the dominance charts the most promising scheduling rules for further simulation-based analysis are suggested, and finally, implications for job shop scheduling research are also discussed.

Chapter 4 begins by defining the research settings of the computational experiments. The rest of the chapter is devoted to reporting the results of the large-scale simulations in well-known weighted and unweighted job shop problems. Finally, the results are analyzed in order to identify a single dispatch priority rule or a family of rules that performs most robustly across different problem instances tested, and so could be considered as dominant rules that define the rules of scheduling behavior for customer order handling. Chapter 5 discusses the implementation aspect of order scheduling standard protocols. It emphasizes the technical specifications and tolerances that need to be considered when designing the etiquette for the decisions of order management and scheduling. The focus of the chapter is on different experiments assessing the sensitivity of selected priority index rules to the level of data aggregation, choice of lead time estimation method, simplification of cost data used, and mixing of different dispatch priority rules within a production system. Further, it summarizes the results of the simulations vis-à-vis the implications of the benchmarking framework. In Chapter 6, some alternative scheduling conventions such as the application of order screening and mixed use of priority rules at different stages of job shops are explored. Together with the rules of behavior and technical specifications and tolerances, these conventions of usage form the key layers of open protocols that form the code of conduct, in this case, for order management and scheduling. Concluding remarks in Chapter 7 include a summary of the thesis, discussion of results recommending the use of selected priority rules as the engine of open scheduling protocols that promote integrated order management, and recommendations for future research.

1.5 Key Terms

Production systems are typically analyzed from the perspective of material flows and internal planning processes. Already Shapiro *et al.* (1992) stressed the importance of looking at the process of order handling and fulfillment from the perspective of customers defining a ten-step Order Management Cycle (OMC). The steps are 1) Order planning, sales forecasting and capacity planning, 2) Order generation, 3) Cost estimation and pricing, 4) Order receipt and entry, 5) Order selection and prioritization, 6) Scheduling, 7) Fulfillment including procurement, manufacturing, assembling, testing, shipping, and installation, 8) Billing, 9) Returns and claims, and 10) Post-sales service. The concept of OMC is not used in this thesis because it would extend the scope of analysis to after-sales services and operational routines such as cost estimation and invoicing. Another concept offered in scheduling literature is Due Date Management (DDM). According to Keskinocak and Tayur (2004), the DDM policy consists of a due date setting policy and a sequencing policy, i.e., it allows endogenous determination of due dates. In their study, DDM covers the alternatives for and the effects of due date setting methods and dispatching rules but does not include inventory decisions. This study, nevertheless, aims to link the customer needs communicated via orders with the planning and control of manufacturing activities, and subsequently, the acceptance and release of orders are also considered. To reflect the idea of integrated order management in production systems with distributed decision-making, a new term OMPPOS referring to the process of Order Management, Production Planning, and Operations Scheduling is launched. The OMPPOS process can be managed using a combination of scheduling rules as a coordination mechanism that allows rational decision-makers to determine the relative importance of customer orders throughout a system, whether a single production unit or an inter-organizational process. Hence, the way in which priority scheduling is linked to order handling is the concern of integrated order management, not an illustration or evaluation of the process itself.

Coordination is a concept commonly mixed with or used as a synonym for integration (e.g. Romano 2003). Yet even the everyday language makes a distinction between the two terms (e.g. Meriam-Webster 2004). Integration is an 'act of combining into a general whole'. It refers to bringing units together, or uniting into a whole. Coordination means 'assuming, arranging in proper order, position or relationship', i.e., acting in a harmonious combination and harmonizing in a common action. Coordination has more management options since different units do not need to be unified and the parties involved are not obliged to some predefined operating modes as they would be in integrated operations. Coordination and integration can also be defined as two different levels of cooperation (Haapanen and Vepsäläinen 1999). In that case integration means the development of prerequisites for cooperation, whereas coordination refers to the alignment of the operations of different parties. Coordination can be executed by standardizing decision-making within the order-delivery process so that there is no room for opportunistic behavior of individuals.

In SCM research, coordination mechanisms normally refer to contractual agreements or incentive structures that can be derived based on agency models or game theory. This study, however, analyzes the power of conventional scheduling heuristics as coordinative mechanisms or protocols supporting the decisions of order management and scheduling within complex systems where decision-making is distributed, postponed, and localized. Integration is considered as a structural decision linked to information systems and organizational structures, and so an integration mechanism can be, for example, an IT-based planning system in which the decision-makers and information available are predetermined. Coordination then is construed as an operational mechanism such as planning process. It concerns primarily information sharing and incentive alignment needed for managing decisions among various actors. In inter-organizational context, for example, a change in the load of the next resource, potentially delaying delivery times of customer orders, cannot be considered without proper coordination mechanisms.

Many different terms such as priority rule, dispatch heuristic, and scheduling rule are used to refer to the principles that determine the relative importance of a single order among all waiting orders when selecting the next one for processing without inserting idle time. Gere (1966), for instance, defined a priority rule as a technique by which a number is assigned to each job in the queue. According to him a heuristic is a rule of thumb, and a scheduling rule is a combination of one or more priority rules or heuristics. This thesis uses dispatch priority rules and priority index rules to refer to the methods that give order-specific priority indices applicable in the decisions of order management and scheduling. It is acknowledged that a variety of dispatch priority rules have been suggested for estimating the relative importance of jobs to be processed especially in job shop scheduling (e.g. Panwalkar and Iskander 1977; Blackstone *et al.* 1982). Due to the absence of appropriate classification of scheduling rules, this thesis introduces a categorization based on the order information used and the type of priority index that helps to identify dispatch priority rules with high informational efficiency. These dominant rules are considered in the search of rules expected to determine the behavior of open protocols applied throughout the OMPPOS process including decisions from order acceptance in sales to lead time estimation and order release in production planning.

2 Concepts and Practices of Order Management and Scheduling

This chapter begins by defining the task of scheduling from the perspective of manufacturers. Moreover, it describes the process of order management. Different alternative approaches to scheduling customer orders in make-to-order production systems are also discussed, and priority scheduling is suggested as one way to integrate the decisions of order handling. Based on published research and a small-scale study of selected progressive Finnish manufacturers this chapter summarizes the empirical evidence on the applications of scheduling rules, and accordingly, categorizes the rules with a new classification scheme. A discussion of why and how priority scheduling, producing order-specific priority indices, can be employed for improving coordination within complex systems concludes the chapter.

2.1 Production Scheduling

Manufacturers can plan their production based on customer orders, shop orders determined on the basis of the level of finished goods inventory, or on a combination of these two. Companies serving their customers from inventories are known as make-to-stock (MTS) manufacturers, whereas companies that have moved the decoupling point of customer orders to raw materials are called make-to-order (MTO) manufacturers. The key tasks of order management differ in these two production environments: MTS manufacturers focus on projecting inventory levels and assuring promised customer service levels, while MTO companies pay more attention to product specifications and adjustment of production capacity to the requirements of customers (Vollmann *et al.* 1997).

Production systems that use both MTS and MTO approaches for planning of operations require diversity that serves coordination and high utilization purposes. Both the hybrid systems as well as the pure MTO systems are potential applications of a priority scheduling protocol. The actual scheduling of customer orders can be carried out in various ways. A lot-for-lot principle is applied if orders cannot be combined or divided for scheduling purposes. Alternatively, orders can be either combined into shop orders to achieve economies of scale and minimum lot sizes, or partitioned into lots to accommodate manufacturing of products in more than one production line, and to meet maximum lot sizes. Besides high on-time performance the production scheduling function of MTO companies aims to maximize resource utilization and minimize inventories (e.g. Hopp and Spearman 2000). To deal with the trade-offs among high capacity utilization, low inventory levels, and short and accurate lead times manufacturers typically design a hierarchical production scheduling system. Next, the structure of production scheduling is described, well-known production scheduling problems are specified, and some principles of priority scheduling are discussed.

2.1.1 Hierarchical Structure of Production Scheduling

The production function of a company can be viewed as a hierarchical model. Companies prepare forecasts on future demands, i.e. aggregate sales over a predetermined planning horizon (e.g. Vollmann *et al.* 1997; Nahmias 2005). This information on anticipated demand is used to develop aggregate plans for both workforce and production, which, consequently, are transformed into production plans that specify production quantities of different products per each time period. This master production schedule is exploded using the material requirements planning (MRP) system to obtain the time-phased requirements for each level of assembly or the final product. The detailed job shop schedule can then be obtained by translating the planned order releases into a set of tasks and the due dates associated with the tasks.

Morton and Pentico (1993, 11-15) emphasized that different levels of abstraction of resources can be used in solving production scheduling problems. They defined that a scheduling system dynamically makes decisions about matching activities in a timely and high-quality fashion and simultaneously maximizes throughput and minimizes direct operating costs (Morton and Pentico 1993, 10). Each of the five levels defined in their classification consider the issues of sequencing, timing, routing, reconfiguration, forecasting, labeling, grouping, aggregation, and disaggregation, and, therefore, should be considered as parts of scheduling. With Level 1 problems, which include location, sizing, and design of plants and warehouses, scheduling methods have not been successful. For Level 2 problems there are both stochastic and deterministic aggregate planning models that consider production smoothing either using external resource changes (hiring, firing, layoff, and subcontracting) or internal changes (overtime, capacity investments, and resource shifting). Short-range planning (Level 3) refers primarily to MRP, shop bidding, and due date setting. Since its planning horizon is 3-6 months, balancing the shop can be conducted either by repeatedly readjusting the master schedule or by negotiating higher prices and slower delivery for the overbooked shop and lower prices and fast delivery when there is slack in the shop schedule. Morton and Pentico (1993, 14) explained that Level 4 scheduling operates using a fairly accurate master schedule of upcoming jobs, priorities, and due dates for the next few weeks. A full schedule for one month might only be developed once a week, using currently updated input and shop status. These schedules may have to be updated due to emergencies or glitches caused, for example, by machine breakdowns or late arrivals. These types of corrections to Level 4 schedules as well as the expediting of rush orders are considered to be a part of reactive scheduling/control (Level 5). In the conventional manual scheduling systems, rescheduling used to be more robust, since changes could usually be incorporated by applying the same simple dispatch priority rule to the changed shop that was normally applied 'on the fly' during the week, Morton and Pentico (1993, 14-15) reasoned. The following section describes the common structure and assumptions of job shop scheduling problems, which is assumed as the standard test bed in this thesis.

2.1.2 Job Shop Scheduling

The task of scheduling is to determine the order in which jobs are to be processed at each resource and to time the jobs, i.e. plan their start and finish times (Conway *et al.* 1967; Baker 1974). The problem of job shop scheduling can be defined, for example, as the sequencing and timing of jobs on machines so that their average lateness is minimized. In solving the scheduling problem decision-makers primarily use information on resources and jobs in hand or soon available. Job-specific characteristics typically employed are processing times p_i and due dates d_i, but also arrival times a_i to the system and release times r_i to the shop floor, to name a few, can be used.

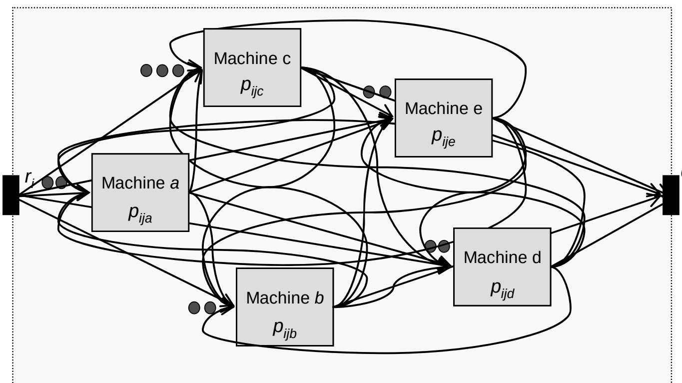

Figure 2-1 Illustration of a job shop.

The most generic type of production system analyzed by scheduling researchers is a job shop, in which jobs are unique, their routings through the system can be complex, and there may be alternative routings available (Figure 2-1). Another production scheduling environment often examined by researchers is a flow shop, where the material flow is linear through all machines or work centers forming the production process (Figure 2-2). The layout of a production facility and the type of product routings impact the complexity of the scheduling problem directly. For instance, the weighted tardiness problem becomes very hard to solve to optimality even in 10-machine systems with more than 30 jobs, not to mention scheduling with multiple objectives (Pinedo 2002, 505). Processing requirements of jobs at different process stages as well as sequence-dependent changeover times also impact the difficulty of scheduling problems.

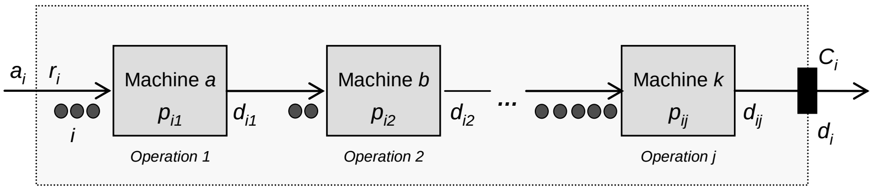

Figure 2-2 Illustration of a multi-stage flow shop.

Scheduling research has used, for example, random, uniform, and proportionate shops as testing environments for alternative rules (e.g. Morton and Pentico 1993). In a random shop, the processing times of jobs are randomly assigned without a link to job size. In a uniform shop, which is considered the most common testing environment (Kutanoglu and Sabuncuoglu 1999; Lejmi and Sabuncuoglu 2002), the sizes of jobs are assumed constant and operation-specific processing times are drawn from a uniform distribution. In a proportionate shop, jobs are first assigned a size and then processing times are generated from a uniform distribution so that the processing times are correlated, or almost proportionate, over operations (Vepsalainen 1984). In addition to these three kinds of shops, alternative scheduling methods are often tested in bottleneck systems with unbalanced resources (e.g. Lawrence and Morton 1993; Kutanoglu and Sabuncuoglu 1999). Other realistic scheduling environments include manufacturing cells, assembly lines, and transfer lines (Table 2-1).

Scheduling environments differ in the number of machines per each process stage or facility. Additionally, the link between shop orders and customer requests as well as the level of uncertainty imposed on the scheduling task can vary. In open shops, inventory is not stocked, whereas in closed shops lot sizing decisions associated with inventory replenishment processes are linked to the sequencing problem (Graves 1981). At times, in both theory and practice, the challenge of production scheduling is reduced by freezing the number of jobs to be scheduled at some point before the start of production. Resulting static scheduling problems are easier to optimize periodically than dynamic scheduling problems where new orders are allowed to arrive continuously.

Table 2-1 Standard production environments in scheduling research (Morton and Pentico 1993, 16).

Type of environment	Characteristics
Classic job shop	Discrete, complex flow, unique jobs, no multi-use parts.
Open job shop	Discrete, complex flow, some repetitive jobs and/or multi-use parts.
Batch shop	Discrete or continuous, less complex flow, many repetitive jobs and multi-use parts, grouping and lotting important.
Flow shop	Discrete or continuous, linear flow, jobs all highly similar, grouping and lotting important.
Batch/flow shop	First half: large continuous batch process, second half: typical flow shop.
Manufacturing cell	Discrete, automated grouped version of open job shop or batch shop.
Assembly shop	Assembly version of open job shop or batch shop.
Assembly line	High-volume and low-variety, transfer line version of assembly shop.
Transfer line	Very high-volume and low-variety linear production facility with automated operations.
Flexible transfer line	Modern versions of cells and transfer lines intented to bring some of the advantages of high-volume production to job shop items.

Researchers studying production scheduling can, in addition to the approach used in determining shop configuration and generating job data, define the objective function for scheduling decisions. Most common performance measures are makespan, flow time, lateness, tardiness, and tardy jobs (e.g. Morton and Pentico 1993; Pinedo and Chao 1999). The focus of analysis can be either on the average or maximum value of each of the measures depending on the researcher's interpretation on what is the most relevant concern for decision-makers. There are scheduling studies that, in addition to the maximum and average values, also report the variances and standard deviations of the performance measures in use (e.g. Jaymohan and Rajendran 2000b). For instance, Jaymohan and Rajendran (2004) expressed as their aim to give managers the opportunity to determine the most relevant objective, and, subsequently, to select the best dispatch priority rule accordingly.

The difference between two key due date based performance measures, lateness and tardiness, is often neglected. The absolute value of lateness depends on how much the completion date of a job differs from its due date (Figure 2-3). If a job is early its lateness (L_i) is negative, and if a job is late the value of lateness is positive. The other indicator, tardiness T_i, measures only the delay of a job from its due date. So, it returns zero when jobs are early or on time. In practice, companies are concerned about the penalty costs for deviating from the planned completion date (Pinedo and Chao 1999). Thus, a relevant pragmatic objective for scheduling is to minimize the cost function comprising of both earliness and tardiness costs. The holding costs and delay penalties can vary among customer orders, and thus some scheduling studies mimic this pragmatic aspect of scheduling by introducing order-specific weights which are then considered in scheduling decisions that aim to minimize weighted average tardiness (e.g. Vepsalainen and Morton 1987; Anderson and Nyirenda 1990; Jensen *et al.* 1995; Kutanoglu and Sabuncuoglu 1999; Jaymohan and Rajendran 2004).

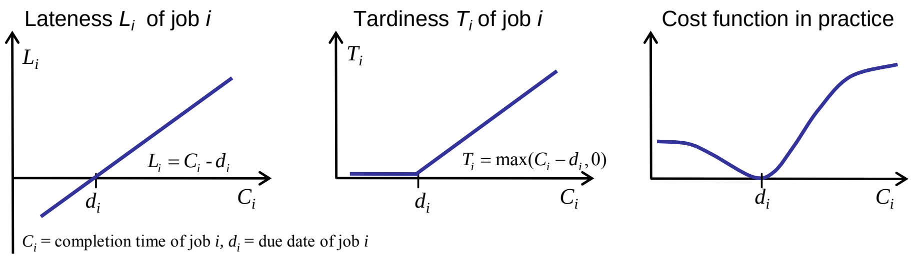

Figure 2-3 Three key due date based performance measures (Pinedo and Chao 1999, 22 & Pinedo 2002, 18).

To create manageable problems for priority scheduling, classical scheduling theory makes many simplifying assumptions about the shop structure, type of resources, jobs, and material flows (e.g. Baker 1974; Miyazaki 1981; Elvers and Taube 1983b; Ramasesh 1990). In addition to the standard assumptions on processing times, changeovers, transfer times, and order availability, the simplifications concern the principles of order management and availability of resources. For example, orders cannot be cancelled (no bulking), and the principles of scheduling are assumed to be consistent over time and all decision-makers. This implies that at each resource, to which decision-making is localized and postponed, orders are dispatched with the same priority and tie-breaking rules. The generalizations about the consistency and coordination of decisions as well as the availability of information may not hold true, especially in complex production systems. The assumptions of equally efficient machines and unavailability of overtime and other temporal resources can also be questioned due to increasing networking and standardization of products and processes.

2.1.3 Priority Scheduling

Manufacturing companies fulfilling customer orders may have to estimate the relative urgency of orders (order priority) continuously. They make scheduling decisions when new orders arrive and accepted orders are dispatched on machines. Although some idle time may be inserted in the schedules when waiting for a soon-to-arrive urgent order, in most cases backlogged customer orders are prioritized daily or even several times per day. The priority scheduling decisions can also be implicit. Implicit decisions refer to situations where production planners, order schedulers, or other customer service personnel do not have shared procedures and they do not necessarily monitor the impact of each order handling decision on the completion times of other customer orders.

Priority scheduling is a scheduling approach that allows decentralization and postponement of dispatching decisions. It refers to a process where a decision-maker selects the next order to be processed on an idle resource using information on the relative priority of orders available. Priority index values can be calculated with various different methods, whose accuracy and complexity vary. In some b-to-c businesses it may be adequate to determine two classes of orders – normal deliveries and expedited deliveries – for managing the operations. In b-to-b business, where different costs including holding costs, tardiness penalties, and expediting charges are imposed, it is more important to apply methods that determine order priorities explicitly and precisely, and thus dispatch priority rules calculating numeric values for order-specific priorities are developed.

Dispatch priority rules can be one-pass heuristics that optimize the problem as a one-machine case (Morton and Pentico 1993, 374), myopic heuristics that by definition consider only local and current conditions, or iterative multi-pass rules. Morton and Pentico (1993, 375) reported that the myopic dispatch heuristics are relatively robust and almost always perform well in empirical studies, but the rules that require due dates can be improved by better lead time estimates determined, for example, via iterative procedures. Another way to improve the results of dispatching rules, they explained, is to consider downstream bottlenecks.

A more pessimistic analysis about the benefit of dispatching rules has been presented by Hopp and Spearmann (2000, 493). They argued that priority rules do not work well all the time because the best choice of what to work on now at a given machine depends on the future jobs as well as on other machines. However, these kinds of findings have typically been drawn on the basis of the performance of dispatching rules in some pathologically difficult cases instead of considering shop arrangements which are most prone to the job priority discipline.

For identifying and comparing different types of dispatch priority rules, a classification that uses order information and use of priority index as the criteria is suggested (Figure 2-4).[2] The first criterion, order information, refers to the source of information and its aggregation level. This cumulative categorization ranges from the job in question to the details of its operations

[2] The motivation for introducing a new classification will be discussed in detail in Chapter 3.

and further to more aggregate data on load and resources. The first category, 'Job attributes', includes priority index rules that use only job-specific characteristics such as total processing time, job due date, and total number of operations. The rules of the second category named 'Operations detail' employ information about individual operations of the order such as operational due date and processing time of the imminent operation. Since a dispatch priority rule may also use knowledge on current load and capacities available in addition to the data on job attributes and operations detail, the third category of order information is 'Load and resources'. These rules consider, for instance, the status of the current machine indicated by its queue length or average utilization rate. It should be noted that this information-based categorization is cumulative, since the estimation of system load on the routing of a particular job naturally uses also job- and operation-specific information.

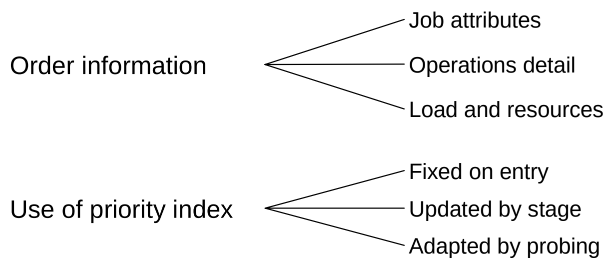

Figure 2-4 Dispatch priority index classification.

The second classification criterion refers to the form of index value and its use in practice. Some dispatch priority rules are static, producing index values that are fixed upon the arrival of orders to the system, while other rules use dynamic information requiring recalculation of order-specific indices during their progress in the system. The first category, 'Index fixed on entry', includes myopic dispatch priority rules that use static information such as due date and total estimated processing time about orders and/or process. Although the processing of an order may include several stages, the priority index value is calculated when the order enters the system, and no updating is needed while it progresses through the system. The second category 'Updated by stage' includes local and global rules that calculate order-specific priority indices on the basis of information such as slack that changes dynamically over time depending on the status of orders and/or machines. With these dispatch priority rules continuous comparison of the relative urgencies of orders is required. The third category, 'Adapted by probing', consists of rules which adjust order-specific priority indices by probing the status of a specific order, or by adjusting it according to the future system status anticipated by simulating the progress of all orders available over some predetermined forecasting horizon. These rules can employ look-ahead parameters, iterative techniques, and statistics calculated using historical data, for example on changeover times and capacity costs. Further, tshe dispatch priority rules of this category assume a certain sophistication level for the scheduling infrastructure and may require re-calculation of order-specific priority indices several times per each stage due to updated information.

Albeit some dispatch priority rules published in literature appear complex, priority scheduling is not complicated especially when the common generalizations and simplifications of scheduling research are used. The fundamental results prove that the shortest processing time (SPT) rule minimizes the mean average lateness, and the earliest due date (EDD) rule minimizes the maximum lateness for static problems in single-machine environments. The optimality of the SPT rule or an expected shortest process time rule with respect to the (expected) mean completion time has been analyzed in more complex environments also (e.g. Kaminsky and Simchi-Levi 2001). It is also known that the weighted version of the SPT rule, which uses order-specific tardiness penalties and/or holding costs to maximize the bang-for-the-buck with low delay penalties locally. Complex job shop environments with high interference among orders have, however, been a fruitful platform for the design and testing of alternative dispatch priority rules, since even for a single objective it is not clear what the dominating rule would be (Keskinocak and Tayur 2004). Before discussing real-life experiences of priority scheduling, the overall order management process is described.

2.2 Order Management

Regardless of the undisputed significance of order management and scheduling, there is relatively little general knowledge on the principles which decisions are based in real-life (Gupta 2002). Based on published production planning and scheduling research, there are, on one hand, highly developed software with algorithms designed for optimizing the use of production capacity, on the other hand, management concepts such as just-in-time and lean manufacturing with the emphasis on the role of process standardization that lately have shaped the development of order management and scheduling practices. Nevertheless, there may be production environments for which neither the mathematical methods nor the pragmatic management approaches are the best way of managing and scheduling customer orders that may have a high variety of lead time requirements. For this reason, prior to assessing the sophistication level and scope of order scheduling and trying to link them to company performance, similarities and differences in decision-making environments should be considered. This section seeks to provide a structure for a discussion about integrating order management by describing the generic process and by outlining alternative order scheduling methods for different scheduling task environments.

2.2.1 Process of Order Management, Production Planning, and Operations Scheduling

Customer order management covering order acceptance, order release, due date assignment, scheduling, and dispatching decisions can be considered as a key operational process for any MTO manufacturer. Pinedo (1995) was among the first to clearly illustrate how each order is processed via capacity planning, scheduling, and dispatching activities to shop floor management. His process description that focused on information flows is extended by specifying key decisions for each stage of the order management, production planning, and operations scheduling (OMPPOS) process (Figure 2-5).

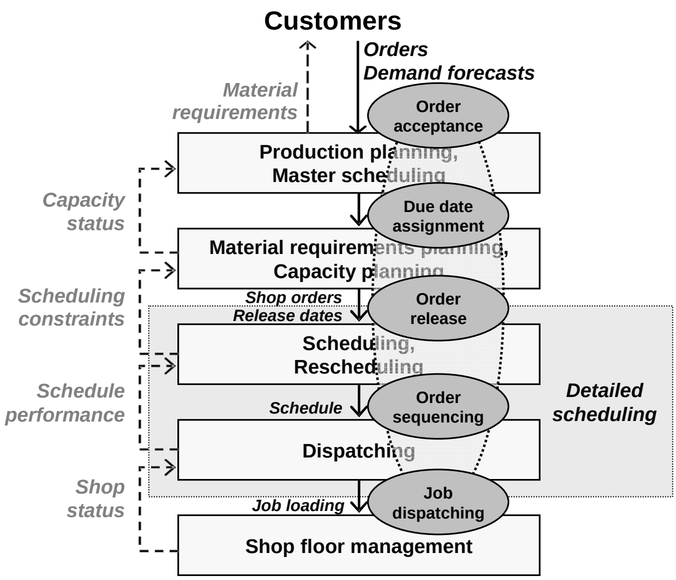

Figure 2-5 Key decisions in different stages of order management, production planning, and operations scheduling (OMPPOS) process (modified from Pinedo 1995, 4).

The units responsible for order handling decisions may have some guidelines for the generic delivery terms including lead time and price, especially if some type of formal agreement such as an annual delivery contract has been established between the supplier and the customer. If delivery terms are not given, customer service departments or other units responsible for order handling define them based on current resource utilization level or other relevant criteria. However, the interdependence of order management decisions may be neglected and their link to production planning and scheduling activities may be weak. Many companies do not do order selection, or order prioritization at all (Shapiro *et al.* 1992), although all orders are seldom equally good for business and productivity in general. Nor do companies excel in customer-based pricing (Shapiro *et al.* 1992), which is a viable mechanism for balancing the customer needs and company capabilities. One of the key questions considered in this thesis is if the whole OMPPOS process can be coordinated on the basis of order-specific priority indices.

2.2.2 Scheduling of Customer Orders

Scheduling research develops techniques for sequencing and dispatching jobs/orders in a way that best achieves the given performance objectives. Over the last two decades criticism has been presented on the relevance of scheduling research in general by arguing that the problem formulations and analysis approaches used by researchers are far from realistic situations, and thus the entire stream of research should be renamed (e.g. McKay *et al.* 1988; McKay and Wiers 1999). There are, nevertheless, operations management studies explaining why one planning and scheduling approach does not fit every manufacturing company. In fact, in some situations an unconventional combination of methods, perhaps even non-optimal for subsystems, can be the best solution from the system perspective (Vollmann *et al.* 1984/1997). This may also apply to scheduling so that the type of method applied fundamentally depends on the type of scheduling task environment.

The selection of a scheduling method is typically outlined by the type of constraints and objectives faced by planners who make the dispatching decisions. The two issues define how customer relationships and the manufacturer’s own production capabilities are considered in production scheduling. The first dichotomy considers how schedulers perceive the limits of production capacity and it divides scheduling task environments on the basis of resource tightness into fixed and adjustable capacity. Fixed capacity refers to production environments where the maximum total throughput of a production process is definite and can only be increased through major investments in machinery and/or other equipment. Adjustable capacity refers to situations in which the actual level of effective production capacity is somewhat ambiguous even for schedulers and/or can easily be increased by adding work shifts, hiring additional workforce, or by outsourcing some production activities to subcontractors. The second dichotomy considers the objective of scheduling and categorizes different scheduling task environments into production-oriented and sales-oriented. In production-oriented systems order handling is driven by productivity requirements, especially capacity utilization, whereas sales-oriented systems use the order handling protocol primarily to support adjustment to customer requirements. Together the two dichotomies form a classification for selecting the most appropriate scheduling discipline (Figure 2-6). The classification should be considered as a managerial tool helping to identify what type of approach fits the scheduling task environment of a particular scheduler in MTO or MTO/MTS manufacturing best.

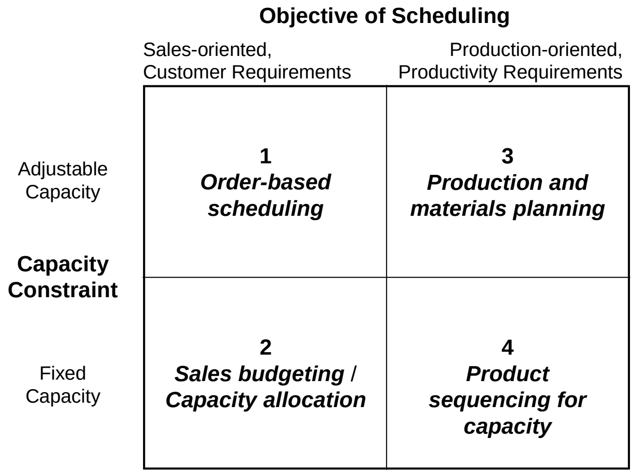

Figure 2-6 Scheduling disciplines matrix classifying alternative approaches for order handling.

There are production schedulers whose main driver is to meet the service requirements of customers. If there is some capacity flexibility in production flexibility in their decision-making environment, they are expected to benefit from heuristics designed for order-based scheduling (Category 1). The scheduling rules can be applied to make reasonable trade-offs between customer service and loading efficiency instead of relying on a single criterion such as due date or customer importance. When linked with pricing, the scheduling rules can also ease the adjustment of production capacity to demand variability. If a sales-oriented scheduler operates with strict production capacity constraints, she may be forced to use more rigid methods such as sales budgeting and capacity allocation to match customer demand with the unit's supply capabilities (Category 2). Production-oriented schedulers who have the possibility to adjust production capacity can benefit from standard planning systems designed for production and materials planning. Then product-specific lead times can be defined by production planning teams, which simplifies the task of order handling and eases conventional material requirements planning (Category 3). It appears that the decision-makers positioning themselves in categories 2 and 3 benefit more of hybrid planning models that combine, for instance, different order decoupling points. Decision-makers interested in saving production capacity in their cyclic production schedules where sequence-dependent changeover times may eat up a significant portion of limited capacity, benefit from product-based sequencing

(Category 4). In fact, product sequences determined in advance also direct customers to order within specific time slots, easing the problem of order scheduling.

The degrees of freedom in the decisions of order management and scheduling are linked to the type of scheduling approach applied. Using the OMPPOS process, including order acceptance, due date assignment, order release, sequencing, and dispatching decisions as the frame, it is illustrated when the final sequence of customer orders is determined in the different decision-making environments (Figure 2-7). For example, decision-makers using product sequencing (Category 4) may agree on the timing of customer orders based on fixed (cyclic) product runs already when the customer orders are accepted. In consequence, the decisions about the lead time estimates, release times, and relative importance of orders are collapsed so that a gatekeeper or an equivalent decision-maker in customer service resolves which orders are accepted and on what conditions. The challenge of this method rises from the fact that not all contingencies can be planned for. Thus, for example, the average utilization of resources can be lower than in systems with excess load and orders with loose due dates.

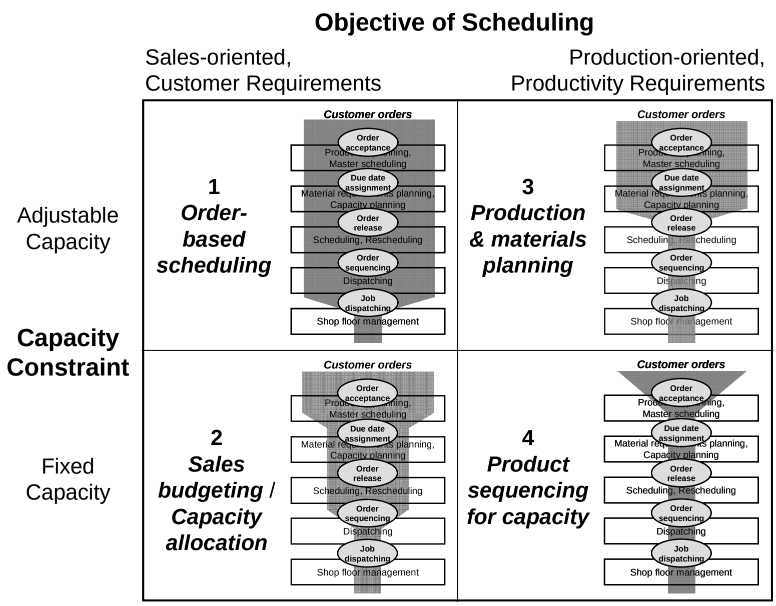

Figure 2-7 Order handling procedures for different scheduling disciplines (shaded areas indicate degrees of freedom maintained until the different stages of the OMPPOS process).

Production planners and schedulers using order-based scheduling methods (Category 1) are expected to rely on distributed decision-making, where order-specific priorities are used to carry customer orders through production. Therefore, the scheduling task environments maintain the highest degree of freedom until the order dispatching decisions that are typically localized and postponed to the shop floor. This approach involves more inherent uncertainty than product sequencing but it can provide a better response to customer needs, especially if there is variability in lead time requests.

The procedures of order handling employed by production systems which are positioned into categories 2 and 3 fall between the two extremes described above. In both, more flexibility, i.e. degrees of freedom in decision-making, is maintained later into the OMPPOS process than with product sequencing. If customer orders are accepted selectively based on sales budgets and/or capacity allocations (Category 2), the most relevant decision is order sequencing, reflecting the relative importance of orders (customers) and determining the lead time. For the decision-makers positioned in category 3 the critical stage is order release, which determines the sequence and timing of orders. For this reason, they can apply a rough estimate such as type of customer or product in order acceptance. It is noteworthy that the discussion above only links the alternative scheduling task environments of production with the procedures of order handling. Their connection to the actual practices of order management and scheduling is left for the future research.

2.3 Applications of Dispatch Priority Rules

In the following the relevant published case studies and surveys are summarized. The findings in 16 selected manufacturing companies are also discussed before the dispatch priority rules used in practice are categorized using the new classification matrix.

2.3.1 Findings of Published Case Studies

The case study of McKay *et al.* (1988) presented an extreme situation of a large job shop machining alloy castings in which all work was behind the schedule during their interview. The researchers identified numerous reasons: extremely variable processing and setup times, preemption of jobs when politically sensitive orders were being pushed through the system, management that used decision-making power on service times without consulting the shop floor management, uncertainty in raw material deliveries, and shortage in skilled manpower. Additionally, the scheduling system had failed to consider all system variability, and so scheduling and dispatching were done manually by a production manager and four expediters. McKay *et al.* (1988) analyzed the impact of dispatching on the work center queue but failed to anticipate its impact in long term and on other orders within the shop. Quite contrary, Halsall *et al.* (1994, 491-492) found on the basis of evidence from four case companies that with different scheduling approaches and in different environments scheduling systems permit relatively good use of resources.

The field study of McKay *et al.* (1995) described the difficulty of automating the planning and scheduling for printed circuit board production. By documenting the principles which one experienced scheduler applied to cope with changes and unexpected events in the environment, they illustrated the challenge of mechanizing decision processes in unstable situations. The scheduler who seemed to work with multiple schedules (political, private, idealistic, and optimistic) had an extensive arsenal of 128 heuristics that he used in the scheduling process. Furthermore, the scheduler typically sensed the nature and amount of instability in the manufacturing system and made some type of prediction about the future events. As it turned out, one-fifth of his predictions actually aggravated to the problem instead of solving it. McKay *et al.* (1995) analyzed the routine and non-routine heuristics as well as the predictions used by the scheduler to identify the potential of decision-making process automation. They concluded that only a part of them could be encoded and automated: 19% and 49% of the heuristics could be encoded fully or partially, respectively, and only a half of the 67 predictions made by the scheduler could be automated. They summarized that experienced schedulers can have inimitable common sense, especially in production where uncertainty is a daily reality due to continuously changing processes, products, and technologies.

There are other field studies that describe real-life decision-making processes. Wiers (1996) examined the role of human intervention by analyzing the decision behavior of four production schedulers in a manufacturing company, and he found significant differences among the schedulers despite of the joint objective. Later, McKay and Wiers (2003) described planning and scheduling practices in a factory consisting of a flow shop and a job shop. As a result, they presented a new decision support system for the integrated planner who performs planning, scheduling, and dispatching for the company. Also Dudek *et al.* (1974), Stoop and Wiers (1996), Wiers (1997), Wiers and van der Schaaf (1997), Crawford (2000), McKay and Wiers (2004) and Kreipl and Pinedo (2004) have reported real-life examples of order handling and scheduling practices.

2.3.2 Findings in Selected Finnish Manufacturing Companies

A small-scale study was carried out in 16 large Finnish industrial companies to understand the status of order management and scheduling in practice and to assess the need for improvement, if any (Kemppainen 2005). Empirical evidence was collected by interviewing experienced practitioners. The personal interviews, lasting from 1.75 hours to 4 hours, were conducted with managing directors (4 respondents) or directors/managers responsible for production (4), logistics (5), and sales and customer service (3). The respondents had worked on average for 13 years for their company producing electrical components and equipment, heavy machinery, metal products, or paper products (more information on the companies is available in Appendix 1). Classifications and findings presented here base on the managers' responses and are prone to errors such as managers' incorrect perception of reality as well as misunderstanding or confusion about terminology used. Hence, this study falls in the category of logical positivist/ empiricist research that relies on people's perceptions of reality (Meredith *et al.* 1989).

The practices of order management and scheduling were investigated, for example by studying the principles applied in order acceptance, lead time estimation, order release, and order scheduling. Key findings include the following:

- Half of the companies (8/16) allocated production capacity to markets and/or customers *a priori*, and the companies not applying a direct allocation mechanism often employed sales budgeting for capacity allocation.
- Companies that considered customer importance as the primary order acceptance criterion (9/16) seemed to have higher flexibility in production capacity.
- Only two companies used order profitability as the main criterion for accepting or rejecting arriving customer orders.
- Most companies (13/16) used workload-dependent lead times: 6 adjusted lead times case-by-case and 7 adjusted standard lead times to current workload.
- Only three of the companies did not schedule slack for the production process.
- Companies with fixed production schedules used capacity allocation as the main order acceptance criterion, and companies with flexible schedules use customer as the main order acceptance criterion.

It was studied further how customer orders are prioritized in conflict situations and found that instructions were typically maintained and developed by sales personnel. Most of the companies ranked customer orders according to rough categorizations or case-by-case instead of applying detailed rules. Only three of the interviewed companies had specified procedures for determining the relative importance of customer orders. In contingencies causing delays the companies typically compared the confirmed delivery dates so that the customer orders with the earliest due dates were given priority. Yet, the confirmed delivery dates did not automatically indicate the urgency of orders because due dates on order sheets were typically the response times confirmed by the supplier not the delivery times requested by customers.

Some of the companies made prioritization decisions based on both customer and due date information, i.e., trying to minimize the anticipated cost of tardiness and expediting consisting of extra hassle, express shipment, and/or reputation loss. Other interesting observations are:

- 10 companies confirmed an existence of customer classification, but only 5 of these companies used it actively in order management decisions.
- Minority of the companies, 5 in total, applied some rules allowing specification of order-specific priorities.
- Only one company had a system for determining order-specific priority indices.
- The customers of 6 manufacturers typically defined order-specific delay penalties, and 2 of the companies employed them in priority scheduling. The remaining 10 companies dealt rarely, if ever, with order-specific delay penalties.

A link between the ranking criteria and customer classifications was observed also: in conflicts the orders of the most important customers (normally identified on the basis of annual sales volume, average sales contribution, or similar measures) were automatically considered the most urgent orders. One fourth of the case companies considered the customer as the only criterion for order prioritization and assessed the externalities of delayed deliveries on the basis of the terms of contracts and potential impact on buyer-supplier relationship. Some of the interviewed managers explained that the principles for order prioritization in contingencies are kept informal, internal, and possibly even confidential due to potential externalities. As an example, a few years earlier one of the companies had communicated its most important customers to the shop floor management to ease distributed decision-making. As a result, the orders of the key customers were produced in shorter time than planned because dispatchers applied the customer ranking in every decision. This produced a preventable inefficiency: the selected orders were rushed ahead of other, perhaps even more urgent customer orders. Moreover, the unnecessary expediting did not improve the service level of the rushed orders either, since their shipments were scheduled and executed according to original production plans.

The analysis of order management and scheduling within the 16 interviewed companies gave limited evidence on the application of formal dispatch priority rules. Thus, to investigate if there is even a need for such scheduling discipline approach, the decision-making environments of the companies was studied using the scheduling discipline matrix introduced earlier. It indicates that most of the managers, 10 out of 16, believe that they have some influence on the production capacity available, and, consequently, they have more alternatives to adjust production to demand (Figure 2-8). There are fewer production-oriented decision-making environments focusing primarily on productivity requirements than sales-oriented decision-makers emphasizing the significance of customer needs. A comparison of the suggested and actual order scheduling methods indicates that six of the case companies (Cases D, E, G, H, N, and O) apply methods that match their scheduling task environment according to the scheduling disciplines matrix. Two of the companies use product sequencing (Cases N and O), three companies rely on order-based scheduling (Cases E, G, and H), and one company prepares schedules primarily based on production and material planning (Case D).

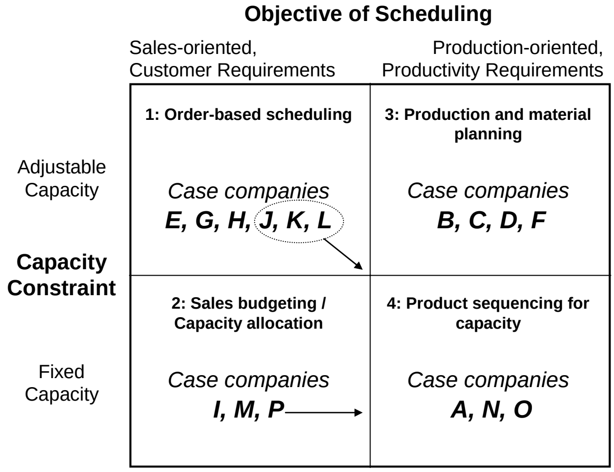

Figure 2-8 Positioning of the selected manufacturing units in the scheduling disciplines matrix.

Companies I, M, and P rely on rigid sales planning systems possibly due to the strong management emphasis on customer-orientation. As indicated in the matrix, they are expected to change into stronger production-orientation since this combination of capacity constraints and scheduling objectives is considered void. Companies J, K, and L, similarly, prioritize customer-orientation although their scheduling task environment would call for production-orientation. In the electronic equipment and component industry, the manufacturer (Case A) and contractors (Cases B and C) are forced to use scheduling disciplines designed for mass production due to the long-term allocations of capacity to specific, possibly customer-specific products. Yet, their production processes could be managed more efficiently with order scheduling methods designed for job shops and/or flow shops.

The type of institutional setting of order handling employed by the case companies was also explored. Our analysis considered the organizational unit responsible for making decisions in three order management decisions (order acceptance, lead time estimation, and final production schedule) (Figure 2-9). The flow of order decisions indicates the following for the four categories identified on the basis of the scheduling discipline matrix:

- Category 1 (Order-based scheduling): Three out of six companies (Cases G, K, and L) have centralized their order handling decisions to the sales and production teams that operate at the plants. There are two machinery manufacturers (Cases E and H) along with one metal manufacturer (Case J) that could benefit of coordinating mechanisms due to distributed decision-making.
- Category 2 (Sales budgeting/capacity allocation): Two contract manufacturers (Cases B and C) have centralized the order handling decisions to production planning team, whereas two machinery companies rely on distributed decision-making (Cases D and F).
- Categories 3 (Production and materials planning): One metal manufacturing company (Case I) has localized some responsibilities to its sales units. Two paper manufacturers (Case P and M) have assigned order handling decisions to the sales and production planning teams that work at the plant.
- Categories 4 (Product sequencing): Case N has centralized responsibilities for order handling decisions to production planning. In two paper manufacturing companies (Cases A and O) plants' sales and production teams share the tasks.

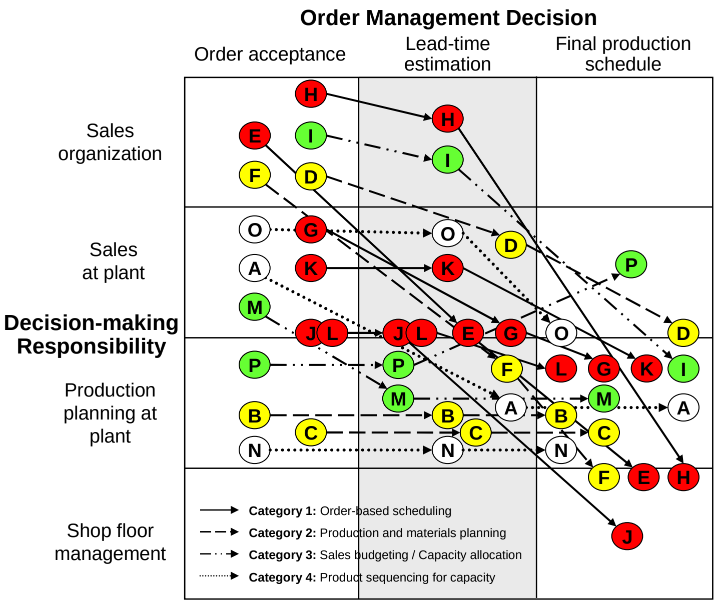

Figure 2-9 Decision-makers for order acceptance, lead time estimation, and dispatching within the selected Finnish manufacturing units.

Although sales and production planning teams located at manufacturing units have a central role in the selected decisions of the OMPPOS process in many of the companies, some of the studied units could use methods for coordinating their order handling process. Companies E, H, and I, especially, could benefit of priority scheduling supporting the coordination of distributed decisions. Companies J, K, and L could also improve their current practices of order management and scheduling with priority scheduling, although, based on the analysis, production-orientation would better match their production processes and product varieties.

2.3.3 Findings of Published Surveys

The survey of Dudek *et al.* (1974) focused on the general sequencing problem, but also addressed specific issues such as the similarity of jobs, importance of setup times and cost, concentration of in-process inventory, availability of data, and criteria of performance evaluation. They found most of the industrial problems to fall into the category of job shop scheduling with or without dependence between jobs, and in practice the task of schedulers is complicated by multiple performance objectives. Among the companies studied the due date performance was the most important performance measure. Moreover, the minimization of setup times/costs, in-process inventory, and makespan were perceived as significant objectives. Dudek *et al.* (1974) recommended that researchers should acquire better understanding of actual scheduling problems via case studies.

Miller (1981, 149) argued that the prioritization of customer orders is simple on high-volume assembly lines compared to typical batch-oriented factories, where literally hundreds of different ways exist for assigning order priorities. As typical examples of dispatching rules he named the most important customer, highest sales value, least cost, earliest due date, and ‘Satisfy most customers’. Two cases described by Miller (1981) used the simple customer due date rule and negotiation based scheduling. In the latter the priorities were heavily weighted to low-cost schedules at the expense of responsiveness.

Green and Appel (1981) examined the operations of one large manufacturing company. In more detail, they asked from 11 experienced industrial engineers and shop foremen and 23 production control supervisors to what extent the nine dispatching rules were used within the company. The rules considered were six general priority rules defined in Conway (1965a, 1965b), the Cost over time rule (Carroll 1965), and two alternative approaches called ‘Program in greatest trouble’ and ‘A friend needs a favor’. Interestingly, most of the dispatch rules that had been recommended for job shop scheduling in the literature were not used or strongly supported by either the shop foremen or the industrial engineers. Based on the composite data comparisons, Green and Appel (1981) found that the foremen strongly preferred the ‘Program in greatest trouble’ approach when the shop was either on schedule or behind the schedule, while the engineers would use that influence rule only when the shop was behind the schedule.

The studies of Halsall *et al.* (1994) confirmed that the production planning system typically is not highly structured, or a significant element for the competitive position of a company. These findings were drawn from two samples of small- and medium-sized UK manufacturing companies (n=28+18) exporting on average 33% of their output out of the UK. Most of the companies had either batch or job production (82%) and produced over half of their output (78%) to customer orders. These characteristics explain why there is uncertainty in setup and processing times, customer requirements, and delivery dates. Further, the study reported that the most common scheduling rules were the earliest due date (EDD) rule, the scheduled start date (externally set priority) rule, and other methods such as the optimized production technology (OPT) focusing on the utilization of capacity at process bottlenecks. The most uncommon rules were job slack per operations, job slack, and shortest imminent operation. Other interesting findings of Halsall *et al.* (1994) were that according to the respondents the management often overrides the planned schedule, the schedules often do not work because of late or out of specification deliveries, and the scheduling system always needs adjustment to be practical.

The large-scale survey of Wisner and Siferd (1995), including 132 responses, provided information on the operating characteristics of MTO facilities for benchmarking. Most of the respondents (80%) answered that there are no tardiness penalties associated with the jobs and the average backlog per machine is less than six jobs in 75% of the cases. Their other interesting findings on the practices of order management and scheduling included:

- Customers specified due dates for over 60% of jobs.
- 58% of the jobs were released immediately upon arrival.
- Earliest due date rule was the most common dispatching rule.
- Three-quarters of all jobs were completed in 30 days or less.

The companies that assigned due dates internally often used either constant slack or estimated total working time for approximating the lead times. If orders were not released immediately, the most common order release method was the workload-oriented release method. Besides the EDD rule, other relatively common dispatching rules were the most important customer, job with similar setup, first-come-first-served, and least slack time. Wisner and Siferd (1995) did not find the much praised shortest processing time rule or delay strategies that are expected to reduce queues and total lead times to be widespread among the respondents.

The order release methods used in practice typically utilize information about due dates and capacity constraints. Fandel *et al.* (1998) analyzed in total 210 production planning and control systems and ERP systems and found that each of the 185 order release methods implemented considered due dates. Majority of the methods, 68%, released orders into the shop floor under consideration of availability. Approximately every fourth of the release and review methods (28%) applied load-oriented release rules, while only 4% used methods based on optimized production technology (OPT) approach. The following section summarizes this discussion of real-life applications by classifying the dispatch priority rules that according to the published research are used in practice into the classification suggested in Section 2.1.3.

2.3.4 Classification of the Common Rules

The scheduling rules discussed above are positioned in the dispatch priority index classification on the basis of the order information and the use of priority index (Figure 2-10). Some of the rules such as earliest due date and shortest imminent operation are easy to categorize. There are, however, approaches whose positioning depends on their actual use in practice. For instance, the approach called ‘Satisfy most customers’ is here qualified as a rule that fixes order-specific index values upon the entry of the order into the system using job attribute data. It could, nevertheless, be applied in a way that employs iterations or other forms of probing to determine which order to process next, and then its position within the classification would be different. Furthermore, some of the methods are not positioned because their functioning is not clearly specified. For example, ‘A friend needs a favor’ selects the next order so that a problem such as shortage, rejection, or loss outside the normal production control system is solved, whereas ‘Program in greatest trouble’ dispatches orders on the basis of what program is identified as being in trouble within the production system. It is anticipated that the dispatch priority rules positioned in the upper right-hand corner of the classification matrix rely on profit planning and use accounting-type measures emphasizing the financial implications of order prioritization. In the lower left-hand corner there would be dispatch priority rules that use information on jobs, possibly also operations, and produce load and delivery profiles similar to the methods of aggregate planning (infinite/finite scheduling).

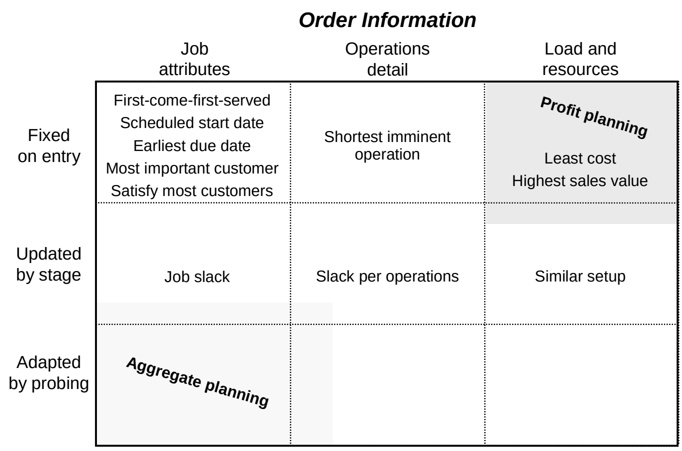

Figure 2-10 Classification of the dispatch priority rules in use according to the prior research.

As apparent from the figure below, only a few of the priority rules applied in practice use other than the basic order attributes in dispatching decisions. Moreover, even stage-updatable rules are uncommon. This situation pegs the question if the priority index rules are, after all, too cumbersome or powerless to be used in practical scheduling problems. Next, the complexity and potential coordination effects of different priority rules in some typical problem settings are estimated.

2.4 Coordination Effects of Dispatch Priority Rules

One obstacle recognized above for the application of heuristic rules is the lack of economic rationale the manager could relate to. What are the general principles for coordination of distributed decisions within a production system and how does the coordinating effect depend on the consistency of the priority index assignment for each job discussed above. There are concepts in economics of decentralized control that lend themselves to the analysis of coordination in scheduling, such as rules rather than discretion, dynamic consistency, and rational expectations. Definitely the limits for coordination effects will also depend on the type of scheduling environment (type of system, load and job characteristics, and managerial objectives) in question. Hence, the compatibility of the technical properties of the rule, the associated economic principles of coordination, and the challenge of the scheduling problem can be evaluated. Conceivably even the efficiency of coordination can be predicted. Consequently, a framework consisting of the three aspects of an application of a priority rule as a coordination mechanism is defined for the evaluation and choice of priority rule:

a. Index providing a consistent rating of a job vis-à-vis other jobs,
b. The economic rationale of the rule, and
c. The requirements of the scheduling problem.

Each of these aspects of what is called coordinability and the interaction of the economic rationale with the other two aspects are discussed. First, the priority index of the rule provides, technically, a rating of the urgency of each job at every moment of time. There are three levels of counting for the impact of the other jobs on the index. An elementary level of coordination can be achieved by a static priority index that assigns a property, such as arrival time to the system (FCFS rule), the due date (EDD rule), or total processing time, as a rating to the job at arrival that remains the same throughout the process. The benefit compared to a random order, for instance, is that the jobs will be sequenced in the same order if they require same resources, thereby eliminating delays due to crossovers. The second level involves updating of the priority index values at each machine, or upon every moment, which adjusts the urgency rating to the interactions among the jobs so far and possibly to other local conditions. Dynamic consistency is maintained by using the arrival time at the machine, or operation due date or slack as part of the priority index. At the third level, some future interactions among the jobs are anticipated and thereby allowed to impact the urgency rating of a job. An example of such a checking of dynamic consistency is probing that refers to anticipating of work or relative priority in the next queue over some predetermined forecasting horizon, and factoring that information in the priority index. The complexity of the priority index calculation usually increases the higher the level of updating and anticipation incorporated in the dispatch priority rule.

The second aspect of coordination mechanisms is the economic rationale of the rule. The minimum level is to make efficient decisions locally, i.e. to apply a greedy heuristic that aims at the best possible use of the resource given the jobs waiting in line. For instance, the SPT and EDD rules provide this type of efficiency by minimizing flow time and maximum tardiness, respectively. The second level of efficiency requirement comes from the necessity to trade one objective off against other objectives. Typical such a rule is COVERT that strikes a balance between the slack and the processing time of the job (Carroll 1965). At the third level, the true impact of the current decisions upon the expected tardiness and the economic consequences of the jobs are anticipated by using, for example, more sophisticated lead time estimation methods (Vepsalainen 1984; Russell *et al.* 1987).

The third aspect is the specification of the scheduling task and the shop environment determining the potential benefits of coordination and the most suitable rules for it. An important issue is a standard specification of the problem setting, such as utilization, due date allowances, and process bottlenecks, and normalized performance measures for relevant objectives. Again, an elementary level of challenge to the coordination mechanism provided by lightly loaded shop with generous due dates, no individual tardiness or holding costs, one objective function, and possibly flexible resources and alternative routings is recognized. In these circumstances, many different dispatch priority rules may perform well and some even optimally, and a low level of complexity will be experienced. The second level involves more complex setting with high capacity utilization and tight due dates, job-specific costs, several objective functions, and dedicated resources. However, there may be features of the scheduling problem that make the coordination easier for many dispatch priority rules, or some specific simple rule. Examples could be a very high utilization, for which the weighted version of the SPT rule works quite well for several criteria, or due dates set by the total work content (TWK) method that helps many rules to perform better. The highest third level of difficulty is provided by scheduling problems with tight and random due dates, resource utilization over 90%, and many objective functions to count for.

The question to be studied during the literature surveys as well as the empirical simulations of this thesis is the relative importance of each of the three aspects of coordination mechanisms for the relative performance of different rules. One may expect there to be systematic interaction effects across the aspects and also some kind of net effect of complexity caused by high levels of all three aspects. For example, earlier results (e.g. Vepsalainen 1984, Raghu and Rajendran 1993; Holthaus and Ziegler 1997) indicate that the added complexity of probing may still benefit in simple unweighted scheduling problems with lateness-related objective, whereas in weighted problems with tardiness criterion and possible iterative methods probing may complicate the procedure so as to hurt the performance. For practical applications, the efficient frontier of priority index rules should be figured out for each relevant setting of job shops or other systems such as supply networks.

2.5 Summary and Discussion

In production planning and scheduling, the power of mathematical methods and the benefits of management approaches such as just in time (JIT) are being emphasized. There can, however, be scheduling tasks for which different types of disciplines are needed, especially if customers request different response times, costs vary among orders, and the OMPPOS process cannot be developed as the competitive advantage. Hence, this chapter suggested a scheduling disciplines matrix which, by considering the tightness of production capacity and the primary objective of scheduling, classifies different scheduling task environments. The matrix outlines where different approaches of order scheduling are expected to be of use. For instance, order-based scheduling examined in detail in this thesis is presumed to be appropriate when there is flexibility in capacity and production schedules are planned to meet the customer expectations in response times and service level primarily. Nevertheless, it should be noted that if priority scheduling becomes the backbone of integrated order management enforcing the coordination of distributed order handling decisions it is less relevant to consider specific characteristics of scheduling task in the design of production scheduling, or the OMPPOS process in general.

This chapter also summarized the prior research on applications of scheduling rules, especially dispatch priority rules, in practice. According to the publications, the earliest due date rule has been found as one of the rules in use, but policies such as first-come-first-served, least slack, most important customer, and perception on what program is in greatest trouble have also been applied. There is empirical evidence that customer orders are released immediately to the shop floor and lead times are assigned externally by customers. If internal due date setting is applied, two different methods (constant slack and estimated total working time) are commonly used. Due date based prioritization of customer orders and workload-dependent estimation of lead times are common also within the Finnish manufacturing companies studied. According to the interviewed managers the companies did not use priority rules systematically in order management, nor did they employ dispatch priority rules in determining the relative urgencies of customer orders in contingencies such as capacity shortage. However, the analysis of the institutional settings of order handling among the selected 16 companies, which can be considered progressive manufacturers, revealed that some of the companies could benefit from applying order-based scheduling such as dispatch priority rules for coordinating the decentralized decisions of order handling. As a summary of the published research, the scheduling rules in use were positioned in a new classification that considers order information used and type of priority index.

The modest use of rule-based scheduling heuristics and priority scheduling, in general, can be due to several reasons, such as inappropriate objectives pursued by scheduling researchers, biased education provided by the schools of business and engineering, or lack of interest in dynamic consistency and robustness of dispatch priority rules desirable for coordinating the local, distributed decisions of order handling. Hence, there is a call for further analysis for which this chapter specified a benchmarking framework. In particular, the framework facilitates comparisons of index-based scheduling heuristics by matching the levels of technical implementation and economic rationale of the rules with the complexity of the scheduling task for which recommendations of rules are required.

3 Preliminaries of Index-Based Scheduling Heuristics

This chapter reviews the prior priority scheduling literature that has developed index-based scheduling heuristics for the decisions of order management and scheduling. It considers competing methods for dispatching, due date assignment, order acceptance, and order release with an objective to identify candidate rules with dominating performance in various relevant, statistically generated problems. The chapter begins by a discussion of the traditions and development of scheduling heuristics. After justifying the review of the existing scheduling rules, it summarizes the findings of more than a hundred simulation studies reviewed for this thesis. Furthermore, the properties of selected priority index rules are described using the rule classification suggested in Chapter 2. Moreover, the methods and techniques available for the other decisions of order management (order acceptance, due date assignment, and order release) are reviewed, and decision-specific dominance charts summarizing the performance of alternative methods on the basis of performance criteria used in them are developed. Finally, implications for job shop scheduling research are discussed.

3.1 Revisitation of Priority Scheduling Research

Research on scheduling methods originated in the 1950s (Sisson 1959; Rowe 1060; McKay *et al.* 1988). As reported by many surveys (e.g. Panwalkar and Iskander 1977; Blackstone *et al.* 1982; Haupt 1989; Ramasesh 1990), numerous studies have since analyzed the power of priority scheduling that relies on simple procedures in the selection of the next job for an idle resource. However, only a few studies have provided a systematic comparison of the alternative methods (Kutanoglu and Sabuncuoglu 1999, Keskinocak and Tayur 2004) that could be considered as the foundation for open order scheduling protocols, which are used when customers have different response time expectations and they accept the classification of orders based on tardiness penalties. Also due to the changing focus of production scheduling – from manufacturing environments to the coordination of inter-organizational processes – a comprehensive literature review is called for. Before detailing the shortcomings of the prior priority scheduling research and describing the approach used in this review, the overall development of scheduling research is summarized.

3.1.1 Traditions of Scheduling Research

In the early stages of the scheduling research there was limited processing capacity available for testing and comparing different order scheduling policies. Thus, relatively small and simplified problems were still solved to illustrate the differences among alternative scheduling techniques in the early 1980s. Over the last decades the processing power of computers has increased considerably, and the perceived practical relevance of the scheduling rules has diminished. Mathematical methods, primarily optimization, have dominated the solutions approaches even in large and complex production scheduling problems where good solutions need to be found in relatively short time. For example, in a deterministic job shop scheduling problem with practically no uncertainty in parameter values, optimization including enumeration methods has been considered superior to the dispatch priority rules as well as the other iterative and constructive methods (Figure 3-1). The declining interest in index-based scheduling methods, in particular among practitioners, can also be due to the increasing use of parameters and intelligent heuristics as a part of the rules. Comprehensive reviews on scheduling techniques can be found in Morton and Pentico (1993) and Pinedo (1995, 2002).

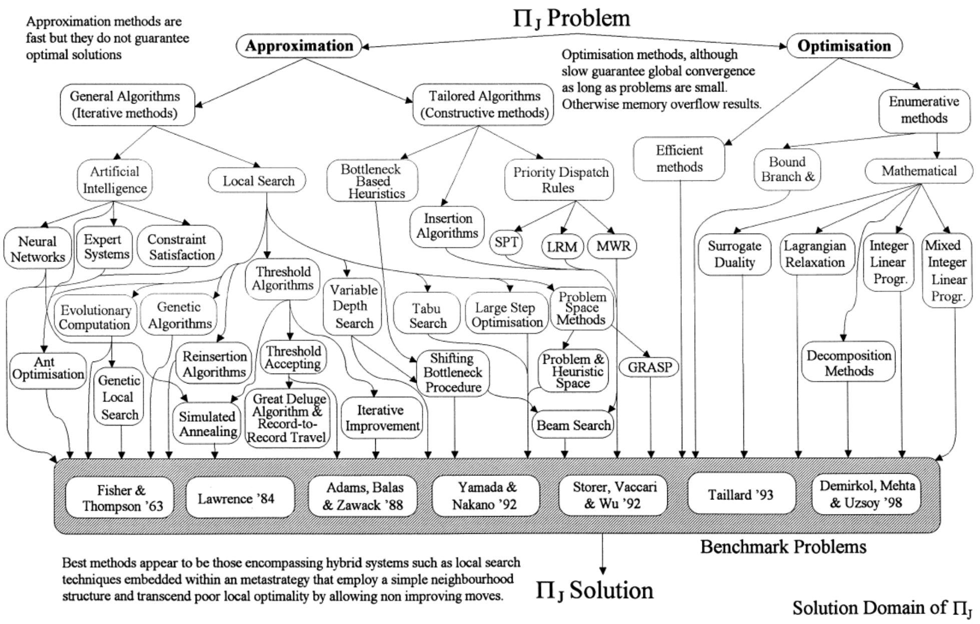

Figure 3-1 Development of deterministic job shop scheduling research (Jain and Meeran 1999, 393).

The development of scheduling research during the 20th century can, according to Gupta (2002, 109-113), be divided into nine paradigms:

1. Might is right: Scheduling problems are not analyzed scientifically.

2. Don't keep the machine idle: Companies accept customer orders on the basis of machine capacities, assign waiting jobs to machines to avoid machine idleness and use Gantt charts to assign and monitor the flow of work through the shop.
3. Tell them what to do: Researchers assume that firms know and can determine the specific products to manufacture along with their production quantities given the flow of customers or market conditions and that the actual manufacturing of these products is the responsibility of the shop supervisors and managers who will use their experience and skills to solve the scheduling problems.
4. Divide and conquer: Researchers focus on describing scheduling problems by making adequate assumptions and developing special purpose algorithms to solve the specific problems.
5. Too complex too expensive: Researchers consider scheduling problems, in general, too complex and too expensive to solve.
6. Something is better than nothing: Researchers develop heuristic algorithms to find approximate solutions and identify the conditions in which specially structured scheduling problems can be solved efficiently in polynomially bounded computational efforts.
7. Give them information to decide: Scheduling models are included in a decision support system and managers are provided with the opportunity to interact with the decision support system thus created.
8. Why bother: It is considered more important to find means to create new structures of work, e.g. JIT, so that scheduling problems do not have to be defined or solved.
9. Let the computers tell us: Scheduling problems are considered as constraint satisfaction problems which can be solved using artificial intelligence systems including expert systems, neural networks and the hybrids, and it is believed that learning mechanisms can be incorporated into computer software to be used in solving practical problems.

Gupta (2002) argued that the dominant of these scheduling paradigms has for the 20th century been 'divide and conquer' because an abundant number of algorithms have been developed and tested. There are, in fact, numerous publications supporting his argument (Table 3-1). The review papers have summarized prolific published studies on the different types of production scheduling problems. Gupta and Kyparisis (1987), for example, found 171 articles on static scheduling problems. Based on the analysis of the articles they concluded that the interest in the scheduling research addressing total tardiness or maximum lateness had declined, whereas problems with earliness and tardiness penalties, among others, were gaining more attention. Many of the review papers, for example Koulamas (1994), summarize that there are abundant optimizing procedures available for the different standard production environments such as single-machine, flow shop, and job shop settings. Hence, more scheduling research that would introduce efficient heuristics for parallel resources or adapt effective algorithms for flow shops and job shops has been called for. Dispatch priority rules that are easy to apply in real-world manufacturing shops (Day and Hottenstein 1970) for the scheduling problems that quickly become NP-complete even for a single-machine (Morton and Pentico 1993, 366-385) have been recently reviewed in Kutanoglu and

Sabuncuoglu (1999) and in Keskinocak and Tayur (2004). Their analyses showed that without any doubt the research on priority scheduling problems has long traditions but it suffers from fragmented testing and comparison of alternative rules.

Table 3-1 Summary of literature reviews on production scheduling problems and methods.

Study	Focus of the literature review
Sisson (1959)	Sequencing methods
Day and Hottenstein (1970)	Sequencing problems and methods
Panwalkar and Iskander (1977)	Dispatching rules
Graves (1981)	Scheduling problems and methods
Blackstone *et al.* (1982)	Dispatching rules for job shop operations
Gupta and Kyparisis (1987)	Single-machine scheduling
Cheng and Gupta (1989)	Due date assignment
Haupt (1989)	Priority-rule based scheduling
Baker and Scudder (1990)	Scheduling with earliness and tardiness penalties
Ramasesh (1990)	Dynamic job shop scheduling
Dudek *et al.* (1992)	Flow shop scheduling
MacCarthy and Liu (1993)	Optimization and heuristic methods
Koulamas (1994)	Heuristic algorithms for total tardiness problem
Jain and Meeran (1999)	Deterministic scheduling problems
Kutanoglu and Sabuncuoglu (1999)	Job shop scheduling with the weighted tardiness criterion
Cheng *et al.* (2000)	Flow shop scheduling with setup times
Kanet and Sridharan (2000)	Scheduling with inserted idle time
Keskinocak and Tayur (2004)	Due date management

Next, the motivation for yet another review of priority scheduling research is clarified by specifying the main limitations of prior research that hinder the development of integrated order management relying on priority index rules as coordinative mechanisms.

3.1.2 Motivation for Review of Priority Scheduling Research

The much cited review paper of Panwalkar and Iskander (1977) identified over hundred different dispatch priority rules. Their work has been accompanied by heaps of publications that have either suggested new methods or discussed the attributes of dispatching rules as criteria for qualitative classifications. There are some encouraging exceptions (e.g. Russell *et al.* 1987, Vepsalainen and Morton 1988; Kutanoglu and Sabuncuoglu 1999; Keskinocak and Tayur 2004), but by and large the priority scheduling research has been fragmented because of at least the following reasons: 1) the design of new or improved rules as the primary goal of research, 2) limited benchmarking of rules across studies, 3) use of case-specific settings and performance measures that can lead to confusing reporting, and 4) arbitrary problem definitions often neglecting customer service orientation.

The bulk of publications in priority scheduling have introduced new rules for sequencing and timing decisions. Comparisons of alternative scheduling methods have then been performed on the conditions of the new rule. Although there are small benchmark problems for testing optimizing scheduling algorithms (e.g. Muth and Thompson 1963; Lawrence 1984; Applegate and Cook 1991), similar standardization of experimental designs used in the benchmarking of index-based scheduling rules has not been carried through even for job shop problems. Instead, case-specific assumptions possibly promoting some types of dispatch priority rules and convenient test settings including, for example, only one due date setting method have been used. Moreover, the results of computational experiments have been reported in raw values and for a varying set of performance indicators which has not promoted systematic comparisons either. Finally, the concern for customer perspective in the studied scheduling problems has been inadequate. For instance, most studies consider only one due date assignment method, typically the TWK method, and neglect the variability in order-specific costs and response time requirements.

Nevertheless, to recommend some priority index rules for open order scheduling protocols, and the resulting integrated order management clear recommendations based on logical comparisons are needed. The systematic comparisons then require definitions of relevant problems and settings as well as consistent use of commensurate normalized performance measures. Consistent settings and standard methods would also ease the recognition of any flaws in rule implementations or in the assumptions of the experiments. Additionally, more analysis on the rationale and scheduling logic of different dispatch priority rules, now overshadowed by the preferences of each researcher, as well as on the impact of the information content of different rules on rule performance is encouraged. In problem definitions the lacking consideration of customer perspective could be taken into account by randomly assigned due dates, comparison of alternative due date setting methods, and observation of order-specific costs leading to weighted problems.

3.1.3 Method of Literature Review

A systematic and thorough search for publications in the area of index-based scheduling heuristics was carried out using journal databases in spring 2004. The databases used were EBSCO, ProQuest, ScienceDirect, Extenza, and Emerald, since they were assumed to provide electronic copies of all relevant academic publications. Numerous sets of keywords covering each order management and scheduling decisions were used to find all relevant research on priority scheduling. For example, priority scheduling rules, scheduling heuristics, dispatching rules, priority rules, and dispatch priority rules were used as keywords when searching for publications that discuss priority-based methods for dispatching decisions. On the basis of the found publications, additional targeted searches were conducted to access key references not identified in the extensive basic search. The resulting collection includes over 200 peerreviewed articles published since the year 1959. Most of these articles discuss dispatching decisions (133 articles), but there are also publications that focus on order release and review (33), due date assignment (32), or order acceptance (10) decision. However, this database of articles cannot include all priority scheduling research. Especially some research results published during the 1970s in some discontinued journals were found difficult to access. Notwithstanding, the database is extensive and comprises the most cited articles, thus, allowing us to reach reliable conclusions about the status of prior priority scheduling research.

The approach for the literature review was determined based on the limitations discussed earlier. The focus of analysis was on the type of rules and techniques tested as well as the test environments and performance measures used in the experiments. Additionally, the main stated results on the relative performance of the compared order management and scheduling methods were analyzed. Extensive listings and categorizations were completed to form the synthesis of the prior results discussed in the remaining part of this chapter. As an example, Figure 3-2 presents a summary of the priority scheduling literature since the 1960s untill today. It illustrates the changing scope of research, charts the trend in the number of publications, defines main publication outlets, and specifies features or add-ins integrated in scheduling rules over time. For example, in the early 1980s rule-based scheduling research explored the impact of order release mechanisms on the performance of dispatching rules.

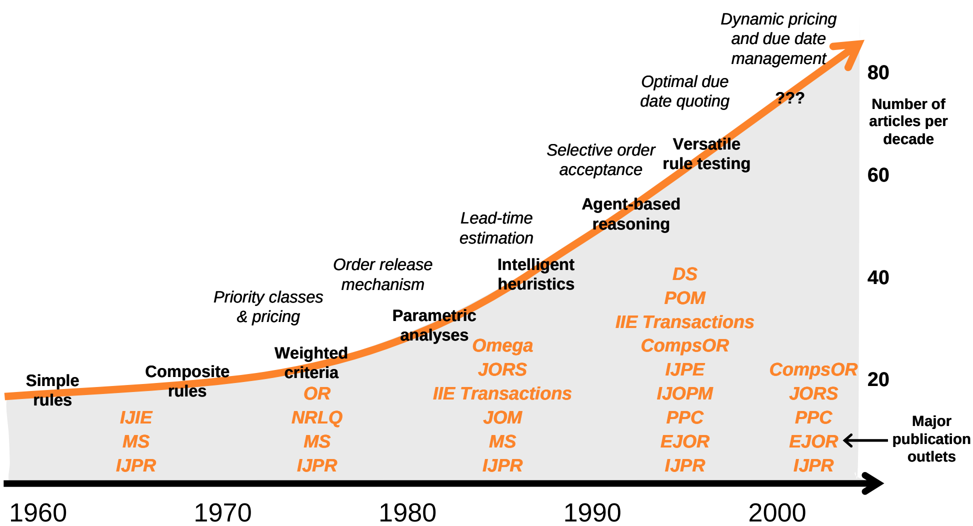

Figure 3-2 Scale and scope of scheduling heuristic research since the 1960s: types of rules, their specific characteristics, main publication outlets, and number of publications.

Next, findings on the performance of standard benchmark rules and related effects of rule types, their information content, and test settings are summarized.

3.2 Dispatch Priority Rules in Production Scheduling

Since the origins of the priority scheduling research thousands of researchers have aimed to identify the most efficient rule, be it called a dispatch priority rule or a scheduling heuristic. Still, in practice, the use of dispatch priority rules that would be more sophisticated than the FCFS principle is uncommon. The standard production planning and scheduling software do not necessarily offer more than some basic static dispatch rules for human planners and schedulers, and not too much has changed from the findings of Conway (1965a, 1965b) reporting that priority rules fairly common in use are EDD, least slack, earliest operation due date, and least slack per remaining operation.

According to Day and Hottenstein (1970), Conway already analyzed 92 priority rules in the 1960s. Even so, the most cited surveys of dispatching rules are the ones by Panwalkar and Iskander (1977) and Blackstone *et al.* (1982) who identified 113 and 34 dispatching rules, respectively. Instead of ranking the performance of identified rules they aimed to recognize attributes of rules that can function as classification criteria. Similarly, Haupt (1989) and Ramasesh (1990) described the characteristics of dispatching rules based on earlier research. A different approach has been pursued in Chang *et al.* (1996) and Kutanoglu and Sabuncuoglu (1999) who have ranked the performance of a variety of dispatching rules in job shop environments. Using the data envelopment analysis Chang *et al.* (1996) assessed the efficiency of 42 non-weighted dispatching rules that they had categorized into six groups based on information content. Kutanoglu and Sabuncuoglu (1999) later compared 17 priority rules and six pricing schemes in a weighted tardiness problem. The findings of these two comparative studies include:

- Scheduling the shortest operation first increases the flexibility of a resource for the further operations, and thereby improves its utilization (Chang *et al.* 1996).
- Scheduling the earliest or the least slack operation first increases the possibility of finishing more jobs on time (Chang *et al.* 1996).
- Use of operational information such as operation due dates and operation processing times instead of job-based counterparts improves the performance of dispatching rules (Kutanoglu and Sabuncuoglu 1999).
- Composite rules integrating, for example, the SPT rule and the CR rule can be very effective especially in reducing weighted tardiness (Kutanoglu and Sabuncuoglu 1999).

These findings are aligned with the previous results that have proved the SPT rule to minimize average flow time and the EDD to minimize the maximum tardiness in a single-machine case (e.g. Conway and Maxwell 1962). Obviously, other publications have also compared the performance of different dispatch priority rules, and thus the findings of prior simulation-based studies that have ranked the standard benchmark rules are discussed next.

3.2.1 Performance of Standard Benchmark Rules

The test settings of computational experiments impact the performance of dispatch priority rules. Still some conclusions about the value of dispatch priority rules can be drawn on the basis of published research. Next the performance of six well-known dispatch priority rules – FCFS, SPT, EDD, SLK, COVERT, and ATC[3] – that have over the years become the benchmark rules for any experimental or analytical study developing new heuristics are discussed. Also some interesting findings about their modifications are presented.

The FCFS rule is considered to be a fair priority rule, especially in service operations. Hunsucker and Shah (1992) found that it performs well in mean tardiness compared, for example, to the SPT rule. Selladurai *et al.* (1995) recognized that the FCFS rule gives higher capacity utilization in some special cases. Notwithstanding, they did not recommend it for manufacturing operations since it is typically outperformed by any other priority index rule.

Probably the most widely tested and modified dispatch priority rule is the SPT rule. Baker and Dzielinski (1960) showed that the version using operation-specific processing times (SPT.O) is the best, when the average of total flow time is considered. Conway and Maxwell (1962) proved the optimality of the SPT.O rule for certain shop conditions, and found it to be robust to errors in processing time estimates. They argued that its shortcomings can be overcome either by rule modifications or by using better procedures for estimating processing times. The study of Rochette and Sadowski (1976) supported the earlier findings on the power of the SPT.O rule. Furthermore, they noted that it is outperformed by the EDD rule if workforce is flexible and rule ranking is done on the basis of mean job tardiness. According to Elvers and Taube (1983b), the SPT.O rule outperforms other dispatch priority rules especially in congested shops. They recommended that the dispatch priority rule employed should vary depending on the system load so that the SLK rule is applied in uncongested shops (utilization: <87.6%), the S/RPT rule is used when the load is moderate (utilization: 87.6%-91.6%), and the SPT.O rule is employed in congested shops (utilization: >91.6%).

Ramasesh (1990) concluded that many consider the SPT rule to be the best dispatch priority rule. Conway (1965a) was the first to summarize that it should be considered as the standard

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3 Abbreviations of all dispatching rules are listed in Appendix 3.

benchmark for all dispatching studies, even though in his experiments the SPT rule did not exhibit the minimum value for any of the performance measures including average queue length and average work-in-process measured with total work. Yet, the dispatch priority rules that performed better than the SPT rule typically included it as an important component. Interesting findings about the applicability of the SPT rule include:

- It exhibits best with externally set due dates (Conway 1965b).
- It is least sensitive to the due date assignment method (Conway 1965b).
- It is least sensitive to forecasting errors in due dates (Eilon and Hodgson 1967).
- It minimizes the number of jobs waiting in queue (Jones 1973).
- It causes the fewest number of setups (Biggs 1985).
- If often minimizes the number of tardy jobs (Holthaus and Rajedran 1997).
- It performs relatively well in all performance criteria (Montazeri and van Wassenhove 1990).

Bassett and Todd (1994) argued that the improvement in the average flow time of jobs achieved with the SPT rule is inappropriately overemphasized. Instead, the management of bottlenecks should be considered as the key to effective work flow in a randomly routed shop.

Various modifications of the SPT rule have been developed to address its pitfalls. For example, the weighted version SPT.T rule is a greedy rule focusing on the trade-off between time and value indicated by order-specific tardiness penalty. Several truncated versions employing the SPT rule in a controlled manner have also been tested to improve the performance of the standard SPT rule especially in tardiness-based measures (e.g. Fry and Philipoom 1989; Schultz 1989; Kannan and Ghosh 1993). The challenge of the truncated rules is the use of parameters that may not always be straightforward or even understandable (Fry and Philipoom 1989). One example of truncated rules is the CEXSPT rule proposed by Schultz (1989). It uses due date information to expedite jobs that are late or behind schedule and employs a heuristic to control the sequencing of jobs with long processing times. The CEXSPT rule is found to be robust against changes in due date tightness, and it does not require estimation of global shop characteristics. Additionally, the mean flow time given by it is nearly as good as by the standard SPT rule without the undesirable side effect of large conditional mean tardiness and some very late jobs. Nevertheless, Kannan and Ghosh (1993) remind that the extent to which truncation is applied must be carefully considered particularly if due date allowances are not constant for all jobs.

The performance of due date based rules such as the EDD rule is excellent when there is enough production capacity. The EDD rule finds a non-tardy schedule, if feasible. The study of Brah (1996) indicated that many other dispatch priority rules produce schedules that are tardier than the one given by EDD, which performs best for both mean and maximum tardiness along with the modified due date (MDD) rule. The EDD rule should be only used in small problems (Volgenant and Teerhuis 1999), and it is considered unsuitable for earliness/tardiness problems with non-zero ready times (Mazzini and Armentano 2001).

The strengths of the two basic priority rules, SPT and EDD, can be combined. Baker and Bertrand (1982) recommended the modified operations due date (MOD) rule that combines the SPT and EDD rules in a subtle way for all tardiness factors. In most of their test settings, the MOD rule was superior to other dispatch priority rules in mean tardiness, although its performance suffered when due dates were extremely loose (Baker and Kanet 1983; Lejmi and Sabuncuoglu 2002). Later Anderson and Nyirenda (1990) composed two new extensions of the MOD rule called the CR+SPT and S/RPT+SPT rules, which are easy to implement without any parameter estimation. They showed that the rules perform better than the MOD rule in various conditions. Also the MDD rule, which Alidaee and Gopalan (1997) demonstrated to be the same as the Wilkinson-Irwin rule and the PSK rule (Panwalkar *et al.* 1993) performs well (Kim 1990; Caskey and Storch 1996).

Surprisingly, many dispatch priority rules rely on information about slack, the time available before the confirmed due date, even though slack-based rules generally do not perform well if some of the jobs are late. Jones (1973) found that the basic SLK rule was superior to the SPT rule. Nevertheless, Adam and Surkis (1980) considered it very costly to implement, and according to Russell (1986) it should be used in large-scale problems, where resource constraints are not very binding. Gere (1966) argued that another slack-based rule, the S/OPN rule, is significantly better in static problems than the standard SLK.J rule and also better than the SPT.O+SLK.J rule, and a modification of the SLK.J rule. Furthermore, Jones (1973) considered the S/OPN rule as the best rule in two indicators, the portion of tardy jobs and late jobs waiting in queue, compared to the FCFS, SPT, and WINQ rules. Miyazaki (1981) also recommended the S/OPN rule along with the CR rule, which was also promoted by Biggs (1985), although Adam and Surkis (1980) had found earlier that the S/RPT rule outperforms the CR rule in many scheduling problems. In practice, the use of the S/PRT rule has been prohibited by its high cost and other implementation difficulties.

Carroll (1965) introduced the cost over time (COVERT) rule especially for the mean tardiness problem. The COVERT rule calculates priority indices on the basis of the slack and the expected waiting time of a job on subsequent machines. Russell *et al.* (1987) found that the overall performance of the COVERT rule is best when it uses dynamic average waiting times with a small look-ahead parameter (*k*=1) and a linear penalty function. Their study also showed that in tardiness measures and with loose due dates the MOD rule is superior to the COVERT rule whose other challengers are the CEXSPT and ATC rules (Schultz 1989; Vepsalainen and Morton 1987). It is noteworthy that the COVERT rule was among the first dispatch priority rules that employed a free parameter for trading off processing time against expected tardiness costs. Its success has been delayed by the fact that only a minority of scheduling researchers has used it as a benchmark rule claiming the difficulty of choosing an appropriate value for the parameter, even though it outperforms many dispatch priority rules in most performance measures (Russell *et al.* 1987). Holthaus and Ziegler (1997) showed recently that the COVERT rule is even more efficient if the four-step coordination rule called LAJD (look ahead job demanding) is used with it. Holthaus and Rajedran (1997) concluded that the COVERT rule and its modified version work well in minimizing mean tardiness but are still outperformed by their RR rule.

Another integrated trade-off heuristic, apparent tardiness cost (ATC) rule, is shown to perform consistently better than the COVERT rule in weighted tardiness problems (Morton and Rachamadugu 1982; Vepsalainen 1984). The ATC rule combines the features of both the SPT and SLK rules and shows robustness not achieved previously by any other dispatch rule in weighted mean tardiness (Vepsalainen and Morton 1987). Vepsalainen and Morton (1988) also examined the coordination of the rule-based scheduling heuristic with global lead time information in situations where lead time estimates are determined either by observing parameters in the queue or by repeated simulations. They found that with lead time iteration the ATC rule is the best rule overall, while the COVERT rule performs well in dynamic job shops with priority-based estimation. Later, Lawrence and Morton (1993) concluded that the ATC rule with bottleneck global pricing and lead time iteration performs better than the basic priority dispatch rules because it produces lower average costs for both weighted tardiness and weighted delay problems. Ow and Morton (1989) applied a modification of the heuristic, called EXP-ET, into the early/tardy problem and learned that it gives relatively good schedules. Volgenant and Teerhuis (1999) suggested that the use of the highly robust ATC rule is justified when the quality of the schedule is important or when no knowledge is available on the problems to be solved, and recommended the SPT.T rule for events where short computing time is important. In summary, the success of the ATC rule seems to be largely explained by its capability to estimate how much the scheduler should wait before dispatching (or releasing) a specific job.

Lately, several studies have introduced new versions of both the COVERT and ATC rules. Kanet and Zhou (1993) suggested a decision theory approach for implementing the ATC and other good dispatching rules. Akturk and Ozdemir (2001) tested the approach of Kanet and Zhou along with other scheduling heuristics and found that also for it the amount of improvement is statistically significant. Chen and Lin (1999) introduced an improved version of the weighted COVERT rule, called the multi-factor (MF) rule, which gives higher priority to the jobs with longer expected waiting time, shorter slack time, and higher ratio of tardiness cost over processing time. They claimed that the MF rule is superior to the weighted versions of the COVERT and ATC rules in total tardiness cost and in the portion of tardy jobs. Another ATC modification called the bottleneck dynamics (BD) heuristic integrates the advanced methods of resource pricing and lead time estimation to the basic rule. Kutanoglu and Sabuncuoglu (1999) found that it outperforms the weighted versions of the COVERT and CR+SPT rule.

3.2.2 Impact of Rule Type and Information Content on Rule Performance

The rankings of dispatch priority rules in experimental studies are influenced by the performance measures used in the benchmarking process. There are, however, some studies that give general recommendations. Baker and Kanet (1983) compared dispatch priority rules that use either operation- or job-specific information and found that the rules using operation-based information appear to be more effective than their job-based counterparts. Another general statement concerns the value-based dispatch priority rules: despite good performance they perform poorly on tardiness-based measures (Ramasesh 1990). Aggarwal *et al.* (1973) found that the time-based rules outperformed their new cost based rule in job lateness and hidden lateness. Hoffman and Scudder (1983) analyzed the relative performance of time-oriented, due date based and value based rules and found that the dispatch priority rules using monetary values provide good performance with only minor sacrifice in mean lateness and mean flow time. In another study, Scudder and Hoffman (1985a) concluded that the cost-based rules perform quite well at moderate utilization levels because most of the jobs can be completed on-time. The value based rules were offered as the first choice for less congested shops, whereas in congested shops the time based rules outperformed in both the level of work-in-process and the portion of tardy jobs in congested shops (Scudder and Hoffman 1985b).

Weighted combinations of the basic dispatch priority rules have been recommended for dynamic scheduling environments (Moodie and Roberts 1968; Emery 1969; Holloway and

Nelson 1974). Ramasesh (1990), nevertheless, concluded in his review that the weighted composite rules are not strongly supported because the results of experimental studies are not strong enough to suggest their superiority. Caskey and Storch (1996) also explained that no advantage, at least in lower mean tardiness, can be gained by allowing individual machines to use different priority dispatch rules as recommended by Raman *et al.* (1988). More recently, Barman (1997) examined the impact of using different rules in a multi-stage process by testing all possible combinations of four simple dispatch priority rules (EDD, SPT, SI^x and SLK). Based on the experiments in a three-stage flow shop he concluded that the use of rule combinations is an excellent strategy except for the SPT rule, which performs poorly in tardiness at each stage. Especially two of the combinations tested (SPT-SPT-EDD and SPT-EDD-SPT) gave excellent results in all three performance measures considered (mean flow time, mean tardiness, and portion of tardy jobs). In addition, the EDD-EDD-SPT strategy was considered to be a good alternative at lower levels of shop load. Jaymohan and Rajendran (2000a) argued that the mixing of dispatch priority rules can result in a high amount of work, and thus a single rule combining elements of some of the generic dispatch rules should be used. They proposed, for instance, the PT+WINQ+SL and PT+WINQ+AT[4] strategies.

One motive for testing dispatch priority rules with different structures is to find approaches that would allow modification of decision criteria when objectives change, instead of only finding hypothetical optimal solutions. Hershauer and Ebert (1975) already introduced a heuristic scheduling system that chooses the best rule from a set of alternatives (SPT, EDD, SLK and NOP) based on both economical and operational performance measures. Baker and Bertrand (1981) tested a dynamic priority scheme that chooses between the SPT and EDD rules depending on the due date tightness. Other mechanisms for the selection of best rule have been considered by Abdallah (1995), Pierreval and Mebarki (1997), Jeong and Kim (1998), and Subramaniam *et al.* (2000). Grabot and Geneste (1994) tested two types of scheduling decisions: 1) best rule selection (multi-pass selection algorithm), and 2) parameter tuning (lead time iteration). They found that their parameterized compromises among the selected classical rules outperformed the generic rules. In their comparative study Kutanoglu and Sabuncuoglu (2001) showed that although multi-pass or iterative algorithms can perform better than single-pass algorithms on average, they are not better than the best single-pass

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[4] PT+WINQ+SL uses information on job-specific processing time, work-in-next-queue, and slack in determining priority indices, while the PT+WINQ+AT rule uses information on processing time, work-in-next-queue, and arrival time.

rule. This holds especially in stochastic environments where fine-tuning of any rule parameter in a series of iterative simulations may not viable.

Intuitively the information utilized by a dispatch priority rule impacts the performance of the rule on any performance measure, and perhaps unexpectedly more information does not necessarily improve the performance. The composite rules utilizing more information than the local status of an operation have been recommended for dispatching of assembly jobs (Maxwell and Mehra 1968). Yet, it has been argued that with heavy load the dynamic adjustment of order due dates using inventory status information can reduce the shop and inventory system performance (Berry and Rao 1975). According to Berry and Rao (1975) the collection and processing of queue waiting time data has only a limited benefit for scheduling decisions, possibly due to the use of simple exponential smoothing models in forecasting the lengths of queues. They explained that the estimation of waiting times would pay off only if the priority content of a queue were measured and incorporated in the model anticipating the waiting times. Graves (1977) presented counterarguments and suggested that it is the Berry and Rao's construction and/or the use of the dynamic information on queue waiting time at individual machines and on the inventory status of individual items, and not the value of the information itself, which is in question. Later, Hausman and Scudder (1982) showed that the direct use of inventory information in determining priorities leads to significantly improved shop performance. More extensive use of information has also been promoted by Holthaus and Rajendran (1997) who encouraged research about dispatch priority rules that include information on processing times, due dates, and total work content of jobs queuing to the resource performing the following operation of a job to better accomplish multiple performance criteria. Barman (1997), another sponsor of the use of estimated waiting times in scheduling heuristics, argued that the more factors are included in waiting time rules the better their performance is.

Besides information content, rule type, and rule structure, the impact of additional features has been analyzed. Kutanoglu and Sabuncuoglu (1999), for example, found that inserted idleness improves the performance of ordinary dispatch priority rules. They also recommended that different pricing schemes should be used with the dispatch priority rules in different manufacturing environments, although myopic pricing is generally efficient. This differs from the conclusions of Lawrence and Morton (1993) who did not find significant differences among the five pricing rules they tested.

3.2.3 Impact of Test Settings on Rule Performance

The interpretation of results of experimental studies that compare dispatch priority rules is challenging because they have typically been conducted in different kinds of production systems under variable shop conditions. Differences in the test settings can be found, for example, in the shop layout, the number of production stages, and the number of parallel machines or machine centers. Graves (1981), in fact, introduced a classification scheme of scheduling problems that outlines most of the alternative test beds based on five criteria:

1. *Requirements generation:* open shop or closed shop
2. *Processing complexity:* one-stage with one processor, one-stage with multiple processors, multi-stage flow shop, or multi-stage job shop
3. *Scheduling criteria:* minimize total tardiness, minimize the number of late jobs, maximize system utilization, minimize in-process inventory, balance resource usage, and/or maximize production rate
4. *Parameter variability:* deterministic or stochastic
5. *Scheduling environment:* static or dynamic

According to the literature review a majority of the comparative studies have been conducted in dynamic multi-stage job shops with deterministic parameter values so that requirements are generated directly by customer orders, as in an open shop. More diversity is found in the performance measures used (e.g. Conway 1965a[5], Aggarwal *et al.* 1973). The three most common measures are (weighted) mean tardiness, mean flow time, and the portion of tardy jobs. Especially the earliest publications used and reported the results of numerous performance criteria. Normalized performance measures, which are independent of the testing environment, have been employed rarely (Vepsalainen and Morton 1987; Jaymohan and Rajendran 2004). All in all, these prevailing practices of the scheduling research make consistent rankings of dispatch priority rules unfeasible despite the benefit of these rankings for practitioners trying to select the most appropriate heuristic. To demonstrate this all simulation studies known to report the performance of the ATC rule are analyzed in detail. These studies (Vepsalainen and Morton 1987; Vepsalainen and Morton 1988; Anderson and Nyirenda 1990; Philipoom and Fry 1990; Kim 1990; Kanet and Zhou 1993; Raghu and Rajendran 1993; Jensen *et al.* 1995; Malhotra *et al.* 1994; Chen and Lin 1999; Kutanoglu and Sabuncuoglu 1999; Jaymohan and Rajendran 2000a; Jaymohan and Rajendran 2004) have

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[5] Compared 17 dispatching rules (RAN, FCFS, FASFS, FOPNR, SPT, LPT, LWKR, MWKR, TWK, NINQ, WINQ, XWINQ, P+WKR(a), P/WKR(a), P/TWK, P+WQ(a), P+XWQ(a)) in a job shop using the following performance measures: jobs in queue (mean and variance), total work (mean and variance), work remaining (mean and variance), mean work completed and the mean of imminent operation work in queue.

used various types of test beds, for example low and high system load with different levels of due date tightness. For each publication, there is an overview of its results reported in the portion of tardy jobs in Figure 3-3.

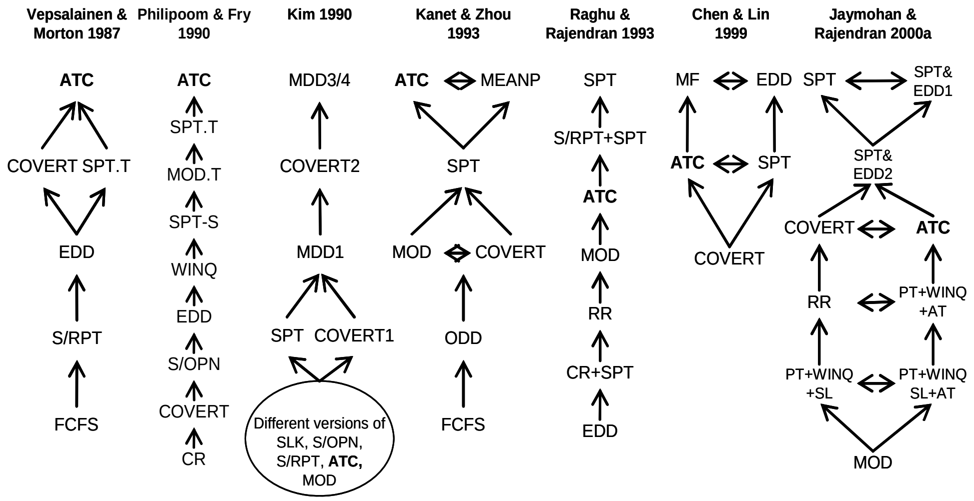

Figure 3-3 Rankings of dispatch priority rules according to the portion of tardy jobs in prior scheduling studies that have analyzed the performance of the ATC rule.

The relative ranking of the ATC rule is fairly consistent throughout the studies. The most interesting observations include the following:

- The ATC rule is outperformed by several versions of the MDD and COVERT rules in the study of Kim (1990).
- The SPT rule gives better results than the ATC rule in the experiments of Raghu and Rajendran (1993).
- According to Chen and Lin (1999) the MF and EDD rules give better results than the ATC rule especially when due dates are loose.
- Three composite dispatch priority rules called the PPP, PPD and PDP rules outperform the ATC rule (Jaymohan and Rajendran 2000a).

The finding of Raghu and Rajendran (1993) cannot be viable if the priority indices are calculated correctly. The ATC rule includes the SPT rule as one of its components and should give at least equally good results. Although Chen and Lin (1999) concluded that their MF rule generally performs best, they observed that the other dispatch priority rules (ATC, EDD, SPT, and COVERT) also perform well in some problem instances. In addition to the inconsistencies in the ranking of the ATC rule the value of the standard benchmark rule EDD appear to be unpredictable. Raghu and Rajendran (1993) found that the EDD rule is outperformed by the SPT and ATC rules in an open shop with 12 machines with all loads regardless of due date tightness and processing time distributions, whereas Chen and Lin

(1999) showed that the EDD rule work better than all other dispatch priority rules under light load, smaller shop configurations, and loose due dates.

There are some scheduling studies that have focused on the weighted tardiness problem in job shops. Their rankings of dispatch priority rules according to the average weighted tardiness are largely as expected. The most striking differences, even contradictory evidence, are found between the results of Jaymohan and Rajendran (2004) and the other studies (Figure 3-4). Jaymohan and Rajendran (2004) found that two trade-off heuristics, the weighted versions of COVERT and ATC rules, are outperformed by several composite rules and weighted versions of some basic rules such as the job slack (SLK.T) and operational due date (ODD.T). Their normalized results of rule performance in standard job shop problem instances report this clearly. The question arises if all previous priority scheduling research on the weighted tardiness problem in standard job shop settings has produced incorrect results. Since Jaymohan and Rajendran (2004) do not present logical reasoning for their results which are even contradictory to the findings presented in prior research they are not considered in the development of dominance relations among the dispatch priority rules tested in mean tardiness problems.

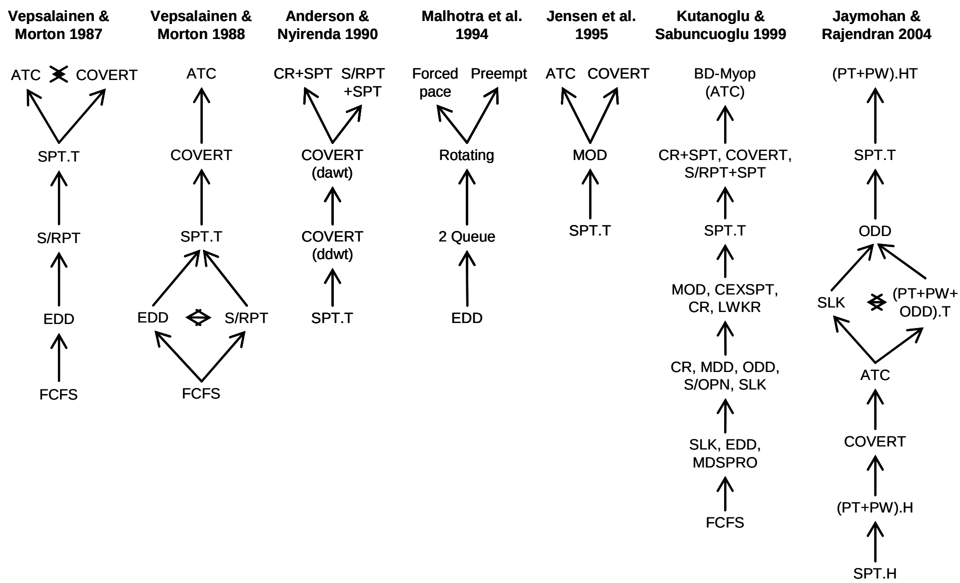

Figure 3-4 Rankings of dispatch priority rules according to (weighted) mean tardiness in prior scheduling studies that have ranked the ATC rule.

The rankings of dispatch priority rules compared in prior research are presented in the dominance chart in Figure 3-5. It indicates that depending on the problem instance the ATC, COVERT, CR+SPT, or S/RPT+SPT rule gives the best results in (weighted) mean tardiness.

This group of priority rules gives consistently better results in mean tardiness than the other standard rules such as the SPT.T rule and many of the due date and slack based rules.

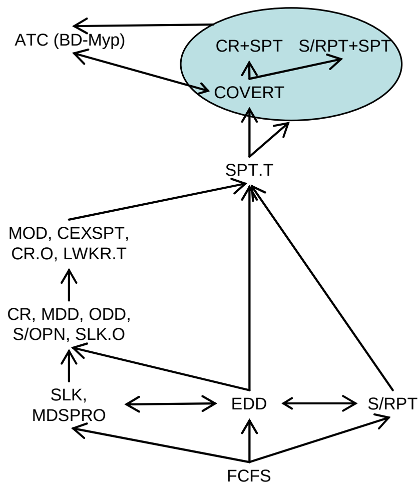

Figure 3-5 Dominance chart of the dispatch priority rules according to mean tardiness performance in job shops.

In addition to the issues introduced in the classification scheme of Graves (1981), the principles applied in job data generation such as arrival rates, processing times, and due dates can impact the rankings of dispatch priority rules. The level of shop load, which varies depending on the arrival rate of jobs, affects the effectiveness of dispatching rules (Elvers and Taube 1983a), and the selection of the dispatch priority rule is more important when the system load is high (Aggarwal and McCarl 1974). The rules giving priority to shorter jobs become more effective when the system load increases (Eilon and Cotterill 1968). Waikar *et al.* (1995) found that with any tested condition the SPT, EDD, LWKR, and S/OPN rules perform better than other rules[6], and that the SPT and EDD rules perform best when shop utilization is above 85%. Also the simple look-ahead rule proposed by Koulamas and Smith (1988) gives better results when machine and server utilization increases or if queue lengths increase. Commonly, order priorities are considered less important in uncongested environments, but Scudder *et al.* (1993) argued that some combinations of dispatching, order release, and due date setting policies may cause unfavorable results. For instance, the MDD rule outperformed the other dispatch rules (SPT, ODD, CR, CR, SLK, and MOD), when the system utilization was below 80% and due date tightness was low, except when used with dynamic flow allowance and immediate order release. Furthermore, Lejmi and Sabuncuoglu

[6] Other dispatch priority rules tested by Waikar *et al.* (1995) were FCFS, DDT, MWKR, MWKR-P, MWKR/P, MOPNR and random.

(2002) explained that variation in system workload over time does not weaken the performance of dispatch priority rules except in high utilization levels. Only then can demand variation can significantly increase the mean tardiness and mean flow time.

Like Randhawa and Zeng (1996), Lejmi and Sabuncuoglu (2002) also tested the impact of processing time variation and found that if it is high, over 40%, the performance of dispatch priority rules tested deteriorates but the rankings of the rules do not change considerably. This is contrary to the finding of Elvers and Taube (1983b) who showed that the accuracy and variation of operation times do not produce significantly different results. In fact, they argued that stochastic processing times do not provide substantially stronger results in most problem instances except for utilization levels between 91.6% and 94.3% (Elvers and Taube 1983a).

The performance of the dispatch priority rules depends on due date tightness. Due date decision rules have the most significant impact on the lateness measures and the variance of flow time (Weeks and Fryer 1976) as well as on the tardiness of jobs completed (Russell and Taylor 1985). Alidaee and Ramakrishnan (1996) reminded that all dispatch priority rules perform equally well when due dates are very loose, while Jensen *et al.* (1995) explained that with tight due dates dispatching is relatively unimportant and eventually some low priority customers will be unsatisfied with the service. Vepsalainen and Morton (1987) argued that the dispatch priority rules using more information, such as the COVERT rule, outperform the simple rules when due date tightness is high, and Lejmi and Sabuncuoglu (2002) found that the global rules are more robust to variation in due dates. Wein and Chevalier (1992) suggested that due dates should be set dynamically, based on the status of order backlog and shop floor, the type of arriving jobs as well as the job release and sequencing policies. Nevertheless, according to Scudder *et al.* (1993) a dynamic due date setting does not improve the shop performance. Other factors that according to prior research impact the performance of dispatch priority rules include:

- order release method (Rohleder and Scudder 1993; Scudder *et al.* 1993),
- use of modified due dates and operation milestones (Kanet and Hayya 1982; Baker and Kanet 1983),
- use of job-specific tardiness penalties (Malhotra *et al.* 1994; Jensen *et al.* 1995),
- product structures (Russell and Taylor 1985; Reeja and Rajendran 2000a),
- product routings (Philipoom and Fry 1990),
- setup times of resources (Kim 1995),
- breakdown parameters of resources (Holthaus 1999), and
- workforce flexibility (Rochette and Sadowski 1976; Scudder 1985),

- shop floor configurations (Rajendran and Holthaus 1999).

Interestingly, the performance of dispatch priority rules is found to be independent of the capacity balance (Philipoom and Fry 1990), the shop size (Hunsucker and Shah 1992), and the dispersion and shape of tardiness penalty distribution (Jensen *et al.* 1995).

3.2.4 Implications for Decision-Makers

Some publications reviewed give practical recommendations for managers or supervisors responsible for production scheduling. Firstly, even simple logical rules can be enough for controlling job shops (Baker and Dzielinski 1960), since the use of any dispatch priority rule except the FCFS rule improves the system performance when the utilization of resources increases (Conway 1965a). Furthermore, for risk-averse managers simple intuitive rules requiring a minimum of data processing are efficient (Goodwin and Weeks 1986). Generally they perform equally well as more complex dispatch priority rules in most performance measures according to Randhawa and Zeng (1996). Secondly, it is important to determine useful performance criteria along with unambiguous tie-breaking rules (Panwalkar and Iskander (1977). Thirdly, the selection of a dispatch priority rule is not as important as the choice of heuristics, such as look-ahead. Instead of encouraging the use of complex scheduling heuristics, Gere (1966) advised companies to implement three practices – the anticipation of the future progress of a schedule, alternate operation, and look ahead heuristic – that can significantly improve the shop performance. The use of combinatorial rules was encouraged by Panwalkar and Iskander (1977) who in the spirit of 1970s claimed to observe a consensus among researchers about the superiority of combinatorial rules over the basic dispatch priority rules. Further, it has been shown that it is more important to be in the right overall area when estimating the costs of idle machines, inventories, long promises, and missed promises instead of having access to accurate cost data (Jones 1973). Moreover, Blackstone *et al.* (1982) argued that when the shop load is approximately 80% and due dates are set internally, due date based rules such as the COVERT and S/OPN work quite well, while processing time based rules perform well in more congested shops. The practical challenge of their advice is how to anticipate the future load of a production system and how to decide when it is the right moment to switch from one dispatch priority rule to another. In multi-stage processes, decision-makers should also be able to decide if the shift from one rule to another is made independently within each stage based on its load or collectively based on the average utilization of all system resources over a specific period of time.

The early scheduling studies focused on finding robust dispatch priority rules such as the COVERT and ATC rules that are superior regardless of the performance measure. Later, heuristic approaches aiming to combine the best characteristics of the generic dispatch priority rules without parameters have been introduced because parameterized rules were considered difficult to implement. For example, the MOD rule and its extensions CR+SPT and S/RPT+SPT are such methods. More recently, some researchers have aimed to identify the best rule for each performance measure (e.g. Rajendran and Holthaus 1999; Holthaus 1999). The use of several performance measures is, however, problematic from the managerial viewpoint because it calls for either a priori decision about the primary objective of the organization or responsive adjustment to changing conditions on the shop floor. Based on the review of prior studies, the major breakthroughs are the COVERT rule (Carroll 1965) and the ATC rule (Vepsalainen 1984, Morton and Rachamadugu 1982). Also the non-parameterized rules introduced by Anderson and Nyirenda (1990) are noticeable advances in priority scheduling research.

3.3 Classification of Dispatch Priority Rules

The state-of-the-art reviews and the publications that have focused on the comparison of alternative methods have suggested classifications of dispatch priority rules. The formal classifications (e.g. in Maxwell and Mehra 1968; Hausman and Scudder 1982; Vepsalainen 1984; Sculli 1987; Morton and Pentico 1993; Pinedo 1995; Pinedo and Chao 1999) have advanced the understanding of the current status of priority scheduling research and facilitated more consistent comparisons analyzing the informational efficiency of dispatch priority rules.

3.3.1 Comparison of Published Classifications

Main decisions in the design of rule-based scheduling heuristics are the selection of rule structure and the information used in it. The categorization of Panwalkar and Iskander (1977) that divides dispatching rules into three groups (basic rules, heuristic scheduling rules, and other rules) according to their structure has been widely adopted. The basic rules are further categorized into three groups that are simple rules, combinatorial rules, and weighted priority rules. Panwalkar and Iskander (1977) defined that the simple rules typically use job-specific information, be it processing times or the queue length at the resource where the job will be directed next. The combinatorial or composite rules are the heuristics that apply different dispatch priority rules to specified groups of jobs or use different dispatch priority rules depending on the shop status and circumstances. The weighted priority rules then combine different simple rules by giving them parameterized weights. According to Panwalkar and Iskander (1977) the heuristic scheduling rules involve a more complex consideration of situation such as anticipated machine loading and the effect of alternate job routing (Figure 3-6). They may also include non-mathematical aspects such as inserting a job in an idle time slot by visual inspection. Panwalkar and Iskander (1977) also classified the dispatch priority rules based on the information that is used in the calculation of order-specific priority index values.

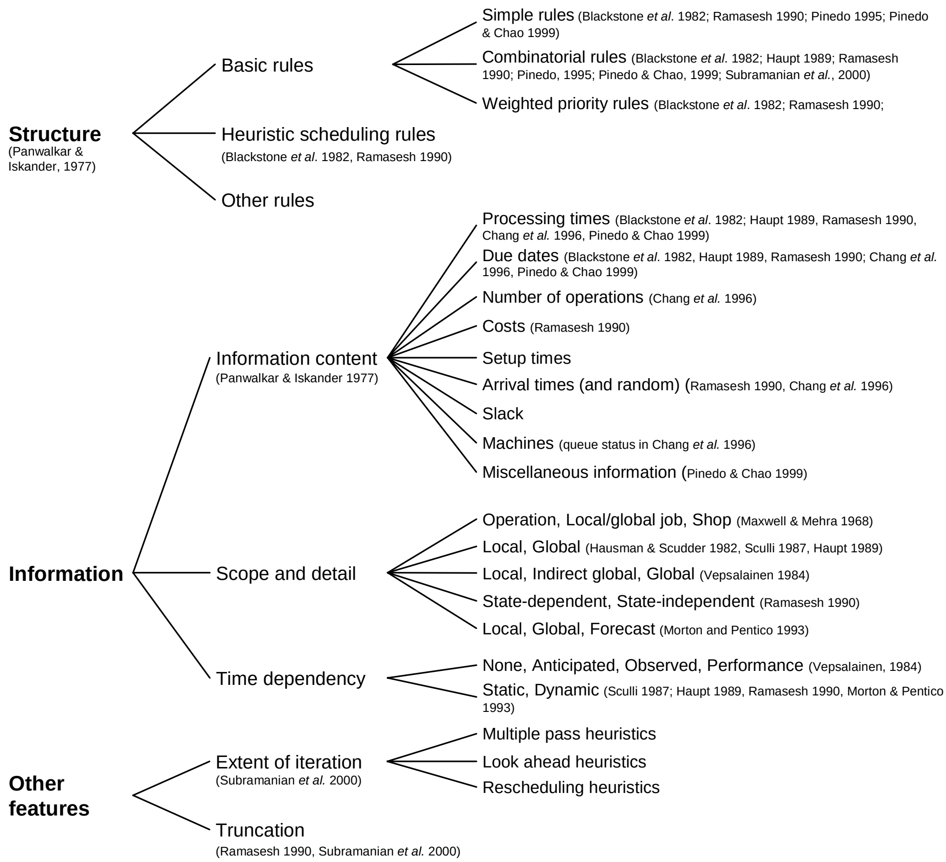

Figure 3-6 Synthesis of the classification criteria used in the previous analysis of dispatching rules.

Other published classifications typically consider only a part of their categories such as processing times and due dates. Chang *et al.* (1996), for example, classified dispatch priority rules using information about processing times, due dates, number of operations, arrival times, and queue status. Ramasesh (1990) then considered costs, or added value, as one of the four categories he introduced for defining the information content of dispatch priority rules. In addition to information content, many of the publications have suggested the scope and detail of information as well as time dependency as functional classification criteria. For instance, Maxwell and Mehra (1968) categorized dispatching rules into four groups depending on what information they use about jobs, machines, and queues in the shop. Later, the division into local and global dispatch priority rules based on the scope and detail of status information became common (e.g. Hausman and Scudder 1982). The local rules utilize information on the current machine and its queue, whereas the global rules use information about the queues of other resources or the system load in general. The division into local and global rules was further developed by Vepsalainen (1984) who divided the global rules into two classes called indirect global and direct global (Figure 3-7). The new class of indirect global rules use information, for example, on expected waiting times that can be derived from aggregate load indicators instead of relying on direct observations. Vepsalainen (1984) also proposed the horizon of information feedback, which ranges from no feedback to performance feedback, as a new criterion for rule classifications. Static dispatch rules typically use only information about jobs and machines, whereas dynamic rules include time-dependent terms such as job-specific slack. The feedback horizon is performance feedback, if any type of forecasting on the future status of the shop is calculated and used.

Scope and Detail of Status Information / ***Type of Information Feedback***	Observable Status	Anticipated Status	Performance Feedback
Local	• Standard rules using job parameters	• Look ahead estimation (single-machine)	• Look ahead adaptation (single machine)
Indirect Global	• Lead time estimation based on shop status	• Dynamic lead time estimation	• Lead time iteration
Global	• Work in other queues as part of index	• Probing of next machine load	• Rule adaptation

Figure 3-7 Classification of state-dependent dispatch priority rules according to the information used in the order-specific priority index (Vepsalainen 1984, 88).

Overall it seems that the oldest rule classifications are the most innovative. They exploit the different dimensions of information usage, although systematic collection and real-time sharing of information has become realistic only recently. The classification of Panwalkar and Iskander (1977) specified both the rule structure and information content most broadly, and later only parts of it have been used (a synthesis of the criteria used in the discussed prior research in Figure 3-6). Naturally, some pragmatic extensions to the categories such as job routing, customer type, product type, profit margin, and order release date could be added.

Scheduling researchers have generally developed new classifications primarily to motivate the design of new methods typically combining or slightly modifying existing priority dispatch rules. In fact, Subramanian *et al.* (2000) pointed that priority scheduling research can be divided into the studies that modify existing rules and the studies that develop new iterative methods. It is argued that a comprehensive classification can, in addition to enhancing the selection of dispatch priority rules for managers, support the convergence of alternative dispatch priority rules into families of rules. None of the classifications found in the priority scheduling literature, nevertheless, supports the identification of factors such as membership to a rule family that can explain the relative performance of dispatch priority rules in different types of decision-making environments and under variety of shop conditions.

3.3.2 Positioning of Rules in the Dispatch Priority Index Matrix

The publications reviewed describe, test, and compare in total over 300 dispatch priority rules in various decision-making environments. After the removal of duplicate versions and minor modifications of the rules[7], there is a short list of about 50 different dispatch priority rules left. These rules are further divided into generic and special rules. The special rules are designed for particular production facilities and decision-making environments, and thus are excluded from the detailed analysis that aims to identify priority index rules for open scheduling protocols. The generic rules, listed in Appendix 2, are classified using the DPI matrix suggested in Chapter 2. It is assumed that the positioning of a rule within the classification predicts its performance as a coordinative mechanism (Figure 3-8).

In addition to the order information and the type of priority index used, the information content of dispatch priority rules could be applied as a classification criterion easing any analysis of their informational efficiency. However, the preliminary analysis showed that such a categorization is fruitless because many dispatch priority rules use a variety of data, making the determination of their dominant information content unreasonable. A structure-based division into basic rules (including any weighted or composite version of the basic priority index rules) and integrated trade-off heuristics that make trade-offs, for example between capacity utilization and on-time delivery, was also considered, and found non-value adding. Next, the classified generic dispatch priority rules are described category by

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[7] Some dispatch priority rules have more than one name or abbreviation, e.g., critical ratio is called CR, CRR, CRRAT and SCR. Also modifications of many of the dispatch priority rules are available then increasing the total number of rules. There are, for example, various adjustments to the ATC rule that typically introduce alternative ways for estimating the expected lead times and waiting times.

category. The formulas for calculating order-specific priority indices are also specified along with the developers of each rule.[8]

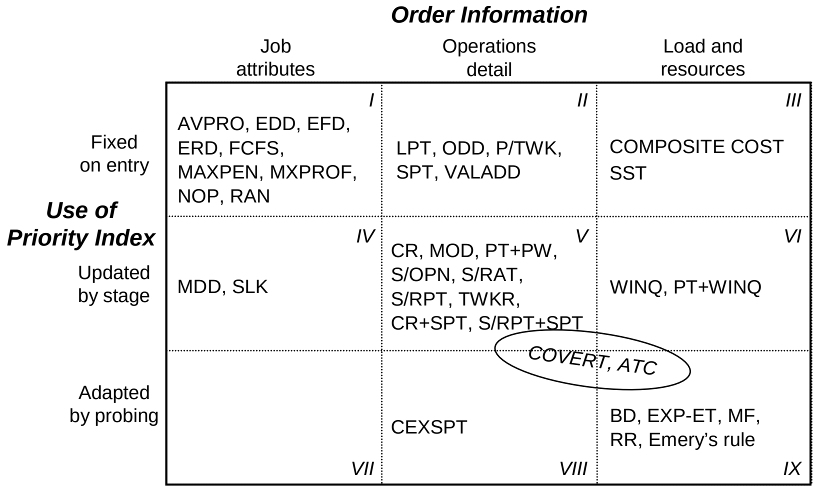

Figure 3-8 Classification of selected dispatch priority rules according to the order information and the use of priority index.

Category I: Priority index fixed on entry based on job-specific information

The dispatch priority rules relying on static data typically use information on job attributes only. Examples of such rules include EDD, number of operations (NOP), and maximum penalty (MAXPEN), of which the EDD rule is one of the standard benchmarks in priority scheduling research (Table 3-2). There are also composite rules such as the average processing time (AVPRO) rule that uses information on total work content and number of operations. Similar to the SPT rule, it gives jobs with short operations priority over others in order to minimize mean flow time and to prevent starving of resources.

Category II: Priority index fixed on entry using operations detail information

Textbook examples of this category are the SPT and operational due date (ODD) rules. The ODD rule prioritizes jobs based on their milestones defined externally for each operation. The longest processing time (LPT) rule has been found quite common in practice (Conway 1965a) despite its consistently poor performance (Chang *et al.* 1996). Both the SPT and LPT rules have modifications that instead of operation-specific processing times use the order-specific processing time as the criterion. Also the FCFS rule and random selection (RAN/SIRO) are queue disciplines, which can be implemented with operation- or job-specific

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[8] If the original source/developer is unknown, the earliest article discussing the logic and/or performance of the rule (e.g. EDD) is specified.

information. The VALADD rule is a cost-based rule that gives highest priority to the job with the highest value-added in the previous operations. The P/TWK rule calculates the ratio between the processing time of the next operation and total processing time, and prioritizes the jobs with the lowest value.

Category III: Priority index fixed on entry using load and resource information

There are two priority index rules that use information about the machine for which the dispatching decision is done. The value of the shortest setup (SST) rule depends on both the machine and imminent operation. The cost-based composite rule prioritizes the operation with the largest total cost of in-process inventory, facilities, lateness, and setups.

Table 3-2 Generic dispatch priority rules that fix the order-specific priority indices on their entry to the system (notation in Appendix 3).

Rule	Definition	Rank and priority index		Source
AVPRO	Average processing time	min	$\sum_{j=1}^{m_i} p_{ij} \Big/ m_i$	Hausman and Scudder (1982)
COST	Composite cost rule	min	$C_1 V_i \left(d_{ijk} - t\right) + C_{2q} K_{1k} p_{ijk}^{-1}$ $+ dC_3 V_i \left(t - d_{ijk}\right)^2 + C_{4k} \bar{s}_{2k} s_{ijk}^{-1}$	Aggarwal *et al.* (1973)
EDD	Earliest due date	min	d_i	Conway (1965b)
EFD	Earliest finish date	min	$C_i = r_i + p_i$	Spachis and King (1979)
ERD	Earliest release date	min	r_i	Baker and Bertrand (1981)
FCFS	First come first served	min	a_{ij}	Baker and Dzielinski (1960)
LPT	Largest processing time	max	p_i	
MAXPEN	Maximum penalty	max	w_i	Kurtulus and Davis (1982)
MXPROF	Most profitable job in the queue	max	$(pm)_i$	Hoffman and Scudder (1983)
NOP	Number of operations	min	m_i	Conway (1965a)
ODD	Operation due date	min	d_{ij} or $a_i + c\sum_{q=1}^{j} p_{iq}$	Conway (1965a)
P/TWK	Relative processing time	min	$p_{ij} \Big/ \sum_{j=1}^{m_i} p_{ij}$	Conway (1965a)
SIO	Shortest imminent operation	min	p_{ij}	Conway and Maxwell (1962)
SPT	Shortest processing time	min	p_i	Baker and Dzielinski (1960)
SST	Shortest setup	min	s_{ijk}	Aggarwal et al. (1973)
VALADD	Value-added	max	V_{ij}	Scudder and Hoffman (1983)

Category IV: Priority index updated by stage using job-specific information

Many of the generic dispatch priority rules are stage-updatable, i.e., order-specific priority index values are time-dependent (Table 3-3). For example, the modified due date (MDD) rule uses information on job due date and its earliest possible completion time so that if a job is already late its relative priority is determined based on its realistic completion time instead of the due date confirmed to customer. The conventional SLK rule gives priority to jobs with the shortest excess time and seeks to minimize the maximum and variance of tardiness.

Category V: Priority index updated by stage using operations detail information

Due date based basic priority index rules include the critical ratio (CR) and MOD rules. The concept of modified operational due dates was first discussed by Baker and Bertrand (1982). They introduced the rule that updates the due date of an operation if the job is already late at the time of the decision. An example of processing time based rules is the least work remaining (LWKR) rule that by prioritizing jobs closest to their completion (least work left) reduces total flow times. This category includes several composite rules such as the process time plus process wait (PT+PW) rule and the different versions of the SLK rule: slack per number of operations (S/OPN), slack per time allowable (S/RAT), and slack per remaining processing time (S/RPT). Various modifications of the PT+PW rule have been tested especially by Jaymohan and Rajendran (2000b, 2004).

Anderson and Nyirenda (1990) introduced two new dispatch priority rules (CR+SPT and S/RPT+SPT) that both combine two well-known conventional rules. These rules have some features of integrated trade-off heuristics because the index calculation does not simply add the values of the two priority index rules but depending on the slack available considers either the SPT rule or the other alternative (CR or S/RPT). In fact, the CR+SPT rule functions similarly as the MOD rule, when jobs are on schedule. Other state-updatable priority index rules that use dynamic information about operations include the operation slack and flow due date designed to minimize the deviation of job completion time from its flow due date.

Category VI: Priority index updated by stage using load & resource information

Examples of dispatch priority rules that use information about the entire production system in the calculation of job-specific priority values are the work in the next queue (WINQ) and the number of jobs in the next queue (NINQ) rules. The PT+WINQ rule introduced by Holthaus and Rajendran (1997) prioritizes jobs with the least work in the current operation and lowest expected load in the next operation. There are also other modifications of this composite rule (e.g. Jaymohan and Rajendran 2000b).

Table 3-3 Dispatch priority rules that update priority indices per each stage (notation in Appendix 3).

Rule	Definition	Rank and priority index		Source
CR	Critical ratio	min	$\frac{d_i - t}{\sum_{q=j}^{m_i} p_{iq}}$	Berry and Rao (1975)
CR+SPT	Combination rule: CR+SPT	min	$p_{ij} \times \max\left\{\frac{d_i - t}{\sum_{q=j}^{m_i} p_{iq}}, 1\right\}$	Anderson and Nyirenda (1990)
LWKR	Least total work remaining	min	$\sum_{j=q}^{m_i} p_{ij}$	Conway (1965a)
MDD	Modified due date	min	$\max\left(d_i, t + \sum_{q=j}^{m_i} p_{iq}\right)$	Baker and Bertrand (1982)
MOD	Modified operation due date	min	$\max\left(d_{ij}, t + p_{iq}\right)$	Baker and Bertrand (1982)
PT+PW	Combination rule: PT+PW	min	$p_{ij} - C_{i,j-1}$	Jaymohan and Rajendran (2000b)
PT+WINQ	Combination rule: PT+WINQ	min	$p_{ij} + W_{i,j+1}$	Holthaus and Rajendran (1997)
P/TWK	Relative length of next operation	min	$\frac{p_{ij}}{\sum_{i=1}^{m_i} p_{ij}}$	Holthaus and Rajendran (1997)
SLK	Slack remaining	min	$d_i - t - \sum_{q=j}^{m_i} p_{iq}$	Conway (1965b)
S/OPN	Slack per remaining operation	min	$\frac{d_i - t - \sum_{q=j}^{m_i} p_{iq}}{m_i - j + 1}$	Bulkin *et al.* (1966)
S/RAT	Slack /remaining allowable time	min	$\frac{d_i - t - \sum_{q=j}^{m_i} p_{iq}}{d_i - t}$	Miyazaki (1981)
S/RPT	Slack /remaining processing time	min	$\frac{d_i - t - \sum_{q=j}^{m_i} p_{iq}}{\sum_{q=j}^{m_i} p_{iq}}$	Bulkin *et al.* (1966)
S/RPT+SPT	Combination rule: S/RPT+SPT	min	$p_{ij} \times \max\left\{\frac{d_i - \sum_{q-j}^{m_i} p_{iq} - t}{\sum_{q=j}^{m_i} p_{iq}}, 1\right\}$	Anderson and Nyirenda (1990)
VALADD	Value-added	max	V_{ij}	Scudder and Hoffman (1983)
WINQ	Work in next queue	min	$W_{i,j+1}$	Conway (1965a)

Category VII: Priority index adapted by probing & job attribute information

None of the generic dispatch priority rules fall in this category. There are, however, modifications of the conventional dispatching rules such as the high response ratio (HRN) rule by Selladurai *et al.* (1995) and the shortest expected processing time (SEPT) rule by Wein and Chevalier (1992) that anticipate the processing and waiting times of jobs.

Cateogry VIII: Priority index adapted by probing & operations detail data

By controlling the scheduling of jobs with long processing times and by employing both job-based and operation-based due date information to expedite late jobs the CEXSPT rule decreases the undesirable property of SPT that results in some very late jobs (Schultz 1989) (Table 3-4).

Table 3-4 Dispatching rules that adapt order-specific priority indices by probing (notation in Appendix 3).

Rule	Definition	Rank and priority index		Source
ATC	Apparent tardiness cost	max	$\frac{w_i}{p_{ij}} \exp\left(-\left[\frac{d_i - t - p_{ij} - \sum_{q=j+1}^{m_i} \left(W_{iq} + p_{iq} \right)}{k\bar{p}} \right]^{+} \right)$	Vepsalainen (1984)
BD	Bottleneck dynamics	max	$\frac{w_i U_{ij}(t)}{\sum_{q=j}^{w_i} R_{k(q)}(t)\, p_{iq}}$	Morton and Pentico (1993)
CEXSPT	Truncated SPT		See note 1	Schultz (1989)
COVERT	Cost over time	max	$\frac{w_i}{p_{ij}} \max\left(0, 1 - \frac{\max\left(0, d_i - t - \sum_{q=j}^{m_i} p_{iq}\right)}{k \sum_{q=j}^{m_i} W_{iq}} \right)$	Carroll (1965)
MF	Multi-factor rule	max	$\frac{w_i}{p_{ij}} \left[W_{iq} - \left(d_i - t - \sum_{q=j}^{m_i} p_{iq} \right) \right]$	Chen and Lin (1999)
RR	Raghu and Rajendran rule	min	$\frac{\left(d_i - \sum_{q-j}^{m_i} p_{iq} - t\right) \exp(-\rho) \times p_{ij}}{\sum_{q-j}^{m_i} p_{iq}} + \exp(\rho) \times p_{ij} + W_{nxt}$	Raghu and Rajendran (1993)
EXP-ET	Exponential early/tardy rule	max	$w_i \exp\left(-\left[\frac{h_i + w_i}{h_i} \right] \frac{S_i}{\bar{p}} \right)$, if $0 \le S_i \le \left(\frac{w_i}{h_i + w_i} \right) k\bar{p}$	Ow and Morton (1989)
			$h_i^{-2} \left(w_i - \left[\frac{(h_i + w_i) S_i}{k\bar{p}} \right] \right)^3$, if $\left(\frac{w_i}{h_i + w_i} \right) k\bar{p} < S_i \le \left(\frac{w_i}{h_i + w_i} \right) k\bar{p}$	
Emery	Emery's rule		See note 2	Emery (1969)
			$x_1 w_{iq}^2 + \left(x_2 \sum_{q=j}^{m_i} p_{iq} + x_3 \right) \frac{1}{p_{ij}} + x_4 \left(\frac{1}{1 + p_i, j+1} \right)$	
			$+ x_5 \times \max\left(0, 1 - \frac{\max\left(0, d_i - t - \sum_{q=j}^{m_i} p_{ij}\right)}{h \sum_{q=j}^{m_i} W_{iq}} \right) \Big/ p_{ij}$	

Note 1. CEXSPT partitions the original queue into 3 queues which are late queue, i.e. $S_{ij}(t)=d_i-t-\Sigma^{mi} p_{iq}<0$, operationally late queue (behind the schedule), i.e. $S_{ij}(t)=d_{ij}-t-p_{ij}<0$, and ahead of schedule, i.e. $S_{ij}(t)\geq 0$. The rule then selects a job with shortest processing time from queue 1, if this job does not create a new late job with $S_{ij}(t)<0$. If it does, then a new SPT job is selected from queue 2, if it does not create a new operationally late job in queue 3. If it does, then a new job is selected from queue 3 (Kutanoglu and Sabuncuoglu 1999).

Note 2. Six screening criteria are used to eliminate non-critical jobs before the calculation of priority values with the weighted function: 1) Priority code indicating the external priority class of a job is considered and only the jobs in the highest priority class pass the screening, 2) Carroll's COVERT rule, 3) Time in queue, 4) Remaining machine and transit time per processing time of current operation, 5) Shortest imminent operation 6) Size of next queue (jobs with operations on machines that are currently underutilized are prioritized).

Category IX: Priority index adapted by probing & load and resource information

The classification of two integrated trade-off heuristics, COVERT and ATC rules, depends on the lead time estimation method used. If order-specific lead times are estimated using a multiple of processing time, the rules can be positioned to Category V. With lead time iteration these methods should be classified into Category XI, and thus these two dispatch priority rules are described next.

In the COVERT rule the priority index represents the incremental tardiness cost per unit of imminent processing time (Carroll 1965). Since the study of Vepsalainen (1984) many researchers have tested the weighted version of this rule (COVERT.T) that is derived by using the weight of a job as a multiplier in the index. Vepsalainen (1984) introduced the ATC rule based on the look-ahead rule developed earlier by Rachamadugu and Morton (1983). Many consider the ATC rule as a composite rule (Akturk and Ozdemir 2001), but actually it is an integrated trade-off heuristic, which considers indirect or direct costs when prioritizing one job over another. The weighted version (ATC.T) integrates the weighted version of the SPT rule (SPT.T) with the urgency factor that depends on the slack available. Vepsalainen and Morton (1987) explained that the ATC rule's look-ahead parameter *k*, measured in the units of average processing time, scales the job-specific slack according to the expected number of critical or close-to-critical jobs. The value of the look-ahead is expected to range between 1.5 and 4.5 depending on the load and type of shop (static versus dynamic). Several statistical indices such as the factors of due date tightness and due date range can be calculated based on the problem data to determine the value of the look-ahead parameter (Pinedo 2002, 339). If the shop load is high and due dates are relatively tight, the parameter should be high to emphasize the SPT.T element of the rule, which prevents congestion by prioritizing short and high value jobs.

Both the COVERT and ATC rules use lead time estimation and delay penalties as parts of priority index calculation. The structural difference between the COVERT and ATC rules is illustrated in Figure 3-9. The COVERT rule uses the worst case waiting time, which is estimated to be twice the total remaining processing time of each job, as a reference for the piecewise-linear look-ahead. The ATC rule applies an exponential function of the slack and estimates the waiting time of a job only in its next operation (local slack). The main benefit of the exponential look-ahead is that when the operation-specific slack of a job is almost used its priority index value increases quickly, and so it gets priority over other jobs with more slack. Vepsalainen (1984) explained that the exponential look-ahead ensures timely completion of short jobs, and by extending the look-ahead far enough it prevents long tardy jobs from overshadowing clusters of short jobs. Morton and Rachamadugu (1982) also tested other forms of look-ahead such as linear for the ATC rule, but found the exponential function of the slack to be somewhat more efficient.

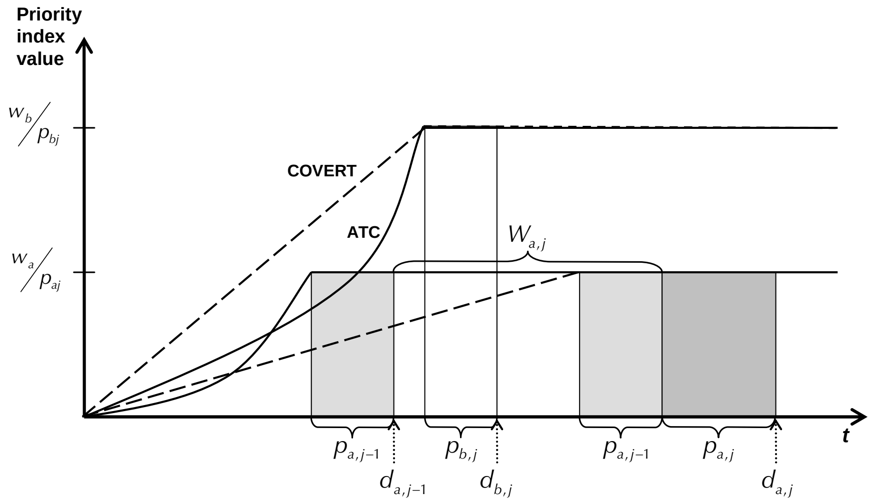

Figure 3-9 Increasing priority index values calculated with the ATC.T and COVERT.T rules for two jobs. Job *a* has two operations remaining, while Job *b* is at its last operation (Vepsalainen and Morton 1988, 106).

The alternative methods for estimating waiting times in the COVERT rule were tested by Russell *et al.* (1987). They compared due date allowance, historic average waiting time, and dynamic average waiting time with two look-ahead values (k=0.5 and k=1.0). Also the impact of the form of delay penalty function – linear or semi-quadratic – was estimated. Based on the computational experiments, they considered the dynamic average waiting time (DAWT) technique with look-ahead value of one and a linear penalty function the best methods for the unweighted COVERT rule. The impact of lead time estimation method on the performance of both ATC.T and COVERT.T rules was estimated by Vepsalainen and Morton (1988). They compared the standard method (a multiple of operation-specific processing time) with two new methods that use global lead time information. Based on simulations they concluded that both the priority-based lead time estimation and the lead time iteration reduce the tardiness costs and portion of tardy jobs compared to the standard method. Their experiments ranked the ATC rule with lead time iteration as the best dispatch priority rule overall. The COVERT rule with priority-based lead time estimation also performed well in dynamic job shops. Next the dispatching rules that rely on probing in the index calculation are described.

The bottleneck dynamics (BD) heuristic by Morton and Pentico (1993) considers the activity price of an operation as a reflection of the current scheduling decision to the weighted tardiness. It trades off the activity price with total remaining resource usage calculated by multiplying the resource price of the machine with the processing time of the operation instead of the current processing time. Kutanoglu and Sabuncuoglu (1999) explained that the BD heuristic prioritizes jobs with larger activity prices and penalizes jobs with longer processing times on bottleneck machines which presumably have higher resource prices. The exponential early/tardy (EXP-ET) rule, which also incorporates cost-based information, was suggested by Ow and Morton (1989). Also Morton and Ramnath (1992) introduced a modification of the ATC rule called the X-RM heuristic. Whenever a resource is idle this dispatching rule assigns a job which is either available at that time, or will be available in the minimum processing time of any job that is currently available (Akturk and Ozdemir 2001). The multi-factor (MF) rule explicitly uses job-specific information about tardiness cost, processing time, and due date (Chen and Lin 1999). The calculation of expected waiting times indirectly utilizes information about job routings and due to the sequence matrix, there is no need to use adjustable multipliers. One of the main benefits of this rule, according to its developers, is that the true dollar value is exhibited in the unit of priority index.

Raghu and Rajendran (1993) introduced a heuristic, later named the RR rule, for minimizing the mean tardiness of jobs. It consists of three components that are process time, due date or slack, and waiting time for the next operation, which retains the due date information even after a job becomes tardy. The RR rule combines the properties of the SPT and S/RPT rules by using weight factors dependent on the historical utilization level of the machine that is loaded. Additionally, this dispatching rule uses a look-ahead that calculates the expected waiting time of a job at its next operation based on its relative urgency among the jobs in the next queue. The benefit of the rule is its capability to adapt to changes in resource utilization and system congestion using parameters not set *a priori*. Despite the look-ahead feature that helps in reduction of job-specific waiting times, the RR rule can even leave a large number of jobs very tardy especially with tight due dates (Raghu and Rajendran 1993, 311). The last method, Emery's rule, is a two-stage dispatching procedure (Emery 1969). At the first stage, it eliminates less urgent jobs based on six screening criteria. At the second stage, jobs that have survived through all screening criteria are given a priority index using a weighted priority function, and then the job with the highest value will be assigned to an idle machine. This procedure utilizes almost all possible information on jobs and the system, but in a complex way. Possibly due to its iterative structure Emery's rule has not been considered in the many comparative studies conducted in the area of priority scheduling.

3.4 Tools for the Decisions of Order Management

Next the methods designed for other decisions of order management are reviewed. The prior research is abundant, and so the focus is on analyzing the differences among the methods available and on identifying why some of them, if any, perform better than the others.

3.4.1 Order Acceptance Rules

The type of business and competitive situation largely define to what extent a manufacturing company can reject customer orders at times when there is shortage of production capacity or other resources. When the selective acceptance of incoming orders is feasible, companies may apply criteria such as their perception on the importance of customer relationships or the contribution of ordered products to sales. During high seasons, personal relationships between the operative personnel of supplier and customer can also become more significant than the price or profitability of orders under consideration. Yet, more systematic approaches could be applied using some of the formal order acceptance methods developed since the early 1990s.

The decision of order acceptance defines the starting point for capacity planning and scheduling. Therefore, the impact of order acceptance rules on shop performance has been tested either with input/output control techniques or scheduling policies. Generally, the research has been motivated by industrial cases leading to testing and use of the policies developed (e.g. Raaymakers *et al.* 2000a). Earlier Philipoom and Fry (1992) observed that a rejection of only a small share of arriving orders can improve the system performance significantly through cost reduction. They concluded on the basis of simulations that their path-based order review is more effective than random rejection or a load-based order review. In the study of Wester *et al.* (1992), their monolithic approach performed best, while hardly any difference was found between the hierarchic approach, i.e. the load-based review in Philipoom and Fry 1992, and the myopic approach (Figure 3-10).

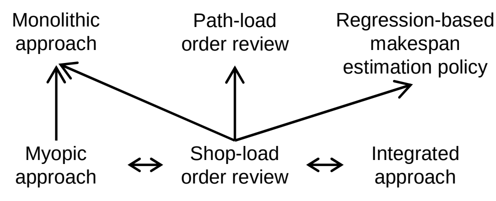

Figure 3-10 Dominance chart of the order acceptance methods according to the results of published studies (each arrow indicates the better method of the two methods linked).

The superiority of the monolithic approach was explained by the selective acceptance mechanism implicitly present in that mechanism. Ten Kate (1994) compared the integrated approach and the hierarchical approach of order acceptance and production scheduling and found the difference between them to be relatively small. In fact, better methods had already been introduced by Philipoom and Fry (1992) and Wester et al. (1992). Raaymakers *et al.* (2000a) compared a new policy, regression-based makespan estimation, to a detailed scheduling policy and a workload policy. They concluded that a detailed scheduling policy was always best in deterministic production situations because complete information on the future status of shop was available. The new policy was superior especially when there was a high demand/capacity ratio and a high product mix variety. The logic of the order acceptance methods, which rely largely on total workload information, and their performance, is summarized in Table 3-5.

Table 3-5 Logic and performance of order acceptance methods.

Method	Description of the method	Performance compared to other methods	Source
Path load order review	Order is rejected, if total workload on machines that are on arriving order's routing is not below predetermined limit.	Outperforms the shop load order review (often statistically better, never worse) and the random review (always statistically better).	Philipoom and Fry (1992)
Shop load order review, Hierarchical approach, Workload-based policy	Order is rejected, if total workload of accepted orders in shop plus work required by new order exceeds predetermined maximum limit for critical work content level of shop or resource. (Requires rescheduling at every order arrival.)	Outperforms random review, but path load order review is better. Not much difference to myopic approach, but monolithic approach performs significantly better. Generally only little difference compared to integrated approach, but performs better in some situations when lead time is large. Worse than makespan estimation policy.	Philipoom and Fry (1992), Wester et al. (1992), Ten Kate (1994), Raaymakers et al. (2000a,b)
Extended myopic approach	Order is rejected, if total workload of accepted orders and new order (including setup times) exceeds certain critical work content level chosen so that no positive maximum lateness occurs. (Applies simple priority scheduling rule.)	Performs slightly worse than monolithic approach in cases with more than 2 product types, if production setups are considered.	Wester et al. (1992)
Monolithic approach	Order is rejected, if lateness occurs in new schedule constructed including all present orders and new order. (Rescheduling at every order arrival.)	Outperforms hierarchic approach and myopic approach, but is only slightly better than extended myopic approach, if setup times are considered.	Wester et al. (1992)
Myopic approach	Order is rejected, if total workload of accepted orders and new order exceeds certain critical work content level chosen so that no positive maximum lateness occurs. (Applies simple priority scheduling rule.)	Not much difference to hierarchic approach but monolithic approach performs significantly better.	Wester et al. (1992)
Integrated approach	Order is rejected, if increase in earliness and tardiness costs due to inclusion of new order is not acceptable. (Rescheduling at every order arrival.)	Little difference compared to hierarchic approach but performs better when load is high and lead time is low.	Ten Kate (1994)
Regression-based makespan estimation policy	Order is rejected, if estimated makespan of order set (calculated on the basis of makespan obtained by simulated annealing and single resource lower bound on makespan based on Carlier 1987) is larger than period length.	This aggregate policy performs clearly better than workload-based policy in terms of capacity utilization when demand/capacity ratio is high and/or product mix variety is high.	Raaymakers et al. (2000a,b)

Wouters (1997) discussed the impact of order acceptance on the total package of planned activities (opportunity costs) and the future level of capacity costs. He explained why it is difficult to evaluate the economic impacts of order acceptance decisions in many practical situations and suggested that information about the contribution margin of the order, the capacity requirement of the order, capacity constraints, costs of additional capacity, cost savings as a results of capacity reduction, commitments, plans, and the remaining idle capacity should be used in the calculation of opportunity and capacity costs. In addition, he argued that managers should consider information about the likelihood and magnitude of error in the calculation of the costs and revenues so that they can estimate the reliability of the economic evaluation of order acceptance decisions (Wouters 1997).

3.4.2 Due Date Assignment Methods

Decision-makers responsible for the OMPPOS process rarely have the luxury of setting the due dates of incoming orders by themselves. It is either the salesmen or the customers who establish order-specific due dates exogenously. Still, there is a segment of scheduling research that focuses on the endogenous due date assignment (Gordon *et al.* 2002a,b) and considers the due date as a decision variable. It is assumed that there is a decision function that involves the setting of due dates and the determination of starting dates for each operation of every order that is about to enter the production system (Cheng and Gupta 1989).

The early methods of due date setting relied strongly on job-specific data (Conway 1965b; Eilon and Chowdhury 1976; Table 3-6). These methods use, for example, information on total processing time (TWK) and number of operations (NOP). Researchers first tested various combinations and extensions of basic methods such as the PPW method, which considers an estimate of job-specific waiting time added to the processing time. Later they started to utilize information about shop status. Weeks (1979), for instance, introduced a method that considers the number of jobs within the system (JIS).

Simple techniques that determine order-specific flow time allowances, based on variables such as slack available and total work content, were compared in Baker and Bertrand (1981), Seidmann and Smith (1981), Kanet (1982), and Panwalkar *et al.* (1982). It was found that if due dates are tight, the due date assignment method is not significant. If due dates are loose, the workload-dependent form of the slack method (SLK) gives the best results. In the intermediate situations the TWK method with the EDD priority rule works well if due dates are workload-dependent. Bertrand (1983) further explored the impact of workload-dependent due dates on job shop performance and concluded that a due date setting method that uses time-phased workload and capacity information can contribute significantly by decreasing the standard deviation of lateness.

Table 3-6 Logic and performance of due date assignment methods.

Method	Description of the time allowance	Performance	First reference
AT+a*PT+ b*JIQ	Proportional to job's total work content and slack that depends on number of jobs waiting on job's routing.	Performs better than TWK and PPW method (Eilon and Chowdhury 1967).	Eilon & Chowdhury 1976
Constant (CON)	Constant time allowance for all jobs.	TWK gives better results (Baker 1984).	Conway 1965b
δ (2-step methodology)	Determined based on a regression approach which consists of two steps.	TWK gives better results only in one setting out of 18 tested (Veral & Mohan 1999).	Veral & Mohan 1999
δ [Sk,t]	Proportional to expected conditional sojourn time of job and part of sojourn time (parameterized method).	Outperforms other three due date setting policies (CON, SLK, PROP) tested (Wein 1991).	Wein 1991
E [Sk,t]	Proportional to conditional sojourn time of job (its total time in system if cμ rule is being used, conditioned on arriving job's class and system state at arrival time).	Outperforms other three due date setting policies (CON, SLK, PROP) tested (Wein 1991).	Wein 1991
Jobs in queue (JIQ)	Proportional to job's total work content and all work center queue on job's routing.	Performs significantly better than rules that use only job-specific characteristics (Ragatz and Mabert 1984).	Ragatz and Mabert 1984
Jobs in system (JIS)	Proportional to job's total work content and general congestion level of shop.	Perfoms poorly compared to JIQ, WIQ and RMR. Yet, outperforms TWK, NOP, TWK+NOP & WEEKS in mean tardiness regardless of dispatching rule (SPT, FCFS, SLK) (Ragatz and Mabert 1984).	Ragatz and Mabert 1984
NOP+TWK+ additional flow time allowance rule	Proportional to job's total work content, slack proportional to job's number of operations, and additional flowtime allowance, which is determined during loading of job's operations based on available machine capacity.	Due date assignment system using time-phase workload and capacity information can contribute significantly to decreasing standard deviation of lateness (Bertrand 1983).	Bertrand 1983
Number of operations (NOP)	Proportional to job's number of operations.	TWK gives better results (Kanet 1982, Baker 1984).	Conway 1965b
Probabilistic cost based method	Determined by estimated flow time and slack factor.		Kaplan and Unal (1993)
Processing plus wait (PPW)	Proportional to job's processing time and expected waiting time.	TWK gives better results (Kanet 1982, Baker 1984).	Kanet 1982
Proposed dynamic due date setting policy (DYN)	Determined based on job's expected waiting time in backlog and job's expected time in shop (conditional to type of job arriving).	Outperforms the CON and PROP policies in variance of job lateness (Wein and Chevalier 1992).	Wein and Chevalier 1992
Regression-based method for assembly shops (REG)	Regression equation (coefficients determined in a pilot run of 1000 jobs) considers both time along job's critical path and number of queuing jobs at all machines when job arrives.	Major improvements in due date-oriented performance measures versus TWKCP method, also if mix of arriving BOM structures varies (Smith *et al.* 1995).	Smith *et al.* 1995
Response mapping rule (RMR)	Sets due-date based on response surface mapping procedures that are used to identify important independent variables and to estimate various functional rule equations.	Provides only marginal improvement over policies such as WIQ and JIQ that use only aggregate information on jobs and shop (Ragatz and Mabert 1984).	Ragatz and Mabert 1984
Sequential rule (SEQ)	Ranks families using next family rule in effect (excluding current family) and depending on position of arriving job determines due date offset based on number of switches required.	Performs best in reducing flow time in systems with family setups (Russell and Philipoom 1989).	Philipoom et al.1989
Slack (SLK)	Equal waiting time or slack for all jobs.	TWK gives better results (Baker 1984).	-
Total work (TWK)	Proportional to job's total work content.	Results in better performance than CON and NOP (Conway 1965). Superior in mean tardiness and usually also in the share of tardy jobs and conditional mean tardiness compared to NOP and PPW (Kanet 1982). Outperforms CON, SLK, PPW and NOP (Baker 1984).	Baker and Bertrand 1981
Total work on critical path (TWKCP)	Total processing time on the longest path of operations in the BOM.	Regression-based method performs better (Smith *et al.* 1995).	Smith *et al.* 1995
Unconstrained capacity assignment rule (TWK+NOP)	Proportional to job's total work content and slack determined based on job's number of operations.	This type of method using time-phase workload and capacity information can contribute significantly to decreasing standard deviation of lateness (Bertrand 1983).	Bertrand 1983
Weeks' jobs in system (WEEKS)	Proportional to number of jobs in system.	Perfoms poorly compared to JIQ, WIQ, RMR, JIS, TWK, NOP and TWK+NOP in all measures (stdev of lateness, mean absolute missed due dates & mean tardiness) regardless of dispatching rule used (SPT, FCFS, SLK) (Ragatz and Mabert 1984).	Ragatz and Mabert 1984
Work in queue (WIQ)	Proportional to job's total work content and all work in workcenter queue on job's routing.	Performs significantly better than rules that use only job characteristics (Ragatz and Mabert 1984).	Ragatz and Mabert 1984
Workload-adjusted TWK rule	Proportional to job's total work content depending on system workload (a variant of TWK and SLK methods).	Performs better than TWK method of Baker and Bertrand (1981), but choice between this and original TWK depends on penalty function (Ragatz 1989).	Ragatz 1989

AT=arrival time, PT=processing time, WT=waiting time

Later Ragatz and Mabert (1984) compared the methods that use information about the number of jobs in the queue (JIQ) and the total amount of work in the queue (WIQ). Compared to the conventional approaches (TWK, NOP, TWK+NOP), the JIQ and WIQ methods were reported to be superior. Their new method, response mapping rule (RMR), which uses more detailed information about jobs and shop, gave a marginal performance improvement over the JIQ and WIQ techniques. The tests of Ragatz and Mabert (1984) also illustrated that knowledge of work center congestion along a job's routing is more useful than information on the general shop conditions. Cheng and Jiang (1998) tested if the dynamic versions of two due date methods (TWK and PPW) perform better than their static counterparts. They found that the dynamic due date models exhibit better due date performance than their static counterparts by providing more accurate and precise estimation of flow times, and the relative performance of the due date methods is not affected by changes in shop loading. They also concluded that the shop performance is better if the dispatch priority rule used incorporates due date information in controlling the decisions of scheduling. For example, the MOD rule is always better than the SPT rule. They recommended that the dynamic due date models should be used with congruous due date dependent dispatch priority rules to obtain the best missed due date performance.

The prior research has emphasized that the selection of a due date assignment procedure has a significant impact on the appropriate choice of a dispatch priority rule, and vice versa (e.g. Eilon and Chowdhury 1976; Weeks 1979; Baker and Bertrand 1981; Ragatz and Mabert 1984; Ragatz 1989; Wein 1991; Enns 1995; Veral and Mohan 1999; van Ooijen and Bertrand 2001; Veral 2001). Weeks (1979) stated the apparent conclusion that the due date performance of a system is better when the due date information is considered in dispatching decisions. Baker and Bertrand (1981) conducted a study in which three due date setting procedures (TWK, CON, SLK) were tested with five priority index rules (ERD, SPT, EDD, EFT, SLK). They found that the type of due date assignment is meaningful only when due dates are not tight. They also considered a dynamic priority scheme which used the features of the SPT or EDD rule, depending on the due date tightness of the system. They concluded that when due dates are loose, there is no need for sophisticated prioritization as long as due dates are assigned according to the workload-dependent form of the SLK method. In intermediate situations, the workload-dependent due dates (TWK) with the EDD dispatch rule yield especially good performance. The study of Wein (1991) analyzed the problem of simultaneous due date setting and priority sequencing in a multi-class queuing system. He tested five priority index rules (SEPT, EDD, SLACK, SLACK/EPT, MDD) and found that the MDD rule performs better than the other rules in most of the situations tested. The type of due date setting, however, had a larger impact on shop performance than priority sequencing.

Figure 3-11 summarizes the results on the performance of the alternative due date assignment methods in the form of a dominance chart. Each arrow in the figure points to the method that is superior of the two methods compared according to the simulation-based studies reviewed. For example: 1) the total work dependent (TWK) due dates are better than constant (CON) due dates, 2) the due dates determined according to the queue length (JIQ and WIQ) are superior to the TWK due dates, and 3) the due dates calculated on the basis of the RMR method outperform the ones given by the JIQ and WIQ techniques.

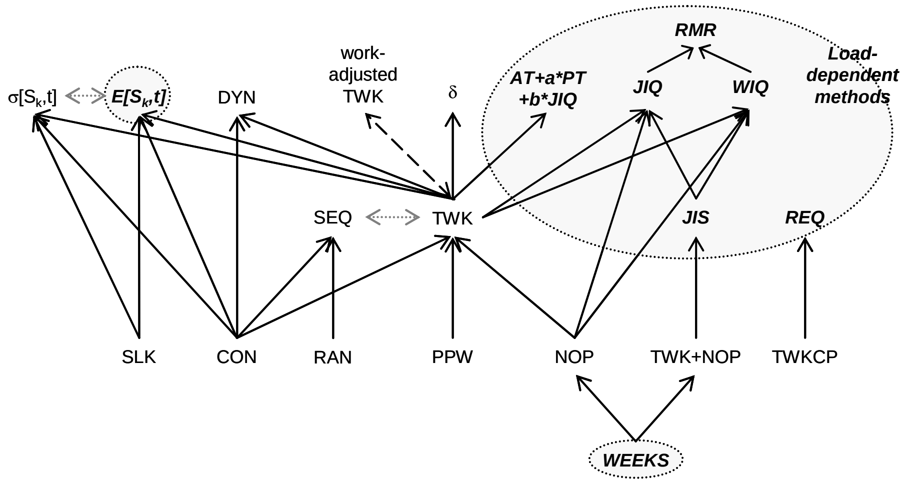

Figure 3-11 Dominance chart of the due date assignment methods according to the results of published studies (abbreviations are defined in Appendix 4).

There are three cases where the relationship between two methods is case-specific. First, the sequential rule (SEQ) performs well compared to the TWK method in reducing flow time in systems with family setups, but in some situations (e.g. low setup level and EDD/T dispatching) the TWK method is better (Russell and Philipoom 1991). Second, the work-adjusted TWK method is better than the original TWK method used by Baker and Bertrand (1981). Ragatz (1989) argued that the selection between it and the original TWK depends on the penalty function. Third, there is virtually no difference between the two methods ($E[S_k,t]$ and $\sigma[S_k,t]$) developed by Wein (1991) regardless of the problem instance and dispatch priority rule used. The methods that consider the shop status perform better than the methods that rely on job-specific characteristics only.

Generalizations implying the best due date setting method cannot be drawn since, for example, the newest techniques introduced in Wein (1991) and in Wein and Chevalier (1992) have not been compared with the methods that performed well in earlier research (Eilon and Chowdhury 1976; Ragatz and Mabert 1984). Overall, the TWK method performs well in various shop conditions, although it makes an interesting assumption concerning the order urgency particularly from the customer perspective. Namely, it assumes that short orders are more urgent than longer orders.

3.4.3 Order Review and Release Procedures

In manufacturing, accepted customer orders are not necessarily released to the shop floor immediately. Instead, a formal order release and review (ORR) system, also called the workload control (WLC) or input/output control, can be applied. An overall analysis by Breithaupt *et al.* (2002) about the strengths and weaknesses of workload control divides its purpose into two categories that are workload norms and workload reduction/balancing (Table 3-7). Generally, different types of order release and review mechanisms control the level of work-in-process by limiting the number of orders released from the pool of backlogged orders. As a result, there is less need to solve ambiguous order urgency issues caused by process capacity bottlenecks and conflicts on the shop floor. A lower WIP inventory also reduces the waiting time of orders within the shop, which results in shorter and typically more predictable flow times. This leads to more transparent operations that are expected to reduce the dependence on sophisticated dispatch priority rules (Bechte 1988; Melnyk and Ragatz 1989; Breithaup *et al.* 2002). This can, nevertheless, be considered either as a benefit or a disadvantage, especially due to the fact that the controlled order release only turns waiting time on the shop floor into waiting time in the backlog (Irastorza and Deane 1974). It can also be argued that it is the task of dispatching to carry orders with heterogeneous response time expectations through the production process while keeping the utilization of resources as high as possible.

Table 3-7 Strengths and weaknesses of the workload control concept (Breithaupt *et al.* 2002, 637).

	Strenghts	Weaknesses
Use of norms	- Shop floor is buffered againts disturbances. - Lead time syndromes are excluded. - The planning interface is facilitated by norms.	- Sensitive to norm setting at low WIP levels. - Anticipation horizon setting is delicate. - Sensitive to the choice of planning period length. - Continuous monitoring of parameters required.
Reducing and balancing workloads	- WIP is kept at a low level. - Transparent shop without rush orders is enabled. - No dependence on dispatch priority rules. - Lead times are made predictable. - Orders can be changed or cancelled late.	- Limited opportunities to choose efficient setup sequences on the shop floor. - Output may drop or pool times may increase when load balancing is insufficient. - Constant norms do not consider natural load flunctuations in job shops.

The impact of a variety of order release mechanisms on shop performance has been tested in several experimental studies since the late 1980s (Table 3-8).

Table 3-8 Logic of order release procedures.

Method	Logic of the release method	Source
Aggregate workload trigger and WINQ selection (AGGWNQ)	Releases new jobs into shop when total uncompleted work in shop falls to 180 hours (selection of released job bases on WINQ).	Melnyk and Ragatz 1989
Backward finite loading (BFL)	Releases jobs at planned start date that is determined by assigning jobs to machines from last operation to first, beginning at job's due date and considering planned loading at each machine.	Ragatz and Mabert 1988
Backward infinite loading (BIL)	Releases jobs on release dates that are calculated by deducting from due date a multiple of processing time and expected waiting time (if calculated release date is before current date, job is released immediately).	Ragatz and Mabert 1988
Bottleneck strategy (BOTTLE), Bottleneck input control	Releases jobs (periodically) when total amount of work at, or in route to, final bottleneck of system is not sufficient to prevent bottleneck from starving.	Roderick *et al.* 1992
CONWIP strategy	Releases jobs into system so that target WIP level, determined by relationship between production rate and WIP, is maintained.	Roderick *et al.* 1992
Critical machine selection (CMS)	Releases job only if queue of first work centre in job's route is empty and there is available operator (release date of job is calculated by deducting from due date multiple of processing time and expected waiting time).	Fredendall and Melnyk 1995
Due date and load-based release (DLR)	Releases jobs periodically from two groups (critical and normal jobs) that are determined based on release dates calculated by deducting from due date a multiple of its processing time and expected waiting time.	Sabuncuoglu and Karapinar 2000
Fixed quantity release strategy (FIXED), UNIFORM	Releases periodically as many jobs as is desired target throughput rate of system.	Roderick *et al.* 1992, Wight 1970
Forward finite loading (FFL, FFIN)	Assigns jobs to machines while taking into account unassigned capacity at each machine so that as machine capacity becomes fully assigned, jobs are assigned capacity further into the future. If forecasted flow time is less than remaining time until due date, release of job to shop may be delayed and flow time recalculated after delay period (for recalculation methods see Wisner 1995).	Kim and Bobrowski 1995
Global input/output strategy (INOUT)	Releases periodically amount of work (not number of jobs) to system, which is specified in advance.	Roderick *et al.* 1992
Immediate release (IMM), Basic model	Releases jobs to shop immediately upon their arrival.	Ragatz and Mabert 1988
Interval release (IR)	Releases jobs periodically according to specified time interval.	Sabuncuoglu and Karapinar 2000
Job trigger shortest slack and work center workload selection (JSSWC)	Releases jobs only if those do not cause released backlog length to exceed maximum specified. In some of versions, orders with negative slack receive special attention (four versions tested).	Hendry and Kingsman 1991
Load-oriented manufacturing control (LOMC)	Periodically reviews orders and with backward scheduling identifies orders whose planned release dates fall within anticipated horizon (=urgent orders), determines load contribution of urgent orders by means of conversion, and loads orders successively from urgent order list until work centres are blocked (loaded until limit specified).	Bechte 1994
Maximum shop load (MSL, MAX, MNJ, WLC), Load-limited approach, Aggregate input control, Control model, Upper bound	Releases jobs (from highest priority job) until either all jobs in backlog file have been released or shop load reaches predetermined maximum level set by management (some versions of this method specify also priority rule).	Ragatz and Mabert 1988, Kanet 1988
Modified infinite loading (MIL, PINF)	Releases jobs on release dates determined based on number of operations of job and number of jobs waiting in queue along job's routing.	Ragatz and Mabert 1988
New order release mechanism (NORM)	Releases orders at rate sufficient to avoid starvation or idle time at bottleneck function, and at same time, to avoid waiting time to be incurred at bottleneck from being too long.	Chan *et al.* 2001
Order release mechanism (ORM)	Ranks orders in backlog giving priority to those orders which can be routed to least loaded station. At each point of release, orders which make up necessary batch size are released for processing (requires solution to MIP).	Lingayat *et al.* 1995
Path-based bottleneck (PPB)	Releases job only if no machine on job's routing will be loaded over managerially-determined capacity threshold.	Philipoom *et al.* 1993
Periodic aggregate loading (PAGG)	Releases jobs periodically, based on aggregate measure (i.e. amount of work in hours).	Sabuncuoglu and Karapinar 2000
Pull from both bottlenecks (PFBB), PFB1, PFB2)	Releases job whenever WIP before each bottleneck is below its respective limit (or when job finishes at first or second bottleneck).	Gilland 2002
Starvation avoidance (SA)	Releases jobs at rate sufficient to avoid starvation or idle time at bottlenecks.	Glassey and Resende 1988
Waiting time (WT)	Releases job if the estimate of its waiting time (assuming that it will be immediately released) is below specified parameter value.	Graves and Milne 1997
Workcenter work load trigger and EDD selection (WCEDD)	Releases new jobs into shop when work in the queue at any work centre drops below 10 hours (selection of released job bases on EDD).	Melnyk and Ragatz 1989
Workload regulating policy (WORKREG, WR)	Releases jobs whenever total work in front of bottleneck is less than predetermined threshold level.	Dessouky and Leachman 1994

The immediate release of orders (IMM) typically performs worse than any delayed release strategy, except in the total time spent within the system (Melnyk and Ragatz 1989). According to Hendry and Wong (1994) the IMM policy works well for decision-makers minimizing the number of late jobs. Its most common alternatives are load-limited approaches defining a maximum workload on the shop floor. Kanet (1988), Melnyk *et al.* (1991) as well as Kim and Bobrowski (1995) ranked the maximum shop load (MSL) policy superior to the IMM policy. Furthermore, Melnyk *et al.* (1994) reminded that to achieve good performance the load-limited approach has to be used with effective planning and variance control.

Many studies have tested the impact of release methods on the shop performance with dispatch priority rules. For instance, Melnyk and Ragatz (1989) assessed the release policies that applied the EDD and WINQ dispatch priority rules, while Hendry and Kingsman (1991) introduced a mechanism with the shortest slack as the job trigger. Hendry and Wong (1994) found that the policy called job trigger shortest slack and workcentre workload selection (JSSWC) outperformed the policies introduced by Melnyk and Ragatz (1989). Later, Fredendall and Melnyk (1995) concluded that a simple priority index rule (FCFS or MOD) or the chosen planning system do not impact the relative performance of the release rules.

Many of the ORR studies aim to identify the best performing technique using, for example, level of work-in-process, lateness, and portion of late jobs as the performance measure. Hence, a dominance chart demonstrating the relative performances of the methods according to prior results reported for the objective functions used in each of the publications can be developed (Figure 3-12). For instance, the bottleneck method (BOTTLE) outperforms three methods: the fixed quantity release strategy (FIXED), the push-based strategy, and the global input/output strategy (INOUT). The CONWIP method (Spearman *et al.* 1990), for one, is superior to the BOTTLE method, and there are other methods that are better than the CONWIP system.

The time-phased methods generally perform better than the load-based ones. Two well performing methods are the new order release mechanism (NORM) and due date and load-based release (DLR). The NORM mechanism releases orders at a rate sufficient, firstly, to avoid starvation or idle times at the bottleneck function of a logistics network, and secondly, to avoid too long waiting times to be incurred at the bottleneck. Its developers Chan *et al.* (2001) rank it superior to several other mechanisms (WT, SA, MSL, WR, CONWIP, UNIF) in the supply chain environment on the basis of their possible performance curve which relates delivery speed of orders to delivery reliability. The principle of the second well-performing mechanism, the DLR method, is to release jobs periodically from two job sets that are called critical and normal jobs (Sabuncuoglu and Karapinar 2000). The urgency of a job is determined by calculating an order-specific release date by deducting a multiple of its processing time and the expected waiting time from its due date. High-priority (or critical) jobs are the ones whose release time is less than current time plus the time fence of planning. Then operation flow times are calculated only for the critical jobs and the load profiles of the workstations are evaluated by adding the processing times of the operations to the corresponding periods' load levels. If the load limits are not exceeded in any of the periods of the load profiles maintained for each workstation, jobs are released either immediately or exactly at their release times. Sabuncuoglu and Karapinar (2000) evaluated the algorithm as good because it does not release jobs too early, i.e. before they are expected to become tardy. The disadvantage of the DLR method is the use of parameters, four in total, that need to be determined based on real or simulated data.

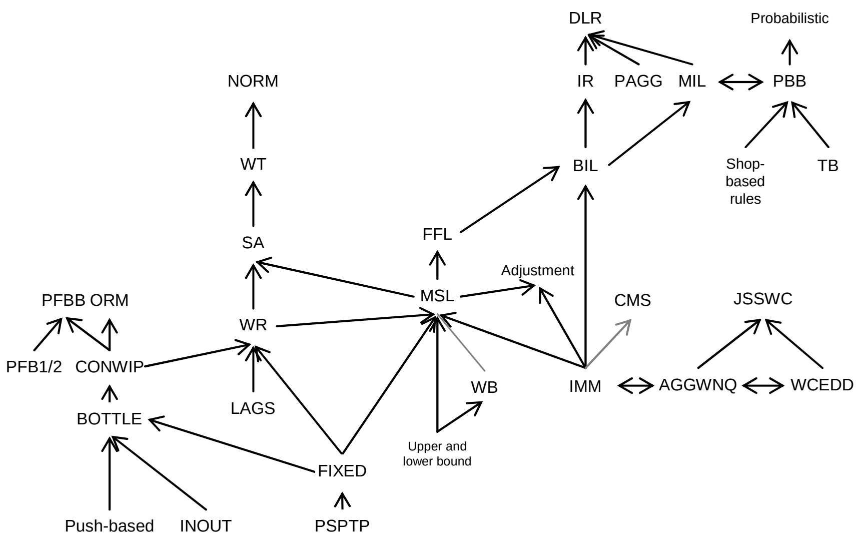

Figure 3-12 Dominance chart of the order release and review rules according to the results of published studies (abbreviations are defined in Appendix 5).

In his review paper Wisner (1995) discussed 26 experimental studies, which had tested seven different order release techniques. He explored, for example, the differences in the test setting (dispatching rules, due date setting, load planning, and shop load) and concluded that in many of the production environments some type of delayed order release strategy was valuable either in monetary or in non-monetary performance measures. Still production systems with high utilization level or tight due dates could benefit from immediate release of jobs (Wisner

1995). Bergamaschi *et al.* (1997) then analyzed 18 different release methods and concluded that they can improve job shop manufacturing as much as JIT practices have improved flow shop production. Their eight-dimensional classification is used here to summarize the logic and performance of 25 different order release mechanisms found in the prior scheduling research. The characteristics of generic methods and their modifications are summarized in Table 3-9 so that each of the 14 modifications marked in grey is listed below its generic form. Based on the analysis the following can be observed:

1. Most of the methods are load-limited but there are also six time-phased release mechanisms.
2. The methods use both continuous and discrete timing conventions.
3. Work quantity is a more common measure of workload than the number of jobs.
4. None of the alternative ways to aggregate workload or to consider the workload over time is dominant among the mechanisms.
5. Most models do not adjust machine capacity during the system's operation or set reference either for the forthcoming periods or for the entire planning horizon.

Table 3-9 Description of order review and release methods according to Bergamaschi *et al.* (1997).

	BFL	LOMC	BIL	DLR	MIL	CMS	BOTTLE	WORKREG	SA	NORM	PBB	CONWIP	PFBB	FIXED	INOUT	FFL	IMM	IR	PAGG	MSL (MAX)	AGGWNQ	WCEDD	JSSWC	ORM	WT
Order release mechanism																									
Load limited	x	x					x	x	x		x	x	x	x	x	x				x	x	x	x	x	
Time-phased			x	x	x	x				x															x
Timing convetion																									
Continuous			x			x		x	x			x	x				x				x	x		x	x
Discrete	x	x		x			x				x			x	x	x		x	x	x			x		
Workload measure																									
Number of jobs					x							x	x	x						x					
Work quantity	x	x	x	x		x	x	x	x		x				x	x			x		x	x	x	x	
Aggregation of workload measure																									
Total shop load												x		x	x				x	x		x			
Bottleneck load							x	x		x			x								x			x	
Load by each workcentre	x	x			x	x			x		x					x							x		
Workload accounting over time																									
Atemporal							x	x	x	x	x	x	x							x	x	x	x		
Time-bucketing	x															x									
Probabilistic		x																							
Workload control																									
Upper bound only	x	x									x					x				x				x	
Lower bound only							x	x	x	x		x	x								x	x			x
Upper and lower bounds																							x		
Workload balancing																									
Capacity planning																									
Active																							x		
Passive	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x
Schedule visibility																									
Limited	x	x	x	x			x	x	x	x	x	x	x	x	x	x				(x)	x	x	x	x	x
Extended																				x					

3.4.4 Interactions of Order Management Decisions

From managerial perspective it is difficult to find arguments for analyzing the different decisions of order management (order acceptance, due date assignment, order release, or order sequencing) in isolation. Nevertheless, there are not many job shop scheduling studies addressing decision-making in the OMPPOS process as a whole. One of the few holistic studies is Wein and Chevalier (1992), which considered due date assignment, order release, and sequencing decisions. They tested different combinations of the policies in a two-machine problem and found that the policy that applies dynamic (DYN) due date setting, workload regulating (WR) job release, and workload balancing (WBAL) sequencing policy outperforms the other conventional policies. They argued that the DYN-WR-WBAL policy can be applied to larger problems if the following two procedures are used: 1) an effective release and priority sequencing policy to minimize the mean work-in-process subject to a constant mean throughput rate, and 2) a procedure for estimating mean conditional sojourn times given the type of entering job, the state of the backlog and shop at the time of arrival as well as the release and sequencing policy from above. Wein and Chevalier (1992) also recommended the following three scheduling principles for practitioners:

1. Base due dates dynamically on the status of the backlog and the shop floor, on the type of arriving jobs, and on the job release and priority scheduling policies used. It can reduce significantly mean flow allowance without increasing a certain level of job tardiness.
2. Regulate the amount of work on the shop floor to be processed by the bottleneck stations. This can significantly reduce the amount of WIP inventory without affecting the throughput rate of the shop.
3. Focus on efficient system performance and ignore due dates when making priority scheduling decisions to get better long-run due date performance.

Wein and Chevalier (1992) argued that these scheduling principles are also applicable to larger production systems than the two-station problem assumed in their analysis.

3.5 Summary and Discussion

In situations where customers decide, based on response time promises and prices, whether or not they place an order, suppliers should be able to quote either the lead time for an agreed price or the price for the requested lead time. To give consistent and reliable lead time and price quotations, manufacturers require a clear logic for managing their OMPPOS process. For production environments with distributed and localized decision-making such coordinative protocols could be developed based on the priority scheduling rules. From managerial viewpoint, the concept of order release and review can also be viewed as an answer to the problem of lead time estimation and order scheduling. Namely, when the amount of work-in-process released to the shop floor is controlled, lead times are easier to standardize and there is less need for order prioritization in dispatching. The use of a workload control mechanism, however, reduces the possibility of manufacturers to respond to customer requirements in delivery times even if priority-based order release were applied. A major benefit of most dispatch priority rules in comparison to the order screening mechanisms is their capability to make a reasonable trade-off between loading efficiency and customer service. In some of the dispatch priority rules this is facilitated by the integrated mechanisms of lead time estimation and order release.

Being aware of the number of alternative rules suggested for order management and scheduling in the priority scheduling literature, it is not a surprise if a decision-maker finds it difficult to select which of the methods to apply. Contradictory findings on the performance of the alternative index-based rules, especially in dispatching decisions, make the task even harder and may encourage the decision-makers to settle with rules of thumb. Keskinocak and Tayur (2004), in fact, stated that based on their review the only unanimous finding of scheduling researchers is that no single due date management policy, i.e. a combination of a due date assignment method and a dispatch priority rule, can perform well in all production environments. Wein and Chevalier (1992) again trivialized the role of scheduling by stating that if production planning is done right, scheduling becomes almost a non-issue. Although partly true, these and similar kinds of evaluations may have influenced the development of order management practices unfavorably.

This chapter discussed the prior scheduling research that has developed and tested index-based scheduling heuristics. The review presented is not an all-inclusive survey of all publications. However, it covers the research comprehensively enough to allow an introduction of dominance charts for each of the key decisions of the OMPPOS process. The dominance charts demonstrate the relative performance of the alternative methods and are designed to help in identifying the most promising candidates for standard open protocols, which define rules of scheduling behavior and conventions of usage as well as the technical specifications and tolerances for the use of priority-based order scheduling in practice. The comparisons of the methods of order acceptance, due date assignment, and order release were done based on the conclusions of the reviewed publications, assuming the performance criteria used in them. The dominance chart of the dispatch priority rules was, nevertheless, built on the basis of the weighted tardiness performance in job shop problems for two reasons. First, weighted tardiness is considered as the most important performance measure, and second, summarizing the relative rankings of all dispatch priority rules in the wide variety of problem instances for all performance measures was found unmanageable.

In order acceptance, according to the review, the monolithic approach, path-load order review, and regression-based makespan estimation policy perform better than the shop-load based review, but there are no results available on their relative ranking. The decision of due date assignment has been studied more, and the summary of the prior research indicates that the load-dependent methods in general perform better than the work content based approaches. The most promising methods include the three approaches proposed in Wein (1991) and in Wein and Chevalier (1992), the work-adjusted TWK method, the 2-step methodology, the composite AT+a*PT+b*JIQ method, and the RMR rule. Additionally, there is a variety of options available for controlling the review and release of customer orders to the shop floor. According to the synthesis of the publications, the most promising methods include the PFBB, ORM, NORM, DLR, JSSWC, and probabilistic approaches.

According to the prior studies reviewed the performance of priority index rules applied in order dispatching depends on the type of decision-making environment, even in job shop scheduling. Based on the review of rule performances in weighted average tardiness four weighted dispatch priority rules (ATC, COVERT, CR+SPT, and S/RPT+SPT) are found to give rather systematically better results than the other rules included in the comparisons. This finding is aligned with the results of Kutanoglu and Sabuncuoglu (1999) who, based on their thorough analysis, concluded that the complex composite rules COVERT and CR+SPT along with the basic form of the BD heuristics are effective for weighted tardiness criterion. It would be justified to take the findings of Kutanoglu and Sabuncuoglu (1999) as the foundation for future research had not more recent comparative study of the weighted (cost-based) priority index rules in standard job shop problems reported conflicting evidence. Jaymohan and Rajendran (2004) reported that the PT+PW, ODD, and SPT rules using the tardiness penalty and/or holding cost as their weight factor are superior to both the ATC.T and COVERT.T rules. Due to these results, a revisitation of priority scheduling in the standard job shop scheduling problems is called for.

The prevalent implications of the review of priority scheduling research generally are linked to the type of analysis and benchmarking done, reporting format used, and consideration of customer perspective in the specification of test settings. Systematic comparisons of alternative dispatch priority rules are a necessity for giving clear recommendations on their use in practice. For consistent comparative analyses, relevant problems and test settings need to be developed and used. The use of normalized performance measures, for one, would provide commensurate results of computational experiments. If the normalized values of the most important performance measures (e.g. weighted mean tardiness, portion of tardy jobs, and work-in-process holding costs), indicating the relevant costs of different approaches were reported instead of raw values, the rankings of alternative rules as well as the comparisons of results across studies and test settings would be easier. In addition to promoting more transparent performance measurement, the normalized results facilitate recognition of any flaws in rule implementations and/or in the assumptions of experiments. Additionally, test problems would be more realistic if customer due dates were randomly assigned, alternative methods for setting due dates were included, and order-specific costs (leading to weighted priority scheduling problems) were considered. Finally, further examination of the rationale and scheduling logic of different rules, now being overshadowed by other preferences of researchers, is encouraged.

Further research is called for to study if there is a robust and well-performing priority index rule or a family of such rules that could form the basis for standard scheduling protocols and the resulting integrated order management. First, consistent comparisons of alternative rules with high informational efficiency are needed to identify robust and well-performing rules. These tests should not include global probing rules that include methods such as lead time iteration that would, to begin with, use uncertain data on, for example, future orders and their processing times, and also, undermine the logic and rationale of standard coordination mechanisms. Local probing methods that include lead time estimation methods can be considered as the candidate rules for open protocols that define not only the rules of scheduling behavior, but also the conventions of usage in different order handling contexts as well as the technical specifications and tolerances for the necessary information and communication.

4 Comparative Analysis of Priority Index Rules

This chapter specifies the methodology of the simulation experiments carried out in this thesis. It first describes the dimensions of job shop scheduling problems solved in the comparisons of the alternative priority index rules, and then specifies how order data and system configurations are generated for the experiments carried out with a tailor-made simulation program. Second, the performance measures applied when analyzing and comparing competing priority index rules are detailed. Moreover, a major part of this chapter is devoted for the reporting and discussion of the results of the large-scale simulations performed in standard job shop environments. In most of the experiments the weighted open job shop scheduling problem is assumed, since hardly any manufacturing company faces a situation where all of its orders would be equally important (i.e. unweighted scheduling problem). The analysis focuses on three cost elements – tardiness penalties, expediting charges, and holdings costs – represented by performance measures that are weighted mean tardiness, portion of tardy jobs, and work-in-process holding costs. Multiple objective functions, some of which are non-linear, make scheduling problems harder. Yet, the problem incidences and objectives considered in this thesis are justified, on one hand, by the traditions of the priority scheduling research, and on the other hand, by the practical concern of manufacturers, which is to keep delivery promises with as low operating costs as possible. This chapter reports extensive comparisons of index-based non-probing priority index rules, and it is wound up by some experiments testing interesting modifications of the best performing look-ahead rules.

4.1 Method of Computational Experiments

This thesis examines the management of customer orders in dynamic production systems. If the relationships that constitute these systems were simple enough, mathematical modeling such as algebra, calculus, or probability theory could be applied to obtain exact information on the problems under very restrictive assumptions (Bose 2002, 257). Job shops are, however, highly complex, and thus valid mathematical models themselves are complex, excluding any possibility of analytical solutions. To gain insights into the relationships among the various components of order management and scheduling process, and especially to predict the performance of different scheduling rules, simulation is used as the modeling approach.

One of the main advantages of simulation is that complex, real-world systems with stochastic elements can be investigated within a long time frame. For this study, it is important that simulation allows us to compare the effects of different operating principles on service reliability as perceived by customers who have got a confirmation for a specific order lead time. Developing a simulation model is, however, typically time-consuming and expensive, and the interpretation of the output data, which gives only estimates of the model's true characteristics for a particular set of input parameters, can be difficult even for deterministic systems (Law and Kelton 2000, 91-93). In order to design and build a simulation model that does not require too extensive amount of coding and complexity and does not result in unacceptably long simulation runs, some aspects of real systems are compromised. In this thesis, a discrete event simulation model is developed, since in production systems state variables describing the system at a particular time relative to the objectives of the study change instantaneously at separated points in time (e.g. Law and Kelton 2000, 3-5; Bose 2002, 263-268). State variables are, for example, the amount of work-in-process inventory, number of tardy jobs, and point of departure from the system for an order.

4.1.1 Simulation Software

A new simulation program was developed for the purposes of this study. This software, called Cosca, is modular in structure. It can be used to analyze the performance of various combinations of scheduling heuristics in a variety of different production system configurations, including flow shops, job shops, or combinations of those. Cosca program can also simulate order management and scheduling policies within integrated supply chains with multiple stages representing different production and transportation activities, although such experiments are not within the scope of this thesis.

The main program is written in Java by a professional developer according to specifications provided by the researcher. Further, alternative decision-making principles employed in the comparative analysis are programmed in Java. The user of the software can configure the test setting, including the specifications of shop layout, resources, customer orders, and decision-making rules, in templates that use XML (http://www.w3.org/XML) and Groovy (http://groovy.codehaus.org) as script programming languages. The simulations are run using J2SE (Java 2 Platform Standard Edition) 5.0 or later (http://java.sun.com/j2se) in a Windows environment. A typical experiment that conducts the simulation of 3,000 jobs for 1,600 times due the size of the experimental design (type of problems and number of replications) can be completed in approximately 4,000 seconds. The type of test setting, for example whether or not an order release mechanism is applied, has an impact on the computation time. Also the type of reporting, i.e. if the results are written into text files or directly into spreadsheet documents, influences the duration of simulation runs.

The test environment is defined by the type and number of resources, customer orders, and their handling and processing on available resources in the form of order routing, i.e., the user gives the parameters for each simulation. In this configuration task, she can utilize standard probability distributions, for example when specifying the properties of customer orders such as arrival times, processing times, and order quantities. The methods used for due date assignment, order release, and dispatching are also user-defined from the selections of rules available. Additionally, multiple reporting formats with different levels of details on processed orders are available. One basic example of the configuration template is exhibited in Appendix 7. In addition Figure 4-1 presents a static class diagram developed using the notation of unified modeling language (UML version 1.3, http://www.uml.org) that describes the main concepts of the simulation program. In the figure, the minus signs (-) refer to private class attributes that are artifacts of the program without any semantic meaning. The static structure of the simulation application program interface (API) that depicts the public methods and attributes as configurable properties is available in Appendix 8.

Our experiments are dynamic job shop problems. Customer orders arrive during the simulation instead of being available when the simulation starts, as in static problems. The processing times and other properties of orders are deterministic, but stochastic elements could be added, for example by including some random breakdowns of machines. The arrival process follows a selected random distribution. In this case, the inter-arrival times of incoming orders are assumed to follow an exponential distribution. In each of the simulation runs the system is loaded continually with orders numbered upon their arrival. Instead of preloading the system a warm-up period, during which performance statistics are not collected unless otherwise stated, is used. To identify when the system generally attains a steady state, some of the shop parameters such as values indicating utilization levels and mean flow times were observed. It was found that job shops studied typically reach the steady-state after 500-750 orders have arrived. This experimental method was used because there are no general guidelines on determining the length of the warm-up interval (Bose 2002, 275).

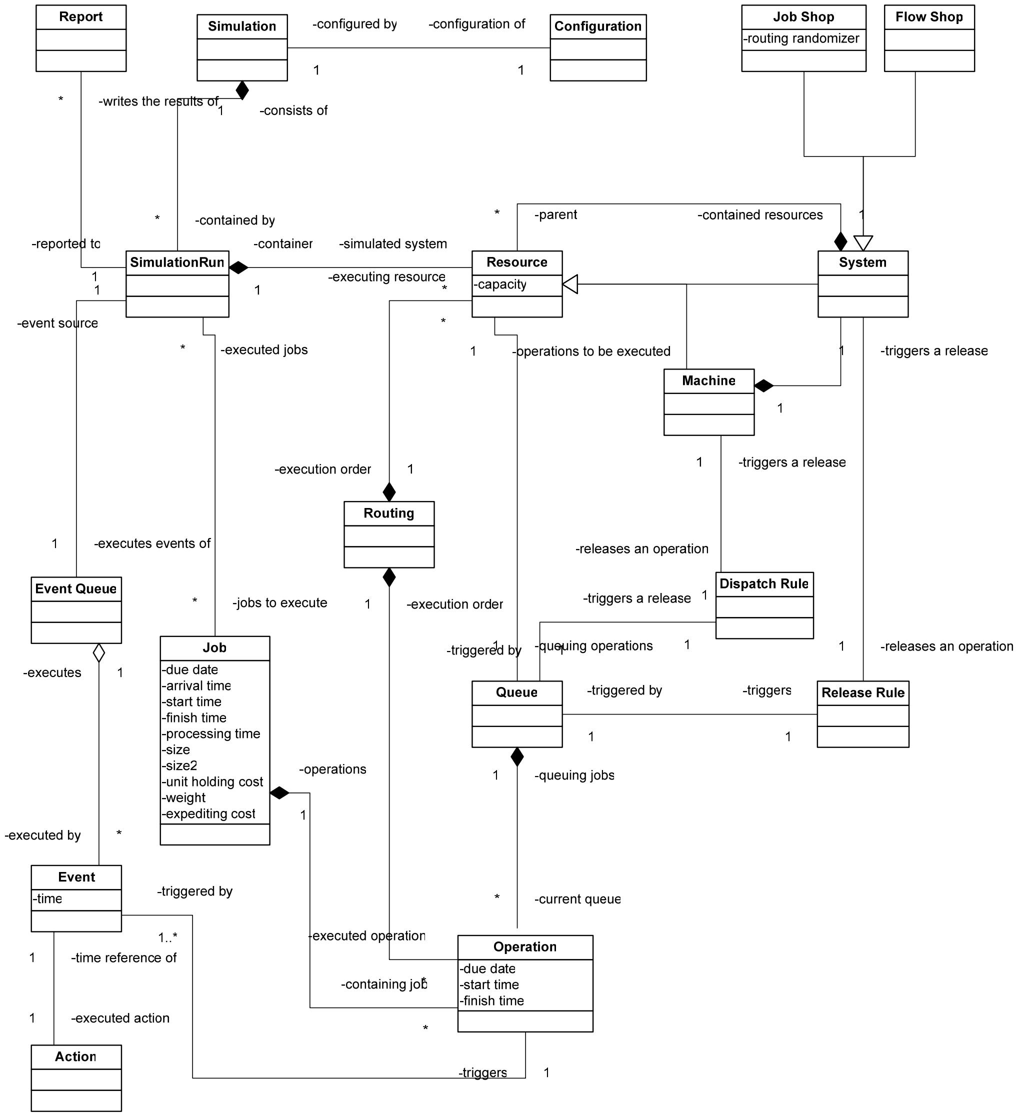

Figure 4-1 Static class diagram of the main concepts of the simulation using the UML notation version 1.3 (Svan 2005).

Typically the total sample size of a job shop simulation, calculated in the number of completed jobs, is over ten thousand jobs (e.g. Conway *et al.* 1967; Blackstone *et al.* 1982). For comparisons of scheduling policies it is, according to Law and Kelton (2000), preferable to conduct a smaller number of replications with longer run lengths. Here the replication method is used instead of the subinterval method or the regenerative method because of its simplicity and ease-of-use (Bose 2002, 275-279). Besides, it has been the most common method in the previous studies analyzing priority scheduling policies. In the experiments, the length of each replication is 2,000 completed orders meaning that output data is collected from the orders numbered 750-2,749 and the shop is loaded until these 2,000 orders are completed. The rundown period is 250 orders.

Law and McComas (1989) argued that common problems in simulation studies are linked, first, to the collection of empirical data, and second, to the determination of input data according to the collected data. If arbitrary probability distributions are used, the output of a single replication of a particular system should not be treated as a true answer. To avoid this pitfall, in this thesis, each problem is replicated 20 times, which allows us to reach appropriate confidence intervals with the determined confidence levels in the comparison of alternative systems. In addition to the adequate number of replications and run length, it is reasonable to apply correlated sampling, i.e., use the same random numbers for the alternatives compared in order to reduce variance (Law and Kelton 2000). Namely, different policies may give different results with different random number streams resulting in different experimental conditions. Altogether the assumptions about the simulation procedure and experimental design are harmonized with the settings used in previous priority scheduling studies.

4.1.2 Output Analysis

The purpose of the experiments, to consistently compare the performance of alternative priority scheduling rules, sets some requirements on the analysis of output data. Clearly comparisons of responses from two alternatives based on a single run only is not an alternative because the superiority of one approach over another cannot be identified by comparing the average values of corresponding performance measures of two alternatives (Law and Kelton 2000, 528). The technique proposed for this type of an analysis is the paired-*t* confidence interval method, which is applicable when the number of replications used in data collection is the same for each alternative (Law and Kelton 2000, 557-559). To compare the performance of more than two alternatives, a confidence-interval approach using the Bonferroni inequality to ensure that the overall confidence level is as preferred can be applied (Law and Kelton 2000, 562). Moreover, all-pairwise comparisons of the expected responses as well as multiple comparisons with the best alternative can be done (Law and Kelton 2000, 564-566). Instead of only comparing the alternative systems, the goal of simulations can be to select the best policy, a subset of best policies, or a predetermined number of best policies using specific methods (Law and Kelton 2000, 567-572).

For the purposes of this thesis, all-pairwise comparisons are appropriate. There are post hoc range tests available for comparing two or more population means after significant differences have been identified. Tukey formula, an analysis of variance procedure, uses the studentized range distribution to make pairwise comparisons between groups. According to Stoline (1981) the Tukey test is among the best methods. Another post hoc test is the stepwise Duncan's multiple range test, which also uses the studentized range statistic. It indicates which pair(s) of means is significantly different based on pairwise comparisons. Both the Tukey and Duncan's tests with a 95% confidence interval are calculated for comparisons and rankings of dispatch priority rules in selected experiments using SPSS version 12.0.1. Due to the complexity and size of the experimental design this study, nevertheless, largely relies on basic graphical and numerical analysis in analyzing the output data.

4.2 Experimental Design

This study seeks time-consistent and rational priority scheduling rules for the design of scheduling protocols. Hence, the experiments are not designed to give comprehensive rankings of the wide variety of scheduling heuristics available. Rather, a relatively large set of priority index rules is tested in relevant job shop environments to recognize which approaches and rules, if any, perform consistently better than others, and are therefore called dominant rules or a family of dominant dispatch priority rules. In addition to these large-scale simulation experiments, also different cases of implementation practices are compared to outline what would constitute an efficient coordination mechanism for MTO production or in hybrid MTO/MTS systems where dispatching decisions are postponed and localized. The following specifications of order data, job shop configurations, and performance measures apply for all experiments discussed in this thesis unless otherwise stated.

4.2.1 Order Data

Order data used consists of 3,000 jobs including the transient period. Orders arrive according to a Poisson process, and their inter-arrival times are derived from an exponential distribution. Mean time between arrivals of orders λ is estimated on the basis of the system load, number of machines, and type of routing within the system considered. It decreases, when more resources are available for processing of orders and when the planned level of resource utilization increases. When the average number of operations per order increases, a lower arrival rate is adequate for reaching the planned level of system load. In the experiments Equation 4-1 turned out to be reliable in determining arrival rates so that realized loads in a steady state are the same as the planned levels of system load.

$$\lambda = \left(\frac{\bar{p}}{x}\right)\left(\frac{m_1 + m_2}{2}\right)\left(\frac{1}{u}\right) \tag{4-1}$$

$\bar{p}$ = average processing time per operation
x = number of machines
m_1 / m_2 = minimum / maximum number of operations per order
u = planned system load

It is assumed that all arriving orders are accepted and immediately released to the shop floor. The use of order review and release mechanisms would, in fact, considerably reduce possibilities to expedite rush orders through the production system when needed. However, as the literature review indicated, formal order release methods are expected to decrease work-in-process inventories as well as the need for order sequencing on shop floor, and therefore their impact on managing due dates and lead times in comparison to some sophisticated dispatch priority rules is assessed in Section 6.1.

Most of the previous studies comparing dispatch priority rules have assumed the total work content (TWK) method for setting order-specific due dates. This assumption is typically justified by referring to prior research reporting the TWK method to be superior in mean flow times compared to other ways of due date assignment, especially the slack and constant methods. Nevertheless, Baker and Bertrand (1982) showed that with high utilization and very high flow time allowance, the slack (RANSLK) procedure gives lower mean tardiness than the TWK method. Further, the results of Ragatz and Mabert (1984) reporting the superiority of other due date setting methods using both job and system information over the TWK method, seem to be neglected in most job shop scheduling studies. Another concern associated with the use of TWK method is linked to the service expectations of customers. In practice, customers define their response time requests on the basis of order size or its processing time requirement only rarely. Customers may, in fact, not even accept suppliers that define their lead time promises and delivery dates based on the total processing times of orders, or alternatively, such a policy could lead to an opportunistic behavior and unnecessary splitting of orders from the customer's side. Owing to the history of priority scheduling research, most of the experiments use more than one due date assignment method. The use of the TWK procedure provides a comparison with earlier studies, the random assignment of due dates (RANSLK) demonstrates an external due date setting, and the constant slack (CONSLK) represents one common practice in industry (Equation 4-2).

$$TWK = r_i + (1+c)\sum_{q=j}^{m_i} p_{iq}$$
$$RANSLK = r_i + \sum_{q=j}^{m_i} p_{iq} + U\left[0, R\bar{p}\right] \qquad (4\text{-}2)$$
$$CONSLK = r_i + \sum_{q=j}^{m_i} p_{iq} + \chi\bar{p}$$

In all of these methods the earliest possible due date depends on the release date and total processing time of an order, i.e., negative slack is not allowed. The TWK procedure returns a multiple of total work, and so automatically allocates more time for longer orders. The multipliers employed are assumed to be 3 and 5 for tight and loose due dates, respectively, similarly as in earlier studies (e.g. Jaymohan and Rajendran 2000a). When the CONSLK method is applied, each order is allocated the same amount of excess time which is calculated on the basis of the average processing time of all orders. The multiplier χ is 6 and 10 for tight and loose due dates, respectively. It should be noted that these multipliers give on average longer flow time allowances than the TWK and RANSLK methods. It is appropriate because in practice lead times are typically long if constant quotations are used. The RANSLK method does not routinely give longer slack for orders requiring more processing than the average. Instead, it assigns due dates over a range of flow allowance that depends on the average processing time of all orders and the level of due date tightness *R*. For loose (tight) due dates *R* is assumed to be on average five (three) times the average order processing time, and so random numbers *U*, representing the multipliers, are generated between 0 and 10 (0 and 6). Previously, Vepsalainen and Morton (1987) used six and three for loose and tight due dates, while Kutanoglu and Sabuncuoglu (1999) used 12, 9, and 6 for loose, medium, and tight due dates, respectively.

Our assumptions on order characteristics, including processing times, sizes, tardiness penalties, holding costs, and the number of operations, are aligned with the assumptions used in earlier simulation studies. Table 4-1 specifies two common test settings used in earlier studies: alternative 1 has primarily been used by Jaymohan and Rajendran (2000a, 2000b, 2004) and alternative 2 has been applied, for instance, by Kutanoglu and Sabuncuoglu (1999) and Lejmi and Sabuncuoglu (2002). The main difference between the two common alternatives linked to the relative difference between tardiness penalties and holding costs, order routings including the average number of operations per job, and due date assignment methods.

Table 4-1 Principles for generating order data in prior simulation-based studies.

		Principles for data generation	
Parameter	**Definition**	**Alternative 1**	**Alternative 2**
r_i	Release date of job *i*	$r_i = a_i$	$r_i = a_i$
p_i	Processing time of job *i*	p_{ij} ~U[1,50]	p_{ij} ~ U[1,30]
m_i	Number of operations for job *i*	m_i ~U[5,9]	m_i ~U[1,10]
w_i	Delay penalty or weight of job *i*	w_i ~U[1,9]	w_i ~U[1,30]
h_i	Earliness penalty or holding cost of job *i*	h_i ~U[1,9]	h_i ~U[1,3]
dd_i	Due date allowance of job *i*	$dd_i = \sum p_{ij} * c$	dd_i ~U[0, 3*$\sum p_{ij}$]

Our experiments assume the following unless otherwise stated. Three alternative policies – no revisits, limited revisits, and revisits without constraints – could be used to determine job-specific routings. No revisits policy refers to systems where each order can be processed on the same machine only once. Limited revisits policy means that a machine can be revisited by an order but two consecutive operations cannot be performed on the same machine. Third policy, revisits without any constraints, does not set any limitations in terms of resources used for processing of an individual order. It illustrates also production processes in which rework of orders is possible. In the experiments limited revisits on resources are allowed (Table 4-2).

Table 4-2 Standard values of parameters used in this study.

Parameter	Value
Order routing	Random, revisits allowed but no consecutive operations on same machine
Number of replications	20
Number of jobs	3000 jobs
Warm-up period	750 jobs
Reporting period (job numbers)	#750 - #2750
Number of machines	10
Machine capacities	Uniform, no bottlenecks
System load (average of all resources)	80 %, 85 %, 90 %, 95 %, 97 %
Number of operations	U[1,10]
Order quantify for holding costs	Fixed (15)
Order size / processing requirements	U[5,25]
Processing times at each machine	Proportionate shop: U[0.33s_i, 0.67s_i], Uniform shop: U[1,31]
Truncation of processing times	max 6*p_{ij}
Weight/tardiness penalty	U[1,31]
Unit holding cost / earliness penalty	U[1,3]
Expediting cost	U[10,100]
Tie-breaker rule	Shortest job first (SPT)
Due date setting method	Random slack with due date range 0-6 (RANSLK 0-6)
Order release method	Immediate (IMM)
Order acceptance policy	All accepted

Each order has a randomly assigned routing through the machines so that the number of operations is determined randomly between 1 and 10. Operation-specific processing times are defined using a probability distribution so that first each order is assigned a size, and then operation-specific processing times are derived from a uniform distribution. The range of values derived at randomly depends on the shop type (uniform or proportionate shop). Total holding and delay costs are determined on the basis of order quantity and cost data, which are also drawn from a uniform distribution. The following order management principles are assumed: all orders are accepted, orders are released immediately, due dates are tight and determined using the RANSLK method, and in ties the shortest order is chosen for processing. All data is presumed to be accurate, except in Section 5.1 testing the effects of errors in the estimates of processing times and tardiness penalties. Besides estimation errors, the simulation program allows for example the specification of additional order characteristics such as order type specific lead time expectations and costs.

4.2.2 Job Shop Environment

To gain permanent coordination benefits in order management and scheduling, an individual manufacturing company should be prepared to adopt an open scheduling protocol without any pressure from its customers or other supply chain partners. Thus, at this stage the analysis focuses on dynamic production systems with classic assumptions used in priority scheduling research. An inter-organizational perspective is still inherently present in the experiments since order management and scheduling decisions always concern at least two players.

To provide results comparable with earlier research a job shop with 10 machines that are continuously available without any parallel machines are assumed. Two different production systems called uniform and proportionate (e.g. Vepsalainen and Morton 1987; Anderson and Nyirenda 1990) are tested. In a uniform shop, job sizes are assumed to be constant and processing times are to be drawn from a uniform distribution. In a proportionate shop, operation-specific processing times are linked to order size so that they correlate and are almost proportionate over all operations. Alternative production environments include job shops with bottleneck resources, conventional flow shops, and flow-dominant systems with entrance workstations, intermediate workstations and exit workstations (e.g. Vepsalainen and Morton 1987; Barman 1998; Rajendran and Ziegler 2001). To estimate the robustness of different policies the experiments are run for five levels of system load representing low (80%), medium (85% and 90%), and high (95% and 97%) utilization. The utilization levels of individual machines can vary from the pre-specified average system load since natural process bottlenecks will develop due to randomness. Table 4-3 summarizes the factorial design for the weighted job shop settings reported in Section 4.3, which consists of 120 problem instances solved with 17 priority index rules.

Table 4-3 Design parameters in the weighted tardiness problems.

Design parameter	Number of levels	Levels
Shop type	2	Uniform, Proportionate
Number of operations per job	2	1-10 operations, 5-9 operations
Due date assignment method	3	Random slack, Total work content, Constant slack
Due date tightness	2	Loose, Tight
Utilization level	5	Low (80 %), Medium (85% & 90%), High (95% & 97%)
Dispatching rules	17	15 weighted rules (ATC, COVERT, CR+SPT, FDD, LWKR, MAXPEN, MF, MOD, ODD, PT+PW, SLK, S/OPN, SPT, S/RPT and S/RPT+SPT) and 2 benchmarks (FCFS and EDD)

Additional assumptions on orders, resources, and processes are needed to define a scheduling problem that is manageable. This study keeps to the assumptions used in earlier scheduling research (e.g. Baker 1974; Miyazaki 1981; Ramasesh 1990):

- An order is ready for processing upon its arrival, and so it can be immediately released to the shop floor.
- The routing of each order is assigned individually.
- There are no alternative routings, which reflects low level of manufacturing flexibility.
- Changeover times are included in processing times.
- Changeover times are sequence-independent, i.e. processing times do not change depending on the sequence of orders and products.
- An order moves directly to the next stage upon completion of one stage, and there are no transfer times between two consecutive stages.
- Each resource processes only one order at a time.
- An operation may not be started before all its predecessors are finished.
- There is no preemption, i.e., the processing of an order cannot be interrupted once started.
- There is no variation in the work rate of the resources.
- Orders are processed without any disruptions such as rework.
- There are no breakdowns or maintenance, i.e. each machine is continuously available for production.
- There are no limiting resources (such as material shortage) other than the machines.
- Queue lengths are not limited, for example due to limited work-in-process storage capacity.
- Orders are independent of each other.
- Orders cannot be divided (no lot splitting).
- There is randomness in order arrivals but the average arrival rate does not change over time as in the experiments of Lejmi and Sabuncuoglu (2002).

This thesis assumes that order-specific cost data, which includes tardiness penalties, expediting charges, and holding costs, are indicators of customer importance, order urgency and order profit. Based on prior research it also could have been assumed that actual processing times coincide with estimated values (Miyazaki 1981; Elvers and Taube 1983b).

4.2.3 Performance Measures

Performance measures used in selecting best dispatch priority rules should correlate with the primary objective of production defined by management, since based on prior research the rankings of dispatching rules depend to some extent on the test environment. Different types of rules perform well under different conditions, and so the efficiency and relative performance of dispatching rules should not be determined on the basis of a single performance measure. Another justification for using multiple measures is that some indicators, such as number of tardy jobs and maximum tardiness are risky as stand-alone measures due to their non-linearity and resulting instability.

Priority scheduling research commonly uses time-based measures such as the flow-time of jobs, portion of tardy jobs, and tardiness of jobs as determinants of performance. The indicators used are typically mean, variance, and maximum values of the measures. In real-life, the strengthening global competition, most manufacturers have to satisfy given service promises as cost-efficiently as possible. This means that both time- and cost-based measures such as mean flow time and weighted tardiness need to be considered. Like Jaymohan and Rajendran (2004), this thesis assumes that today the focus of manufacturing companies is on satisfying customers. Since customers have varying degrees of importance, it is practical to assign a customer importance index derived on the basis of relevant costs (job-specific tardiness penalties, holding costs, and/or expediting charges) that can be incorporated in dispatching rules and performance measures. As a result, minimization of total costs, especially tardiness penalties, is considered as the primary objective of scheduling.

This study focuses on analyzing weighted mean tardiness, tardy jobs, and holding costs to provide comparability with previous simulation-based studies, to stress the most important objectives, and to avoid reporting of unnecessary details (Table 4-4). The portion of tardy jobs is an important normalized measure, since it defines the service level. The work-in-process (WIP) measure calculates the cost of holding orders from the start of their first operation to the completion of last operation. If only WIP holding costs were measured earliness would be rewarded. Thus, also the values of work-in-system (WIS) holding costs are calculated. Nevertheless, it is not a relevant measure if customers accept early shipments.

Table 4-4 Selected standard and normalized performance measures (Vepsalainen & Morton 1987).

Measure	Definition	Formula	Normalized value
WT	Weighted tardiness	$\sum_{i=1}^{n} w_i [C_i - d_i]^+$	$\dfrac{\sum_{i=1}^{n} w_i [\max(C_i - d_i)]}{nmpw}$
WL	Weighted lateness	$\sum_{i=1}^{n} w_i (C_i - d_i)$	$\dfrac{\sum_{i=1}^{n} w_i (C_i - d_i)}{nmpw}$
TJ	Tardy jobs	$\sum_{i=1}^{n} \delta(C_i - d_i)$	$\dfrac{\sum_{i=1}^{n} \delta(C_i - d_i)}{n}$
WIP	Work-in-process holding cost	$\sum_{i=1}^{n} o_i (C_i - a_i)$	$\dfrac{\sum_{i=1}^{n} o_i (C_i - a_i)}{nmpo}$
WIS	Work-in-shop holding cost	$\sum_{i=1}^{n} o_i (\max\{C_i, d_i\} - a_i)$	$\dfrac{\sum_{i=1}^{n} o_i (\max\{C_i, d_i\} - a_i)}{nmpo}$

New notation:
m = average number of operations per job, p = average processing time, w = average delay penalty of the jobs, o = average holding cost per unit time for the jobs, $\delta(x) = 1$, if $x>0$ and 0 otherwise.

For each of the measures (except tardy jobs) unweighted and weighted averages, maximum values, and variances are computed. In addition, the averages of tardiness, lateness, WIS holding costs, and WIP holding costs are normalized, since the raw values of these performance measures depend on problem sizes. The normalization is done using a simple transformation method that considers the number of orders, the average number of operations per order, the average processing time of an operation, and either the average delay penalty or the average holding cost per unit of time.

4.3 Comparisons in Weighted Job Shop Problems

Weighted rules are compared in job shops where both customers' lead time requests and order-specific costs are heterogeneous. A large-scale simulation study is carried out to provide a solid foundation for analyzing what dispatch priority rules work best for non-delay scheduling in these complex production systems. It compares a set of reasonable weighted priority index rules that have been identified from the prior research in a variety of relevant job shop environments.

4.3.1 Priority Index Rules Tested

The performances of priority index rules, 15 in total, that have been suggested for the weighted tardiness problem are re-examined (e.g. Vepsalainen and Morton 1987; Anderson and Nyirenda 1990; Jaymohan and Rajendran 2004). The rules use cost data indicating the importance of orders typically in the form of tardiness penalties (Table 4-5). In addition to these rules two standard benchmark rules, the arrival time based FCFS and the due date based EDD rule, are tested. Moreover, a simple practical rule called MAXPEN.T[9], which seeks to minimize total costs by making dispatching decisions on the basis of order-specific tardiness penalties only, is also tested to give an idea on the performance of common managerial rules.

Table 4-5 Definitions and formulas of weighted priority index rules.

Rule	Definition	Weight	Rank and priority index	
ATC.T	Apparent tardiness cost	Tardiness penalty	max	$\frac{w_i}{p_{ij}}\exp\left(-\max\left(0,\frac{d_i-t-p_{ij}-\sum_{q=j+1}^{m_i}\left(W_{iq}+p_{iq}\right)}{k\bar{p}}\right)\right)$
COVERT.T	Cost over time	Tardiness penalty	max	$\frac{w_i}{p_{ij}}\max\left(0,1-\frac{\max\left(0,d_i-t-\sum_{q=j}^{m_i}p_{iq}\right)}{k\sum_{q=j}^{m_i}W_{iq}}\right)$
CR+SPT.T	Critical ratio + SPT	Tardiness penalty	min	$\frac{p_{ij}}{w_i}\max\left\{\frac{d_i-t}{\sum_{q=j}^{m_i}p_{iq}},1\right\}$
FDD.T	Flow due date	Tardiness penalty	min	$\left(a_i+\sum_{q=1}^{j}p_{iq}-t\right)\times h_i$, if $FDD_{ij}\le t$, $\left(a_i+\sum_{q=1}^{j}p_{iq}-t\right)/h_i$, otherwise.
LWKR.T	Least work remaining	Tardiness penalty	min	$w_i/\sum_{q=j}^{m_i}p_{iq}$
MAXPEN.T	Maximum penalty	Tardiness penalty	max	w_i
MF.T	Multi-factor rule	Tardiness penalty	max	$\frac{w_i}{p_{ij}}\left[W_{iq}-\left(d_i-t-\sum_{q=j}^{m_i}p_{iq}\right)\right]$
MOD.T	Modified due date	Tardiness penalty	min	$\max\left(d_{ij},t+p_{iq}\right)$, where $d_{ij}=a_i+c\sum_{q=1}^{j}p_{iq}$
ODD.T	Operational due date	Tardiness penalty	min	$\left(a_i+c\sum_{q=1}^{j}p_{iq}-t\right)\times w_i$, if $ODD_{ij}\le t$, $\left(a_i+c\sum_{q=1}^{j}p_{iq}-t\right)/w_i$, otherwise.
PT+PW.HT	Processing time plus process wait	Holding cost and tardiness penalty	min	$\left(p_{ij}-\left(t-C_{i,j-1}\right)\right)/h_i$, if $t\le ODD_{ij}$, $\left(p_{ij}-\left(t-C_{i,j-1}\right)\right)/\left(h_i+w_i\right)$, otherwise.
SLK.T	Slack	Tardiness penalty	min	$\left(d_i-t-\sum_{q=j}^{m_i}p_{iq}\right)\times w_i$, if $slack\le 0$, $\left(d_i-t-\sum_{q=j}^{m_i}p_{iq}\right)/w_i$, otherwise.
S/OPN.T	Slack per remaining operation	Tardiness penalty	min	$\frac{w_i\left(d_i-t-\sum_{q=j}^{m_i}p_{iq}\right)}{m_i-j+1}$
SPT.T	Shortest processing time	Tardiness penalty	min	$\frac{w_i}{p_{ij}}$
S/RPT.T	Shortest remaining processing time	Tardiness penalty	min	$\frac{w_i\left(d_i-\sum_{q-j}^{m_i}p_{iq}-t\right)}{\sum_{q=j}^{m_i}p_{iq}}$
S/RPT+SPT.T	Shortest remaining processing time + SPT	Tardiness penalty	min	$\frac{p_{ij}}{w_i}\times\max\left\{\frac{d_i-\sum_{q-j}^{m_i}p_{iq}-t}{\sum_{q=j}^{m_i}p_{iq}},1\right\}$

[9] Rule abbreviations are annexed with T and/or H to indicate if tardiness penalty and/or holding cost are used.

The purpose of this experiment is to recognize priority index rules that make appropriate trade-offs between formal planning and responsiveness. Hence, adaptive probing rules that strive to freeze detailed production schedules, potentially causing nervousness, prepared on the basis of data whose quality may not be high, are excluded. Nevertheless, lead time estimation methods can be used as a part of priority index rules to indirectly consider system load in the approximation of total throughput times. In fact, two of the tested rules, ATC.T and COVERT.T, estimate order's expected waiting time during remaining operations using methods that require a setting of parameters. With both of the rules the priority-based lead time estimation is applied because Vepsalainen and Morton (1988) showed it to outperform the lead time estimation using order-specific work content data. For simplicity, the look-ahead factor *k* used by both rules to indicate the number of critical jobs in the machine queue is assumed to be three (ATC.T) or two (COVERT.T) for all levels of system load. The value of the average processing time at the current machine that is used by the ATC.T rule is estimated on the basis of historical data. Additionally, a simplified version of the MF.T rule which considers the worst case waiting time at the current machine by adding operation-specific processing times of all the orders in the machine queue currently, is included.

Throughout the thesis the results of experiments are reported extensively for a base case, which is a uniform shop of 10 machines. There the number of operations per customer order varies between one and ten and tight due dates are assigned randomly (RANSLK 0-6). Typically two levels of load, 85% and 95%, are considered to represent the behavior of different rules well with medium and high utilization. Thus, detailed statistics are reported only for them. Yet illustrative charts are used to demonstrate the behavior of dispatch priority rules on all tested levels of system load. Differences and similarities of rule performance in other problem instances compared to the base case are discussed in Section 4.3.2.

4.3.2 Performance of Weighted Rules in Uniform Shop

In the base case there are three priority index rules that outperform the other rules in weighted mean tardiness, especially with high system load and tight due dates (Table 4-6). This group consists of ATC.T, COVERT.T, and CR+SPT.T rules (Figure 4-2). With loose due dates and medium (85%) system load also the slack-based rules (SLK.T, S/OPN.T, S/RPT.T, and S/RPT+SPT.T) as well as the MF.T and EDD rules perform well. In other problem instances these rules typically give 0.5-1.5 times, sometimes even four times, higher weighted mean tardiness. There are significant differences among the dispatch priority rules, but the relative differences do not increase concurrently with system load. In weighted maximum tardiness the MF.T and SLK.T rules give excellent results. With medium load the MF.T rule is better, whereas the SLK.T rule gives better results with high system load.

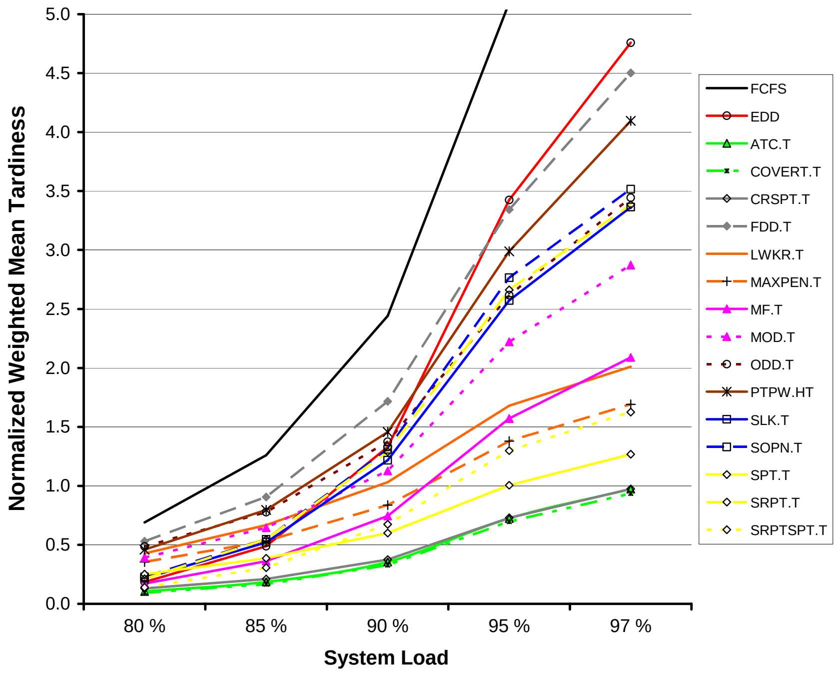

Figure 4-2 Normalized weighted mean tardiness of the priority index rules in a uniform shop when tight due dates are assigned randomly (weighted job shop problem).

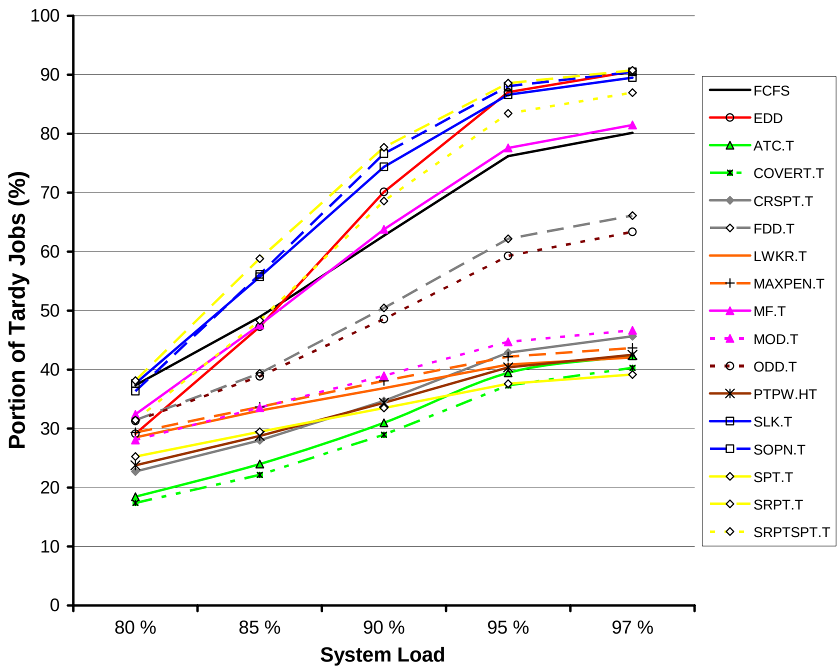

Figure 4-3 Portion of tardy jobs with the priority index rules in a uniform shop when tight due dates are assigned randomly (weighted job shop problem).

In the portion of tardy jobs (TJ%), the ATC.T and COVERT.T rules perform best. As the system load increases the relative performance of processing time based rules improves, and the SPT.T and PT+PW.HT rules work well (Figure 4-3). Besides these rules, the LWKR.T and MAXPEN.T rules are relatively efficient. The due date and slack-based rules, although efficient in minimizing maximum tardiness, fail to complete orders on time.

Table 4-6 Performance of the priority index rules with medium and high system load in a uniform shop when tight and loose due dates are assigned randomly (mWT=mean weighted tardiness, TJ=portion of tardy jobs, mFT=mean flow time, rFT=relative flow time compared to the best performing rule, WIP=work-in-process holding costs, WIS=work-in-system holding costs).

	System load 85%													
	Random slack (range 0-6)							**Random slack** (range 0-10)						
Rule	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**
FCFS	1.26	25697	48.9	367	1.38	4.17	5.26	0.79	24710	31.6	367	1.38	4.17	6.80
EDD	0.49	9397	47.3	325	1.22	3.69	4.49	0.10	5652	14.7	330	1.24	3.76	6.10
ATC.T	0.18	9411	24.0	310	1.16	3.53	4.60	0.05	5105	9.6	324	1.21	3.68	6.14
COVERT.T	0.17	10036	22.1	317	1.19	3.60	4.59	0.05	5203	9.0	322	1.21	3.66	6.15
CR+SPT.T	0.21	11025	28.0	310	1.16	3.53	4.73	0.08	6528	14.8	322	1.21	3.67	6.32
FDD.T	0.90	61658	39.4	313	1.17	3.44	4.82	0.60	57872	25.1	313	1.17	3.44	6.54
LWKR.T	0.67	24343	33.0	349	1.31	3.97	5.66	0.48	22535	23.6	349	1.31	3.97	7.31
MAXPEN.T	0.53	14400	33.7	355	1.33	4.04	5.68	0.38	13864	23.8	355	1.33	4.04	7.33
MF.T	0.36	5691	47.6	341	1.28	3.88	4.59	0.10	3763	19.0	372	1.39	4.23	6.16
MOD.T	0.64	60904	33.5	317	1.19	3.60	5.23	0.45	56959	23.0	317	1.19	3.60	6.91
ODD.T	0.78	61784	38.9	312	1.17	3.55	4.93	0.51	58250	24.9	312	1.17	3.55	6.62
PT+PW.HT	0.80	68806	28.7	267	1.00	3.04	4.80	0.57	65462	18.9	267	1.00	3.04	6.57
SLK.T	0.52	6082	55.7	348	1.31	3.96	4.70	0.11	4351	22.9	350	1.31	3.98	6.17
S/OPN.T	0.55	10308	56.1	346	1.30	3.94	4.62	0.09	5028	17.5	344	1.29	3.92	6.10
SPT.T	0.39	13577	29.4	300	1.12	3.42	5.19	0.27	13138	20.3	300	1.12	3.42	6.92
S/RPT.T	0.55	9863	58.8	349	1.31	3.97	4.62	0.11	4867	21.7	356	1.34	4.05	6.11
S/RPT+SPT.T	0.31	7481	48.3	318	1.19	3.62	4.51	0.07	3798	17.7	309	1.16	3.51	6.11

	System load 95%													
	Random slack (range 0-6)							**Random slack** (range 0-10)						
Rule	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**
FCFS	5.10	59361	76.2	760	1.56	8.64	9.12	3.92	57410	61.9	760	1.56	8.64	9.94
EDD	3.42	26093	87.1	637	1.30	7.24	7.44	1.88	20790	66.4	632	1.29	7.19	7.89
ATC.T	0.72	28927	39.4	578	1.18	6.59	7.11	0.40	24361	25.2	599	1.23	6.83	7.89
COVERT.T	0.70	30650	37.3	588	1.20	6.69	7.12	0.37	24131	22.6	607	1.24	6.91	7.89
CR+SPT.T	0.73	29845	42.9	580	1.19	6.61	7.25	0.42	26372	28.1	600	1.23	6.84	8.22
FDD.T	3.34	212588	62.2	579	1.19	6.26	7.07	2.59	208470	44.1	579	1.19	6.26	8.37
LWKR.T	1.68	53975	40.8	664	1.36	7.56	9.04	1.38	53259	31.5	664	1.36	7.56	10.52
MAXPEN.T	1.38	33118	42.2	714	1.46	8.14	9.55	1.14	32652	32.5	714	1.46	8.14	11.02
MF.T	1.57	13012	77.6	602	1.23	6.86	7.13	0.93	11031	58.9	639	1.31	7.28	8.00
MOD.T	2.22	221459	44.7	603	1.23	6.84	8.16	1.86	216966	33.8	603	1.23	6.84	9.61
ODD.T	2.62	205799	59.3	584	1.19	6.63	7.48	2.03	201885	42.5	584	1.19	6.63	8.77
PT+PW.HT	2.99	233744	40.4	489	1.00	5.55	6.99	2.53	230022	29.5	489	1.00	5.55	8.54
SLK.T	2.57	11539	86.6	675	1.38	7.68	7.92	1.57	9829	70.8	671	1.37	7.63	8.36
S/OPN.T	2.76	24082	88.1	673	1.38	7.65	7.85	1.63	18876	71.2	666	1.36	7.58	8.20
SPT.T	1.00	32486	37.6	567	1.16	6.46	7.99	0.81	31991	28.2	567	1.16	6.46	9.55
S/RPT.T	2.66	25155	88.6	661	1.35	7.53	7.72	1.59	18688	73.9	664	1.36	7.56	8.14
S/RPT+SPT.T	1.30	26836	83.5	609	1.25	6.92	7.19	0.79	20016	64.6	606	1.24	6.90	7.82

Further, processing time based rules succeed in carrying at least short orders through the production system. The PT+PW.HT rule is superior to the other dispatch priority rules in normalized work-in-process holding costs (WIP) at any level of system load (Figure 4-4).

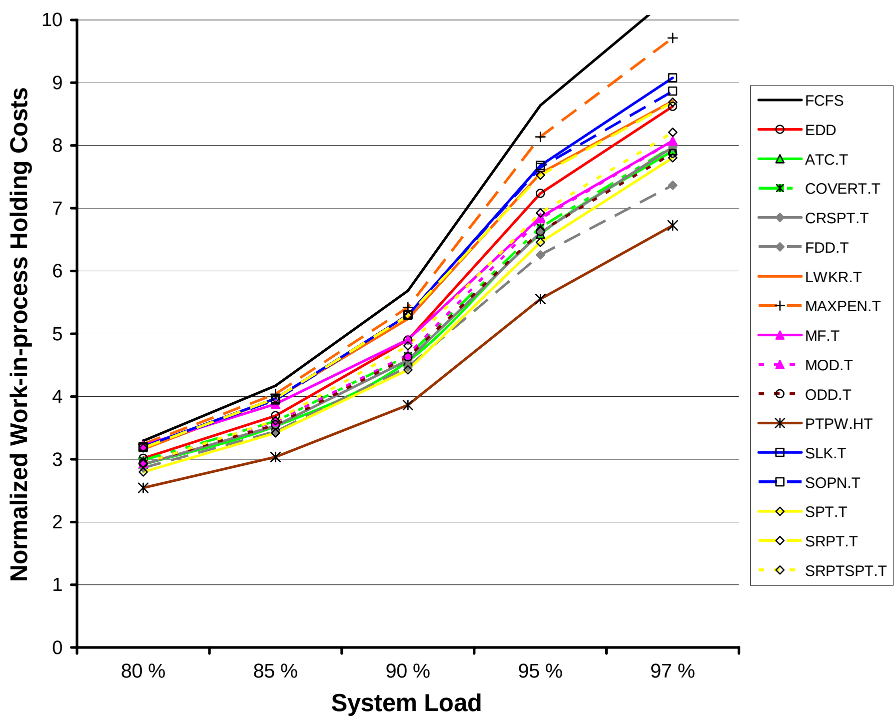

Figure 4-4 Normalized work-in-process holding costs with the priority index rules in a uniform shop when tight due dates are assigned randomly (weighted job shop problem).

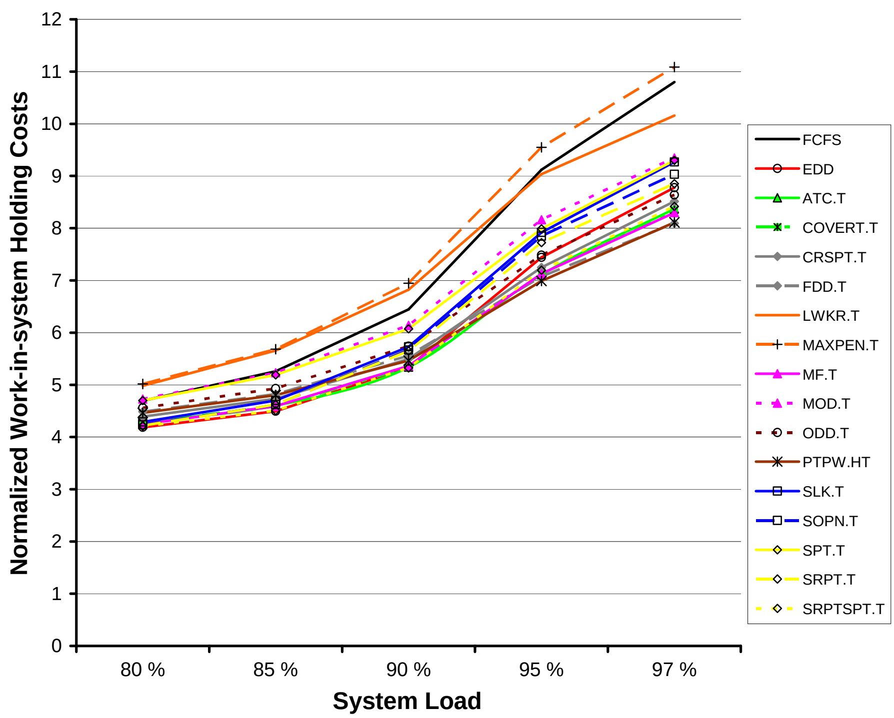

Figure 4-5 Normalized work-in-system holding costs with the priority index rules in a uniform shop when tight due dates are assigned randomly (weighted job shop problem).

In work-in-system holding costs (WIS) the superiority of the PT+PW.HT rule is not as clear, since the ATC.T, COVERT.T, CR+SPT.T, and the FDD.T rules give about the same results also when due dates are tight and the system load is high (Figure 4-5). With medium load, the PT+PW.HT rule is outperformed by many of the tested dispatch priority rules because in this case it does not benefit from early orders canceling out late deliveries. In general, longer flow time allowances, i.e. loose due dates, reduce the portion of tardy jobs and level of tardiness. Higher system load then reduces the performance of all dispatch priority rules due to congestion on shop floor. However, the changes in test settings do not significantly impact the rankings of the tested priority index rules.

Table 4-7 Performance of priority index rules with medium and high system load in a uniform shop when due dates are assigned using the TWK method (number of operations per order 1-10).

	System load 85%													
	Total work content (multiplier 3)							**Total work content** (multiplier 5)						
Rule	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**
FCFS	0.77	20752	47.2	362	1.38	4.12	4.76	0.24	15016	18.8	362	1.38	4.12	6.23
EDD	0.27	7679	29.4	309	1.17	3.51	4.26	0.03	3698	3.8	314	1.20	3.57	6.02
ATC.T	0.08	8420	11.9	294	1.12	3.34	4.40	0.01	3052	1.6	301	1.15	3.42	6.03
COVERT.T	0.07	8641	9.5	303	1.15	3.45	4.40	0.01	2546	1.2	303	1.15	3.44	6.03
CR+SPT.T	0.11	8965	17.3	297	1.13	3.38	4.52	0.03	5285	6.2	308	1.17	3.50	6.16
FDD.T	0.54	49870	29.5	310	1.18	3.41	4.47	0.26	44778	11.6	310	1.18	3.41	6.22
LWKR.T	0.34	19843	20.6	338	1.29	3.84	5.17	0.19	16417	11.5	338	1.29	3.84	6.79
MAXPEN.T	0.36	13174	26.4	347	1.32	3.94	5.37	0.22	12022	16.5	347	1.32	3.94	6.99
MF.T	0.22	5309	33.6	337	1.28	3.83	4.38	0.03	2740	6.2	376	1.43	4.28	6.04
MOD.T	0.42	54174	23.7	310	1.18	3.53	4.89	0.24	49131	12.5	310	1.18	3.53	6.56
ODD.T	0.34	45874	23.7	310	1.18	3.52	4.48	0.16	40739	8.5	310	1.18	3.52	6.23
PT+PW.HT	0.47	59806	14.6	263	1.00	2.98	4.45	0.26	54395	6.4	263	1.00	2.98	6.25
SLK.T	0.33	5461	42.3	338	1.29	3.84	4.44	0.02	2316	8.2	334	1.27	3.79	6.04
S/OPN.T	0.35	8504	41.2	333	1.27	3.79	4.36	0.02	2265	3.7	329	1.25	3.74	6.01
SPT.T	0.21	11390	19.0	292	1.11	3.31	4.86	0.12	9920	10.8	292	1.11	3.31	6.59
S/RPT.T	0.35	8572	45.4	336	1.28	3.82	4.36	0.02	2421	7.0	342	1.30	3.89	6.01
S/RPT+SPT.T	0.16	6351	30.7	303	1.15	3.45	4.27	0.01	1414	4.5	289	1.10	3.29	6.01

	System load 95%													
	Total work content (multiplier 3)							**Total work content** (multiplier 5)						
Rule	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**
FCFS	4.46	49380	85.2	732	1.53	8.32	8.44	2.91	42215	66.9	732	1.53	8.32	8.89
EDD	2.97	23275	83.8	601	1.26	6.83	6.96	1.42	18020	54.5	591	1.24	6.71	7.41
ATC.T	0.53	26690	26.9	544	1.14	6.18	6.71	0.26	21103	14.5	549	1.15	6.23	7.38
COVERT.T	0.50	27673	22.3	550	1.15	6.24	6.69	0.23	20338	11.0	563	1.18	6.40	7.41
CR+SPT.T	0.54	27200	31.7	548	1.15	6.22	6.82	0.28	22962	17.7	561	1.17	6.36	7.76
FDD.T	2.85	214767	62.6	569	1.19	6.16	6.57	1.94	208725	35.3	569	1.19	6.16	7.74
LWKR.T	1.21	51072	30.4	639	1.34	7.25	8.27	0.90	48597	20.7	639	1.34	7.25	9.64
MAXPEN.T	1.12	31490	35.9	684	1.43	7.78	8.96	0.88	30551	25.9	684	1.43	7.78	10.38
MF.T	1.33	12050	73.5	575	1.20	6.53	6.68	0.69	10191	47.4	612	1.28	6.96	7.54
MOD.T	1.82	234129	37.4	576	1.20	6.55	7.55	1.45	228546	24.9	576	1.20	6.55	8.92
ODD.T	1.98	224548	57.1	568	1.19	6.46	6.82	1.36	218851	29.8	568	1.19	6.46	8.01
PT+PW.HT	2.48	251528	28.9	478	1.00	5.44	6.44	1.95	244254	17.0	478	1.00	5.44	7.91
SLK.T	2.26	11308	84.5	641	1.34	7.28	7.41	1.21	8945	60.6	631	1.32	7.16	7.79
S/OPN.T	2.43	23143	85.8	633	1.32	7.19	7.29	1.17	16724	57.7	609	1.27	6.92	7.51
SPT.T	0.75	31025	28.7	545	1.14	6.18	7.45	0.57	29925	19.5	545	1.14	6.18	8.97
S/RPT.T	2.34	24426	86.8	623	1.30	7.07	7.17	1.16	16970	61.3	612	1.28	6.96	7.49
S/RPT+SPT.T	1.12	24129	79.2	577	1.21	6.55	6.72	0.56	15626	50.7	562	1.17	6.37	7.25

The results of experiments with due dates that are determined using data on total processing times of orders indicate that a change of the due date setting procedure does not modify the list of best performing rules (Table 4-7). Especially in flow times and holding costs there are only minor changes. TWK-based due dates ease the flow of orders through the system, and so most of the rules produce lower WIP holding costs. In tardiness-based measures, the absolute results of well performing rules are influenced more. Different types of rules perform well when due dates are determined adding a constant slack to order-specific total processing time. If due dates are loose, the slack-based rules as well as the EDD and MF.T rules perform well in weighted mean tardiness and portion of tardy jobs as well as the ATC.T, COVERT.T, and CR+SPT.T rules, especially in non-congested job shop (Table 4-8).

Table 4-8 Performance of priority index rules with medium and high system load in a uniform shop when due dates are assigned inserting a constant slack (number of operations per order 1-10).

	System load 85%													
	Constant slack (6*avg procTime)							**Constant slack** (10*avg procTime)						
Rule	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**
FCFS	0.23	17176	12.5	362	1.38	4.12	7.23	0.02	7333	1.3	362	1.38	4.12	11.04
EDD	0.02	3107	2.6	326	1.24	3.70	7.03	0.00	50	0.0	338	1.29	3.84	11.02
ATC.T	0.01	2563	1.1	317	1.21	3.61	7.04	0.00	0	0.0	320	1.22	3.64	11.02
COVERT.T	0.01	2725	0.9	314	1.19	3.57	7.05	0.00	2	0.0	280	1.06	3.18	11.02
CR+SPT.T	0.02	4754	4.6	321	1.22	3.65	7.16	0.00	1855	1.0	334	1.27	3.79	11.04
FDD.T	0.19	45498	5.9	310	1.18	3.41	7.18	0.07	36914	1.4	310	1.18	3.41	11.08
LWKR.T	0.25	19971	11.9	338	1.29	3.84	7.93	0.13	16404	6.3	338	1.29	3.84	11.59
MAXPEN.T	0.21	12349	12.3	347	1.32	3.94	7.97	0.11	10880	6.6	347	1.32	3.94	11.62
MF.T	0.03	2950	6.2	394	1.50	4.49	7.07	0.00	732	0.2	454	1.73	5.16	11.02
MOD.T	0.23	49470	10.1	310	1.18	3.53	7.58	0.11	40991	4.4	310	1.18	3.53	11.31
ODD.T	0.15	41220	6.5	310	1.18	3.52	7.24	0.06	32711	1.8	310	1.18	3.52	11.11
PT+PW.HT	0.30	55260	6.3	263	1.00	2.98	7.30	0.14	46628	2.4	263	1.00	2.98	11.15
SLK.T	0.03	2597	8.3	344	1.31	3.91	7.06	0.00	151	0.6	343	1.31	3.90	11.02
S/OPN.T	0.02	2234	3.0	342	1.30	3.89	7.02	0.00	12	0.0	352	1.34	4.01	11.02
SPT.T	0.12	10815	8.7	292	1.11	3.31	7.61	0.06	9117	4.4	292	1.11	3.31	11.37
S/RPT.T	0.02	2606	5.8	360	1.37	4.10	7.03	0.00	425	0.4	383	1.46	4.36	11.02
S/RPT+SPT.T	0.01	1767	4.9	293	1.12	3.33	7.03	0.00	106	0.4	290	1.10	3.29	11.02

	System load 95%													
	Constant slack (6*avg procTime)							**Constant slack** (10*avg procTime)						
Rule	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**
FCFS	2.85	46113	51.2	732	1.53	8.32	9.84	1.30	35894	27.7	732	1.53	8.32	12.30
EDD	1.17	16721	46.9	612	1.28	6.95	8.18	0.19	8504	12.6	637	1.33	7.24	11.20
ATC.T	0.22	20087	12.3	579	1.21	6.59	8.23	0.04	7275	3.0	610	1.28	6.94	11.23
COVERT.T	0.22	20033	9.9	596	1.25	6.77	8.30	0.03	7119	2.2	579	1.21	6.58	11.24
CR+SPT.T	0.26	22832	15.7	586	1.22	6.66	8.65	0.09	15289	6.5	635	1.33	7.22	11.69
FDD.T	1.81	210687	26.5	569	1.19	6.16	8.62	1.15	201515	10.1	569	1.19	6.16	12.06
LWKR.T	1.04	51314	20.7	639	1.34	7.25	10.86	0.75	48615	14.1	639	1.34	7.25	14.20
MAXPEN.T	0.85	31159	20.9	684	1.43	7.78	11.30	0.64	30052	14.3	684	1.43	7.78	14.63
MF.T	0.63	9798	42.7	644	1.35	7.33	8.44	0.16	6403	14.4	740	1.55	8.42	11.49
MOD.T	1.43	228756	21.2	576	1.20	6.55	9.93	1.06	219480	13.3	576	1.20	6.55	13.27
ODD.T	1.33	219397	24.2	568	1.19	6.46	8.99	0.89	210266	11.1	568	1.19	6.46	12.34
PT+PW.HT	2.09	248297	16.9	478	1.00	5.44	9.06	1.57	238898	9.9	478	1.00	5.44	12.55
SLK.T	1.09	8933	55.3	652	1.36	7.41	8.64	0.23	5106	21.2	656	1.37	7.45	11.35
S/OPN.T	1.05	15535	51.9	640	1.34	7.28	8.35	0.11	5599	11.7	656	1.37	7.46	11.14
SPT.T	0.58	30458	16.5	545	1.14	6.18	9.98	0.42	28990	11.0	545	1.14	6.18	13.46
S/RPT.T	1.03	16385	55.6	645	1.35	7.34	8.33	0.13	6219	15.6	685	1.43	7.80	11.15
S/RPT+SPT.T	0.52	15883	47.0	578	1.21	6.57	8.17	0.08	5073	13.7	551	1.15	6.26	11.17

It explains why production schedulers may find it reasonable to quote long lead times and apply slack-based rules. Moreover, the results of the experiments display the benefits of the right dispatch priority rule. With medium load and loose due dates, for instance, the ATC.T rule finds a non-tardy schedule, whereas the SPT.T rule leaves over 5% of orders late. Overall, the results show that the use of constant slack in quoting of due dates to customer orders is reasonable if the customers' lead time requests are homogeneous and relatively long. It implies that customers can plan their purchases well in advance and by doing so allow suppliers to select the easiest dispatch priority rule and/or utilize the variability in lead time requests.

4.3.3 Comparative Analysis

Comparisons of the previous results to the problem instances where the production system is a proportionate shop and the number of operations per order varies between five and nine show that there are only limited differences in rule rankings. Some dispatch priority rules perform consistently better than others in both types of job shops. In weighted mean tardiness and portion of tardy jobs the rules are the ATC.T, COVERT.T and CR+SPT.T, whereas in holding costs the processing time-based PT+PW.HT rule outperforms the others. It is counted how often each priority index rule is among the best three rules in weighted average tardiness, in portion of tardy jobs, and in normalized WIP holding costs in all 48 problem instances tested. The 48 problems consist of two shop types, two different number of operations per order, two levels of system loads, three due date setting methods, and two levels of due date tightness.

In normalized weighted mean tardiness, the COVERT.T rule performs best in almost all of the problems (Table 4-9). Only the ATC.T rule outperforms it slightly in a uniform shop when loose due dates are set with the CONSLK method. The ATC.T rule ranks the second best in more than 90% of the problems. It is the CR+SPT.T, S/RPT+SPT.T, or S/OPN.T rule that ranks the third best. The rule rankings show that the S/RPT+SPT.T and S/OPN.T rules succeed when the system load is medium and due dates are set with the CONSLK method.

Table 4-9 Best priority index rules in weighted mean tardiness (figures define how many times each rule produced the lowest weighted mean tardiness in the 48 problems).

	ALL	Shop type		Number of operations		System load		Due date setting			Due date tightness	
Rule		UNIF	PROP	1-10	5-9	85 %	95 %	CON	RANSLK	TWK	Loose	Tight
ATC.T	6	3	3	4	2	10	0	5	0	1	5	1
COVERT.T	46	22	24	22	24	18	24	14	16	16	23	23
EDD	1	1	0	0	1	1	0	1	0	0	1	0
S/OPN.T	3	1	2	1	2	3	0	2	0	1	3	0
S/RPT+SPT.T	1	0	1	1	0	1	0	0	0	1	1	0

When the portion of tardy jobs is the ranking criterion, six different dispatch priority rules rank the best at least once (Table 4-10). The COVERT.T rule is the best except if loose due dates are set by inserting a constant slack. In these problems the ATC.T, EDD, and S/OPN.T rules can also give non-delay schedules with no late customer. In normalized work-in-process holding costs the PT+PW.HT rule is the best rule. The second and third best rules are normally the SPT.T, FDD.T, S/RPT+SPT.T, ATC.T, and COVERT.T rules, but also the CR+SPT.T and ODD.T rules perform well. The flow-time based rules, FDD.T and SPT.T, work well when the shop is congested.

Table 4-10 Best priority index rules in portion of tardy jobs (figures define how many times each rule produced fewest tardy jobs in the 48 problems).

	ALL	Shop type		Number of operations		System load		Due date setting			Due date tightness	
Rule		UNIF	PROP	1-10	5-9	85 %	95 %	CON	RANSLK	TWK	Loose	Tight
ATC.T	4	2	2	2	2	4	0	4	0	0	4	0
COVERT.T	44	23	21	20	24	22	22	14	14	16	21	23
EDD	1	1	0	0	1	1	0	1	0	0	1	0
PTPW.HT	1	0	1	1	0	0	1	0	1	0	0	1
S/OPN.T	2	1	1	0	2	2	0	2	0	0	2	0
SPT.T	1	0	1	1	0	0	1	0	1	0	1	0

For further comparisons the averages of normalized weighted mean tardiness and its 95% confidence interval with the dispatch priority rules are shown in Figure 4-6 for the base case with high system load. Further, it illustrates outliers among the 20 replications, if any. Clearly the ATC.T, COVERT.T, and CR+SPT.T rules as well as the PT+PW.T rule perform better than the other rules consistently. Further investigation of their robustness confirms that these rules minimize weighted mean tardiness regardless of the problem instance.

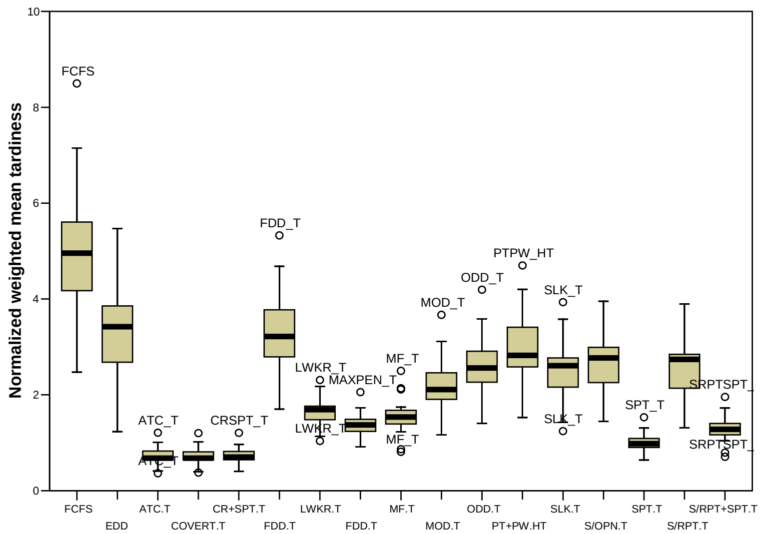

Figure 4-6 95% confidence interval of weighted mean tardiness in the base case when system load is 95% (weighted job shop problem).

On the basis of the portion of tardy jobs the priority index rules can be divided into three groups in the base case (Figure 4-7). The first group includes, besides the ATC.T, COVERT.T, CR+SPT.T, LWKR.T, MAXPEN.T, MOD.T, and PT+PW.HT rules. The second group consists of the FDD.T, MF.T, and ODD.T rules, and the third group includes the poorly performing slack-based rules as well as the benchmarks rules (FCFS and EDD).

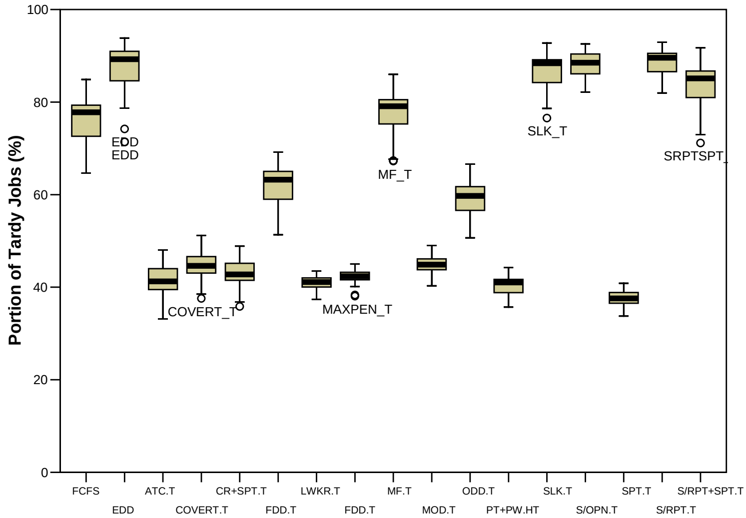

Figure 4-7 95% confidence interval of the portion of tardy jobs in the base case when system load is 95% (weighted job shop problem).

In WIP holding costs differences among the priority index rules are not as noticeable (Figure 4-8). The three best rules are the PT+PW.HT, SPT.T, and FDD.T. However, the ATC.T, COVERT.T, and CR+SPT.T rules as well as the due date based rules work rather well also.

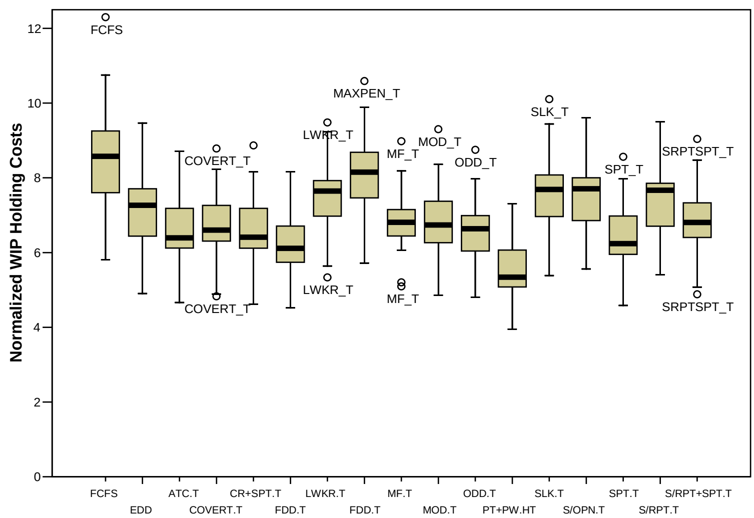

Figure 4-8 95% confidence interval of normalized work-in-process holding costs in the base case when system load is 95% (weighted job shop problem).

Post hoc tests are run for eight dispatch priority rules recognized as the best candidates for scheduling protocols on the basis of the large-scale simulation study. These rules are divided into subsets using Tukey and Duncan's statistics calculated for normalized weighted mean tardiness, portion of tardy jobs, and normalized WIP holding costs (Table 4-11). The dispatch priority rules ranked in the same subset have a comparatively equal mean value of the dependent variable, and different subsets indicate that the mean values of the subsets are different at 95% confidence level. According to Duncan's test the COVERT.T, ATC.T, and CR+SPT.T rules form a subset that is superior to the other rules in weighted mean tardiness. On the basis of WIP holding costs the PT+PW.HT rule is significantly different from the other rules considered.

Table 4-11 Rankings of eight selected priority index rules according to normalized weighted mean tardiness, portion of tardy jobs, and WIP holding costs with Tukey and Duncan's tests in the base case for all replications of all system loads.

Normalized weighted mean tardiness

		Subset for α = .05				
	Rule	**1**	**2**	**3**	**4**	**5**
Tukey-b	COVERT.T	1				
	ATC.T	1				
	CR+SPT.T	1				
	SPT.T	1	2			
	S/RPT.T+SPT.T		2			
	MAXPEN.T		2			
	MOD.T			3		
	PT+PW.HT				4	
Duncan's	COVERT.T	1				
	ATC.T	1				
	CR+SPT.T	1				
	SPT.T		2			
	S/RPT.T+SPT.T		2	3		
	MAXPEN.T			3		
	MOD.T				4	
	PT+PW.HT					5

Portion of tardy jobs

		Subset for α = .05					
	Rule	**1**	**2**	**3**	**4**	**5**	**6**
Tukey-b	COVERT.T	1					
	ATC.T	1	2				
	SPT.T	1	2				
	PT+PW.HT		2	3			
	CR+SPT.T		2	3	4		
	MAXPEN.T			3	4		
	MOD.T				4		
	S/RPT+SPT.T					5	
Duncan's	COVERT.T	1					
	ATC.T	1	2				
	SPT.T		2	3			
	PT+PW.HT		2	3			
	CR+SPT.T			3	4		
	MAXPEN.T				4	5	
	MOD.T					5	
	S/RPT+SPT.T						6

WIP holding costs

		Subset for α = .05		
	Rule	**1**	**2**	**3**
Tukey-b	PT+PW.HT	1		
	SPT.T	1	2	
	ATC.T	1	2	
	CR+SPT.T	1	2	
	COVERT.T	1	2	
	MOD.T	1	2	
	S/RPT+SPT.T		2	
	MAXPEN.T			3
Duncan's	PT+PW.HT	1		
	SPT.T		2	
	ATC.T		2	
	CR+SPT.T		2	
	COVERT.T		2	
	MOD.T		2	
	S/RPT+SPT.T		2	
	MAXPEN.T			3

Table 4-12 shows the results of Duncan's test for medium and high system load separately. With medium load, the group of the COVERT.T, CR+SPT.T, and ATC.T rules forms a subset that is significantly different from the other five subsets in normalized weighted tardiness. With high load, this best subset is extended by the SPT.T rule. If the portion of tardy jobs is the dependent variable, the best subset consists of the COVERT.T and ATC.T rules with medium load. With high load, the COVERT.T rule alone outperforms the other rules. When the normalized WIP holding cost is considered the PT+PW.HT rule is superior to other rules, regardless of the system load. It should be noticed that these types of comparisons, producing rankings of dispatch priority rules, can be performed for all problem instances using the extensive data on key performance statistics collected in the experiments. These results showing that the differences among the different types of priority index rules are statistically significant are presentable examples from the problems considered in the simulations.

Table 4-12 Rankings of eight selected priority index rules according to normalized weighted mean tardiness, portion of tardy jobs, and WIP holding costs with Duncan's test when system load is either 85% or 95% in the base case.

Normalized weighted mean tardiness (Subset for α = .05)

Load	Rule	1	2	3	4	5	6
85%	COVERT.T						
	CR+SPT.T	1					
	ATC.T						
	SPT.T		2				
	S/RPT+SPT.T			3			
	MAXPEN.T						
	MOD.T				4		
	SLK.T						
	S/RPT.T					5	
	PT+PW.HT						6
95%	COVERT.T						
	CR+SPT.T	1					
	ATC.T						
	SPT.T						
	S/RPT+SPT.T		2				
	MAXPEN.T						
	MOD.T			3			
	SLK.T				4		
	S/RPT.T						
	PT+PW.HT					5	

Portion of tardy jobs (Subset for α = .05)

Load	Rule	1	2	3	4	5	6
85%	COVERT.T	1					
	ATC.T						
	CR+SPT.T						
	PT+PW.HT		2				
	SPT.T						
	MOD.T			3			
	MAXPEN.T						
	S/RPT+SPT.T				4		
	SLK.T					5	
	S/RPT.T						6
95%	COVERT.T	1					
	ATC.T						
	CR+SPT.T		2				
	PT+PW.HT			3			
	SPT.T						
	MOD.T				4		
	MAXPEN.T						
	S/RPT+SPT.T					5	
	SLK.T						6
	S/RPT.T						

WIP holding costs (Subset for α = .05)

Load	Rule	1	2	3	4
85%	PT+PW.HT	1			
	SPT.T				
	CR+SPT.T				
	ATC.T		2		
	COVERT.T				
	MOD.T				
	S/RPT+SPT.T				
	S/RPT.T				
	SLK.T			3	
	MAXPEN.T				
95%	PT+PW.HT	1			
	SPT.T				
	CR+SPT.T				
	ATC.T		2		
	COVERT.T				
	MOD.T				
	S/RPT+SPT.T			3	
	S/RPT.T				
	SLK.T				4
	MAXPEN.T				

The comparisons of alternative scheduling rules should consider total costs here primarily tardiness penalties and holding costs. Thus, the performance of the tested priority index rules is illustrated in four representing problem instances in Figure 4-9.

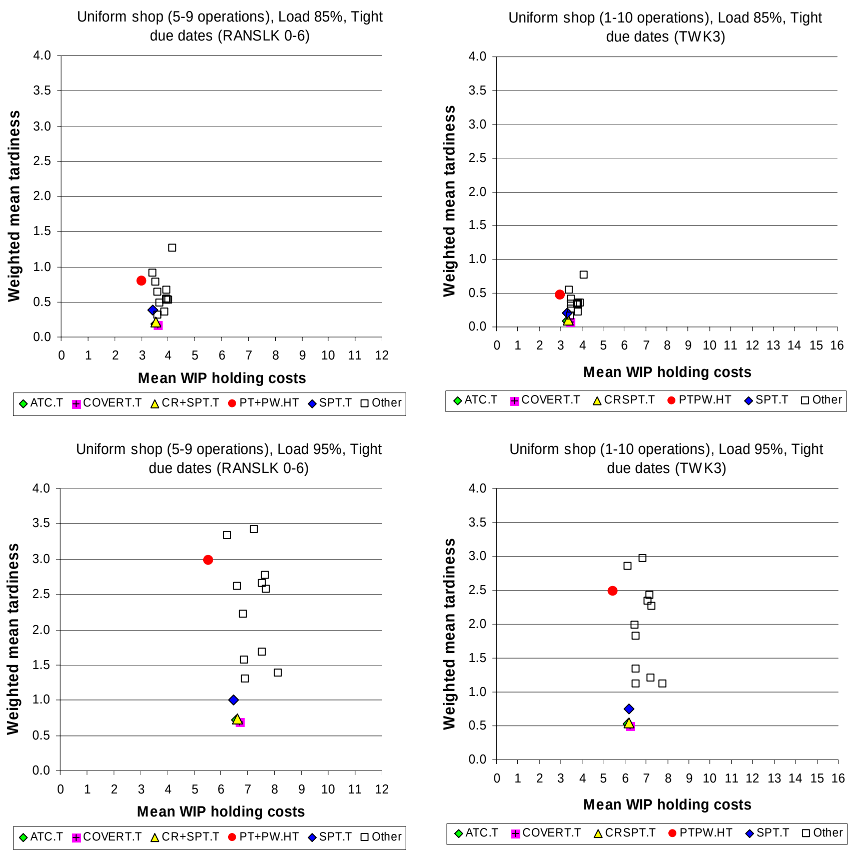

Figure 4-9 Inventory holding and tardiness costs with all tested priority index rules in four selected instances of weighted job shop problems.

It is observed that the ATC.T, COVERT.T, CR+SPT.T, and PT+PW.HT rules form an efficient frontier for both levels of system load. Depending on how meaningful average flow times reflected in holding costs and delivery accuracy indicated by tardiness penalties are for decision-makers, they select the most suitable rule from this group of dominating priority index rules. Usually there are higher costs per time assigned for tardiness, and so the rules that perform well in weighted tardiness are preferred over others. Furthermore, it is easy to see from the normalized values that there is less variability in WIP holding costs than in tardiness penalties which makes the choice of the priority index rule easier. In addition to the holding costs and tardiness penalties discussed companies should also consider one-shot hassle costs caused by each tardy order, for example due to expediting it in production, shipping it via a different route, using another mode of transport, informing the customer, and other administrative costs caused by rescheduling.

4.4 Reviewing Rule Rankings in Unweighted Job Shop Problems

Most of the job shop scheduling research has analyzed the performance of dispatch priority rules without order-specific weights such as tardiness penalties and holding costs. Thus, also the rankings of most promising unweighted rules are reviewed in job shop problems with no differences among orders in terms of urgency or importance. This experiment, in which all customer orders have equal tardiness penalties and holding costs, is a special case of the weighted job shop problem. Besides demonstrating the performance of the priority index rules designed for the weighted problem in this case, the experiment eases the comparison of these results to the findings of prior priority scheduling studies.

4.4.1 Priority Index Rules Tested

Two criteria were used in the selection of priority index rules for this experiment. First, the rule has to produce an order-specific index usable in dispatching decisions, and second, it must have been considered promising in prior research discussed in Chapter 4. As a result, 20 different types of dispatch priority rules are included. The rules are:

- Due date based rules: EDD, CR, FDD, ODD
- Process time based rules: AVPRO, SPT
- Slack based rules: SLK, S/OPN, S/RPT
- Composite rules: AT-RPT, OPSLK/PT;ODD, PT+PW
- Trade-off heuristics: ATC, COVERT, CR+SPT, PT+WINQ, PT+WINQ+SL, RR, S/RPT+SPT

The simplest rules: arrival time based FCFS, due date-based EDD, and processing time based SPT are considered as benchmarks. It should be noted that some of the selected dispatch priority rules, for example COVERT, were considered in the weighted problems already. Here the unweighted versions of these rules are tested. The formulas of the priority index rules not discussed before are presented below (Table 4-13).

Table 4-13 Formulas of selected unweighted priority index rules.

Rule	Definition	Rank and priority index	
AT-RPT	Arrival time-total remaining process time	min	$a_i - \sum_{q=j}^{m_i} p_{iq}$
CR	Critical ratio	min	$\dfrac{d_i - t}{\sum_{q=j}^{m_i} p_{iq}}$
OPSLK/PT; ODD	Proportional operational flow slack; ODD	max	$\max\left\{t + p_{ij} - ODD_{ij};0\right\}/p_{ij}$
PT+WINQ	Process time plus work-in-next-queue	min	$p_{ij} + W_{i,j+1}$
PT+WINQ+SL	Process time plus work-in-next-queue plus slack	min	$p_{ij} + W_{i,j+1} + \left(d_i - t - \sum_{q=j}^{m_i} p_{iq}\right)$
RR	Raghu and Rajendran rule	min	$\dfrac{\left(d_i - \sum_{q-j}^{m_i} p_{iq} - t\right)\exp(-\rho)\times p_{ij}}{\sum_{q-j}^{m_i} p_{iq}} + \exp(\rho)\times p_{ij} + W_{nxt}$

According to the results presented in prior research there are also other dispatching rules such as the truncated versions of SPT and Emery's rule that have produced promising results. They are excluded for two reasons: lack of order-specific priority indices usable by decision-makers and ambiguous logic potentially prohibiting their use in practice. For instance, the screening criteria of Emery's rule would require major assumptions by decision-makers, and thus would not provide a solid foundation for standardization of order scheduling.

The experiments of the unweighted job shop problems are run for the base case only, since the previous set of experiments demonstrated the impact of the number of operations per order and shop type to be only minor on the performance of dispatch priority rules. These two design parameters had practically no implications on the rankings of the rules. However, three different due date assignment methods are considered to illustrate the impact of lead time estimation policy (type of flow allowances and due date tightness) on the power of dispatch priority rules. Otherwise the simulations follow the experimental design defined earlier.

4.4.2 Performance of Unweighted Rules in Uniform Shop

The unweighted versions of the ATC, COVERT, and CR+SPT rules perform well when orders have equal weights also. Generally, in mean tardiness, the best rules are ATC, CR, CR+SPT, PT+WINQ, PT+WINQ+SL, RR, and S/RPT+SPT (Table 4-14). With high system load and tight externally assigned due dates, the ATC, COVERT, and CR+SPT rules outperform the others (Figure 4-10). The iterative RR rule also works well, especially with medium system load. The EDD rule gives low maximum tardiness in any problem instance, as expected. Also the slack-based rules reduce very late orders, a relevant concern in practice.

Table 4-14 Performance of 20 unweighted priority index rules with medium and high system load in a uniform shop when tight due dates are assigned using the TWK, RANSLK, or CONSLK policy (unweighted job shop problem).

	System load 85%														
	TWK (multiplier 3)					**RANSLK** (range 0-6)					**CONSLK** (6*avg procTime)				
Rule	**mT**	**maxT**	**TJ (%)**	**WIP**	**WIS**	**mT**	**maxT**	**TJ (%)**	**WIP**	**WIS**	**mT**	**maxT**	**TJ (%)**	**WIP**	**WIS**
ATC	0.20	1768	13.8	3.25	4.20	0.37	2286	28.4	3.43	4.37	0.01	439	0.9	3.56	7.02
AT-RPT	0.61	2387	32.6	3.56	4.61	0.89	2591	40.1	3.60	4.89	0.18	2140	4.8	3.56	7.19
AVPRO	0.85	4019	18.6	3.43	4.85	1.20	4548	30.8	3.48	5.20	0.61	3949	9.8	3.43	7.62
COVERT	0.13	1354	14.5	3.37	4.13	0.31	1982	32.3	3.50	4.31	0.01	151	0.9	3.42	7.02
CR	0.21	304	44.5	3.58	4.21	0.47	656	55.8	3.74	4.47	0.02	87	8.3	4.04	7.03
CR+SPT	0.22	1754	21.5	3.30	4.22	0.41	2709	34.1	3.42	4.42	0.03	751	3.1	3.71	7.04
EDD	0.26	301	29.4	3.51	4.26	0.49	362	47.3	3.69	4.49	0.02	128	2.6	3.71	7.03
FCFS	0.76	787	47.2	4.12	4.76	1.26	994	48.9	4.17	5.26	0.22	650	12.5	4.12	7.23
FDD	0.51	2316	29.8	3.53	4.51	0.88	2636	40.2	3.57	4.88	0.17	2087	5.1	3.53	7.18
ODD	0.44	2495	25.7	3.52	4.44	0.90	2420	39.7	3.56	4.90	0.18	2292	5.7	3.52	7.19
OPSLKPT;ODD	0.37	2296	22.2	3.22	4.37	0.72	2337	34.9	3.24	4.72	0.14	2064	4.2	3.22	7.15
PT+PW	0.46	2612	14.6	2.99	4.46	0.79	3195	28.7	3.03	4.80	0.29	2453	6.3	2.99	7.31
PT+WINQ	0.34	1719	16.8	2.94	4.34	0.68	1924	30.5	2.99	4.68	0.15	1553	5.4	2.94	7.17
PT+WINQ+SL	0.23	316	25.0	3.02	4.23	0.53	392	44.3	3.20	4.53	0.07	245	7.4	2.98	7.08
RR	0.12	460	15.3	3.06	4.12	0.32	617	33.9	3.27	4.32	0.01	100	1.0	3.34	7.02
SLK	0.43	358	38.0	3.83	4.43	0.67	414	53.1	3.96	4.67	0.03	144	3.9	3.93	7.04
S/OPN	0.31	526	31.8	3.76	4.31	0.57	655	52.3	3.94	4.57	0.00	47	1.0	3.98	7.02
SPT	0.46	2612	14.6	2.99	4.46	0.79	3195	28.7	3.03	4.80	0.29	2453	6.3	2.99	7.31
S/RPT	0.32	537	37.7	3.83	4.32	0.58	674	56.3	3.98	4.58	0.01	74	3.0	4.19	7.02
S/RPT+SPT	0.22	1153	25.2	3.35	4.22	0.41	1877	44.7	3.50	4.41	0.01	135	1.6	3.15	7.02

	System load 95%														
	TWK (multiplier 3)					**RANSLK** (range 0-6)					**CONSLK** (6*avg procTime)				
Rule	**mT**	**maxT**	**TJ (%)**	**WIP**	**WIS**	**mT**	**maxT**	**TJ (%)**	**WIP**	**WIS**	**mT**	**maxT**	**TJ (%)**	**WIP**	**WIS**
ATC	1.97	9956	46.1	5.67	5.97	2.40	9649	56.7	6.07	6.40	0.87	6454	22.1	6.44	7.88
AT-RPT	2.92	8911	64.3	6.53	6.92	3.37	9300	64.3	6.66	7.37	1.73	8681	26.8	6.53	8.74
AVPRO	3.50	13178	28.7	6.38	7.50	4.12	14429	39.5	6.63	8.12	3.04	13054	18.5	6.38	10.05
COVERT	1.89	8511	57.1	5.71	5.89	2.36	8839	67.9	6.12	6.36	0.74	4910	28.3	6.40	7.75
CR	2.68	1638	89.0	6.59	6.68	3.23	2329	87.7	7.02	7.23	0.89	1082	55.3	6.87	7.90
CR+SPT	2.01	9859	56.5	5.75	6.01	2.40	9671	63.5	6.05	6.40	0.92	6911	28.2	6.51	7.94
EDD	2.96	818	83.8	6.84	6.96	3.44	918	87.1	7.23	7.44	1.17	606	46.9	6.95	8.18
FCFS	4.45	1842	85.2	8.33	8.45	5.11	2189	76.2	8.63	9.11	2.84	1747	51.2	8.33	9.85
FDD	2.76	9234	64.3	6.42	6.76	3.35	8702	63.8	6.61	7.35	1.69	9094	26.9	6.42	8.70
ODD	2.73	8921	65.3	6.46	6.73	3.40	9247	63.3	6.64	7.41	1.74	8807	27.6	6.46	8.75
OPSLKPT;ODD	2.28	9401	55.2	5.83	6.28	2.88	8910	56.9	5.97	6.88	1.49	9239	21.3	5.83	8.50
PT+PW	2.44	11329	28.9	5.44	6.44	2.99	10590	40.4	5.55	6.99	2.05	11222	16.9	5.44	9.06
PT+WINQ	1.96	5544	39.6	5.18	5.96	2.57	5865	47.5	5.33	6.57	1.40	5449	20.9	5.18	8.41
PT+WINQ+SL	2.14	847	69.8	5.79	6.14	2.88	1012	76.6	6.32	6.88	1.01	643	40.8	5.58	8.02
RR	2.21	2282	67.7	5.96	6.21	2.84	2998	75.9	6.52	6.85	0.65	967	30.3	5.97	7.66
SLK	3.40	904	83.4	7.27	7.40	3.91	991	86.3	7.68	7.91	1.62	677	51.6	7.42	8.63
S/OPN	3.32	1879	83.8	7.23	7.32	3.87	2218	87.8	7.68	7.87	1.21	1148	45.3	7.25	8.22
SPT	2.44	11329	28.9	5.44	6.44	2.99	10590	40.4	5.55	6.99	2.05	11222	16.9	5.44	9.06
S/RPT	3.18	1960	85.4	7.09	7.18	3.67	2327	88.4	7.48	7.67	1.20	1234	49.3	7.31	8.21
S/RPT+SPT	2.34	8059	78.6	6.17	6.34	2.68	8735	83.6	6.42	6.69	0.91	4705	41.9	6.24	7.92

Processing time based rules (AVPRO, PT+PW, and SPT) cut down the portion of tardy jobs (Figure 4-11). Additionally, the PT+WINQ rule which uses information on workload on an order's next machine gives low mean flow times and low WIP holding costs, regardless of the due date setting method or system load. Moreover, the PT+WINQ+SL rule gives excellent results in maximum tardiness, and is fairly good in mean tardiness and mean flow time also.

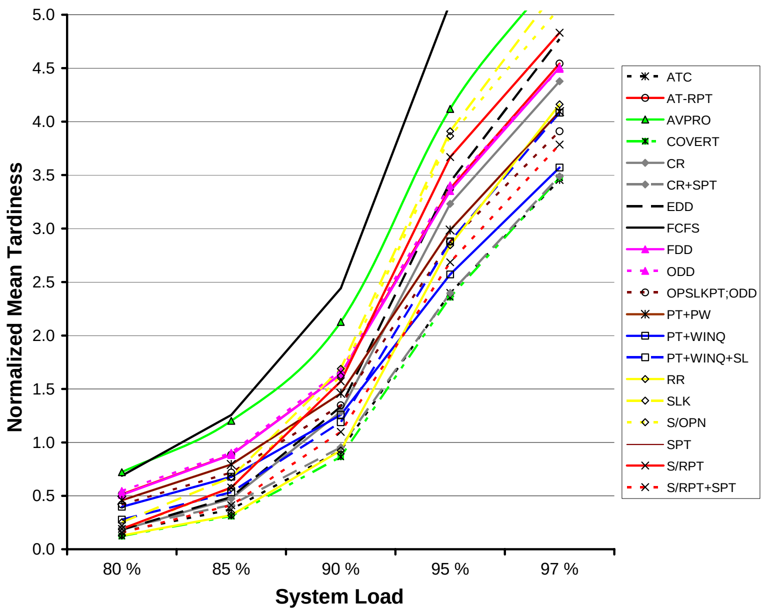

Figure 4-10 Normalized mean tardiness of selected unweighted priority index rules in a uniform shop when tight due dates are assigned randomly (unweighted job shop problem).

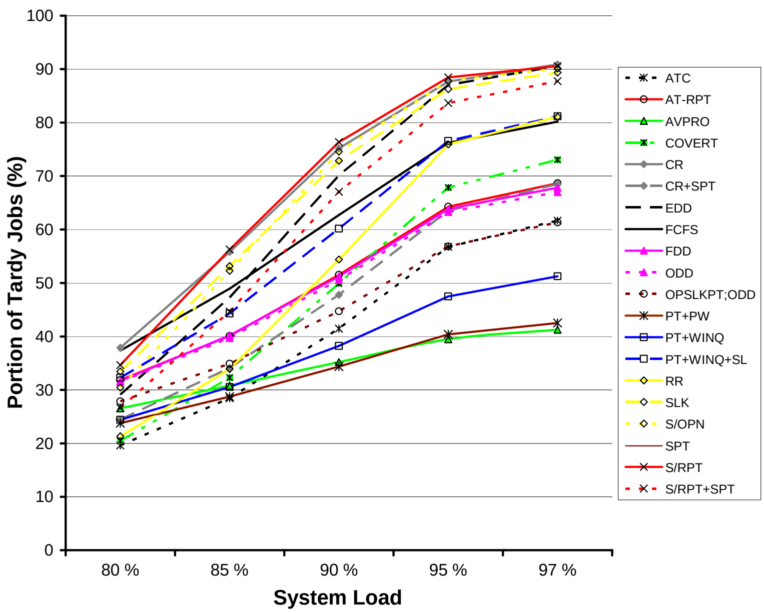

Figure 4-11 Portion of tardy jobs of selected unweighted priority index rules in a uniform shop when tight due dates are assigned randomly (unweighted job shop problem).

In normalized WIP holding costs, the differences among the tested dispatch priority rules are relatively small (Figure 4-12). In addition to the simple processing time based rules the COVERT and PT+WINQ rules work well. It should be noted that in normalized WIS holding costs (Figure 4-13) there is even less variance among the priority rules. This implies that, after all, it may not be that important to focus on the flow of orders through the shop.

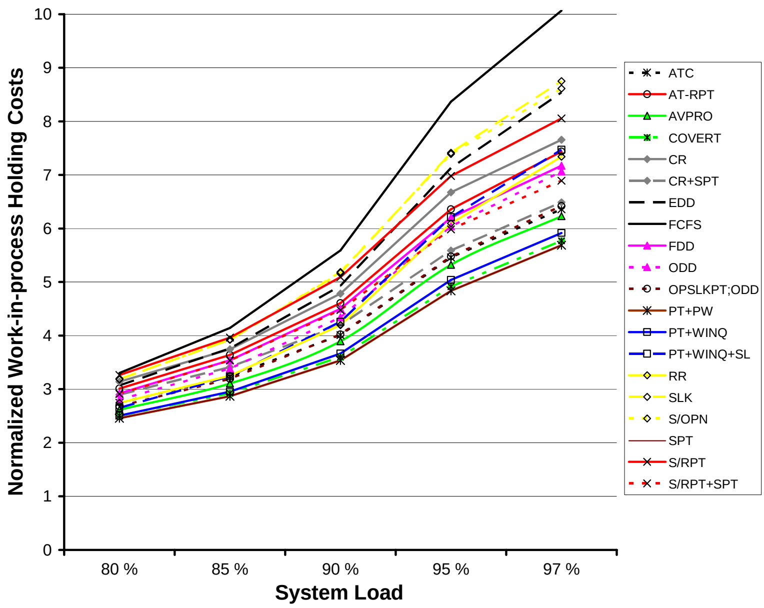

Figure 4-12 Normalized WIP holding costs of unweighted priority index rules in the base case when tight due dates are assigned randomly (unweighted job shop problem).

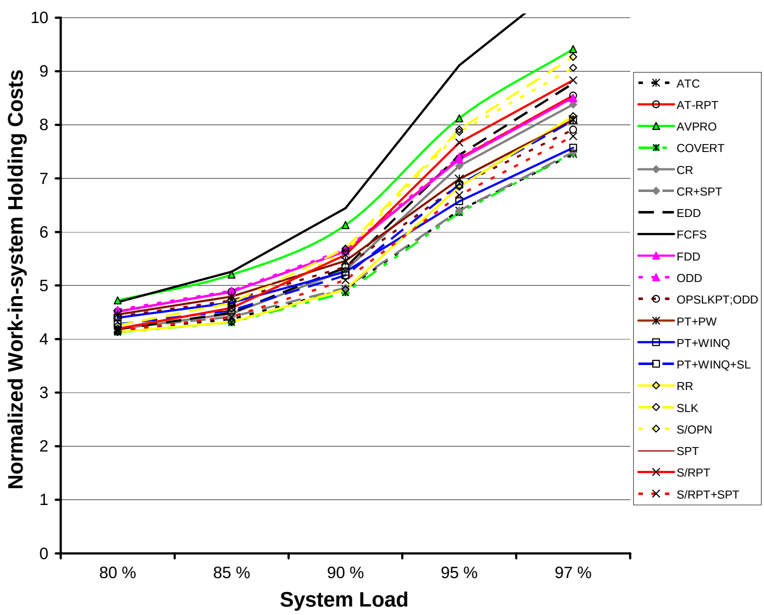

Figure 4-13 Normalized WIS holding costs of unweighted priority index rules in the base case when tight due dates are assigned randomly (unweighted job shop problem).

All in all, this review of unweighted job shop problems shows that the dispatch priority rules that are good in the weighted problems (ATC, COVERT, CR+SPT, and SPT) work robustly in this special case also. The dispatch priority rules that anticipate the future status of jobs and/or system by probing, such as the PT+WINQ and RR rules, also work relatively well. The probing rules, however, set high requirements on data availability and processing. To give an example, solving these job shop problems takes 20 times longer with the RR rule than with the other rules. More importantly the probing rules assume that decision-makers know operation-specific processing times in advance accurately, and for that reason are not considered as candidates for standard protocols in order management and scheduling.

4.5 Modifications of Best Performing Rules

The large-scale simulations discussed above demonstrated that there is a group of priority index rules that performs well and robustly in weighted job shop problems. Thus, it is further examined if the performance of these efficient rules (ATC, COVERT, and CR+SPT) could be improved by minor modifications in the data used.

4.5.1 Test Setting for Different Look-ahead Rules

The following four modifications of three well-performing look-ahead rules (ATC, COVERT, and CR+SPT) are tested in the base case:

1. *.H rules consider order-specific holding costs instead of order-specific tardiness penalties as their weight factor.
2. *.HT rules consider both order-specific holding costs and tardiness penalties as their weight factor.
3. *H.T rules include order-specific holding costs in priority index values by adding the ratio of it and the operation-specific processing time to the index value given by the standard weighted version of the rule.
4. *R.T rules modify the first component, tardiness penalty per operation-specific processing time, by using remaining processing time instead of operation-specific processing time.

The selected rules are tested holding costs as their weight factor since this type of modification has been tested by Jaymohan and Rajendran (2004) for other priority index rules as a way to minimize weighted flow times. The second modification seeks to minimize total costs, and therefore considers both the order-specific delay costs and holding costs. The third modification increases the relative importance of small high-value jobs whose priority index value with the conventional rule versions tends to increase only close to the promised delivery date due to short look-ahead. The expected benefit of the fourth modification is that it gives priority to jobs close to completion, and so should at least reduce the portion of tardy jobs. In total, the experiment includes six versions of the ATC, COVERT and CR+SPT rules because also the standard unweighted and weighted versions are included as benchmarks. The SPT rule and its modifications are included as benchmarks. Further, it should be noted that the ATC and COVERT rules are tested with the same parameter values as in the earlier comparisons.

4.5.2 Results in Weighted Job Shop Problems

Analysis of the rule performances in a uniform shop reveals that by using data on both holding costs and tardiness penalties the rule performances can improve in mean flow time, WIP holding costs, and portion of tardy jobs, especially when the system load is not high (Table 4-15). The addition of the SPT.T component into the considered rules slightly decreases the WIP and WIS holding costs as well as the mean flow times. However, the impact of the SPT.T component on weighted mean tardiness, portion of tardy jobs, and maximum tardiness is often negative, depending on the due date assignment method. Figure 4-14 illustrates the tardiness penalties and holding costs with all rules tested. The illustration of costs implies that, even when modified, the performance of the three best rules – ATC.T, COVERT.T, and CR+SPT.T – is very much alike.

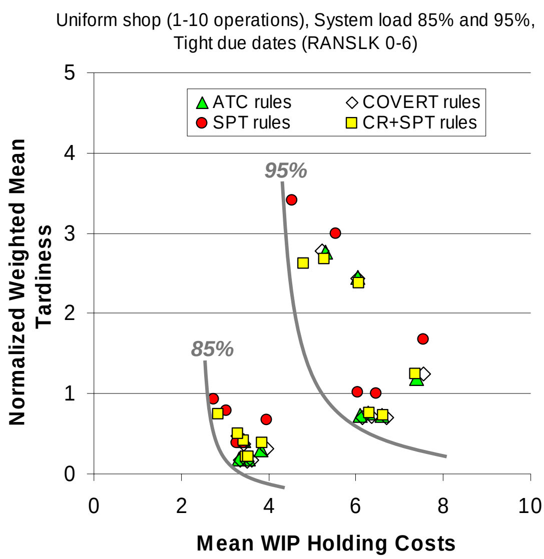

Figure 4-14 Holding and tardiness costs of the tested weighted versions of the ATC, COVERT, CR+SPT, and SPT rules with medium and high system load in a uniform shop.

Table 4-15 Performance of the ATC, COVERT, CR+SPT, and SPT rules with medium and high system load in a uniform shop when tight due dates are assigned using the TWK, RANSLK, or CONSLK policy.

	System load 85%														
	TWK (multiplier 3)					**RANSLK** (range 0-6)					**CONSLK** (6*p)				
Rule	**mWT**	**maxWT**	**TJ (%)**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**WIP**	**WIS**
ATC	0.25	41783	15.7	3.26	4.22	0.42	47179	28.9	3.43	4.42	0.02	15907	1.3	3.60	7.03
ATC.H	0.29	50771	14.5	3.16	4.18	0.49	68182	27.2	3.29	4.35	0.03	13520	1.2	3.56	7.03
ATC.HT	0.08	8953	11.8	3.29	4.32	0.19	11685	24.5	3.47	4.52	0.01	3054	1.0	3.60	7.03
ATC.T	0.08	8420	11.9	3.34	4.40	0.18	9411	24.0	3.53	4.60	0.01	2563	1.1	3.61	7.04
ATCH.T	0.09	9100	11.4	3.19	4.35	0.19	10928	23.7	3.33	4.55	0.01	3220	1.4	3.10	7.05
ATCR.T	0.15	14977	11.3	3.61	4.68	0.31	18567	23.8	3.83	4.93	0.01	4659	0.9	3.68	7.06
COVERT	0.20	35031	16.1	3.29	4.17	0.38	49320	31.3	3.43	4.36	0.01	8568	1.3	3.55	7.02
COVERT.H	0.28	46534	13.7	3.18	4.16	0.48	61448	27.7	3.30	4.32	0.03	13645	1.4	3.54	7.02
COVERT.HT	0.07	8784	9.0	3.36	4.30	0.16	10603	22.5	3.52	4.49	0.01	2744	0.8	3.56	7.04
COVERT.T	0.07	8641	9.5	3.45	4.40	0.17	10036	22.1	3.60	4.59	0.01	2725	0.9	3.57	7.05
COVERTH.T	0.07	9000	8.7	3.20	4.32	0.17	11225	21.9	3.36	4.53	0.01	3746	1.0	3.16	7.05
COVERTR.T	0.16	15888	13.0	3.84	4.67	0.31	18272	25.8	3.97	4.90	0.01	4165	1.2	3.66	7.07
CR+SPT	0.22	37427	21.5	3.30	4.22	0.41	55424	34.1	3.42	4.42	0.03	17168	3.1	3.70	7.04
CR+SPT.H	0.28	50847	19.3	3.18	4.18	0.50	71749	31.6	3.29	4.35	0.04	21190	3.3	3.57	7.04
CR+SPT.HT	0.05	5938	13.6	2.95	4.19	0.21	11738	28.9	3.47	4.60	0.02	4522	4.1	3.64	7.09
CR+SPT.T	0.06	4996	13.6	3.00	4.28	0.21	10978	27.9	3.53	4.73	0.02	4754	4.6	3.65	7.16
CR+SPTH.T	0.48	69772	16.8	2.79	4.42	0.75	80503	28.3	2.85	4.66	0.26	62382	7.1	2.88	7.26
CR+SPTR.T	0.23	17170	15.7	3.72	4.94	0.39	21240	26.4	3.85	5.21	0.07	11901	5.3	3.70	7.44
SPT	0.47	59806	14.6	2.98	4.45	0.80	68806	28.7	3.04	4.80	0.30	55260	6.3	2.98	7.30
SPT.H	0.63	78322	16.7	2.70	4.39	0.93	92343	28.4	2.75	4.66	0.42	74731	7.3	2.70	7.27
SPT.HT	0.20	12681	18.4	3.18	4.75	0.38	14760	29.1	3.27	5.06	0.12	12207	8.3	3.18	7.52
SPT.T	0.21	11390	19.0	3.31	4.86	0.39	13577	29.4	3.42	5.19	0.12	10815	8.7	3.31	7.61
SPTR.T	0.34	19843	20.6	3.84	5.17	0.67	24343	33.0	3.97	5.66	0.25	19971	11.9	3.84	7.93

	System load 95%														
	TWK (multiplier 3)					**RANSLK** (range 0-6)					**CONSLK** (6*p)				
Rule	**mWT**	**maxWT**	**TJ (%)**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**WIP**	**WIS**
ATC	2.13	225506	45.5	5.69	6.03	2.44	216999	54.8	6.04	6.42	1.03	162765	22.5	6.51	7.96
ATC.H	2.38	265250	38.5	5.02	5.45	2.77	261456	48.1	5.31	5.77	1.15	184808	18.9	6.15	7.69
ATC.HT	0.57	32153	29.4	5.89	6.36	0.76	34107	41.4	6.28	6.76	0.25	22213	14.0	6.50	8.06
ATC.T	0.53	26690	26.9	6.18	6.71	0.72	28927	39.4	6.59	7.11	0.22	20087	12.3	6.59	8.23
ATCH.T	0.55	32235	26.8	5.81	6.39	0.73	34482	38.7	6.10	6.75	0.23	22712	11.8	5.93	8.10
ATCR.T	0.90	45464	23.3	6.93	7.60	1.19	47286	35.1	7.38	8.06	0.35	31259	10.0	6.93	8.67
COVERT	2.08	208207	51.4	5.67	5.96	2.43	203500	60.7	6.04	6.38	0.91	145032	26.7	6.44	7.85
COVERT.H	2.36	261961	36.6	4.91	5.40	2.78	273623	48.3	5.24	5.73	1.14	185353	19.0	6.09	7.67
COVERT.HT	0.52	32387	23.7	5.92	6.33	0.72	33131	38.9	6.35	6.76	0.22	22936	10.5	6.55	8.05
COVERT.T	0.50	27673	22.3	6.24	6.69	0.70	30650	37.3	6.69	7.12	0.22	20033	9.9	6.77	8.30
COVERTH.T	0.51	34188	22.0	5.80	6.33	0.70	32945	36.6	6.16	6.74	0.21	22690	9.0	5.98	8.09
COVERTR.T	0.95	44409	30.8	7.14	7.56	1.25	50221	40.8	7.56	8.04	0.38	34391	12.9	7.21	8.72
CR+SPT	2.05	223608	56.5	5.74	6.01	2.38	214484	63.5	6.06	6.40	0.96	170622	28.2	6.51	7.94
CR+SPT.H	2.30	260559	46.2	5.06	5.42	2.67	264047	54.6	5.29	5.72	1.11	192032	23.0	6.10	7.68
CR+SPT.HT	0.31	19218	28.1	4.63	5.31	0.76	35847	45.4	6.31	6.85	0.27	25000	17.6	6.53	8.28
CR+SPT.T	0.30	13824	26.6	4.77	5.55	0.73	29845	42.9	6.61	7.25	0.26	22832	15.7	6.66	8.65
CR+SPTH.T	2.18	250166	28.4	4.63	5.94	2.63	261284	38.6	4.79	6.32	1.70	242551	16.6	4.77	8.56
CR+SPTR.T	0.99	47392	25.4	7.02	7.88	1.24	53344	35.0	7.36	8.36	0.52	41383	12.0	6.91	9.66
SPT	2.48	251528	28.9	5.44	6.44	2.99	233744	40.4	5.55	6.99	2.09	248297	16.9	5.44	9.06
SPT.H	2.92	285058	27.9	4.42	5.79	3.42	291226	37.9	4.53	6.19	2.49	282529	16.2	4.42	8.51
SPT.HT	0.76	36011	28.7	5.82	7.08	1.02	38538	37.6	6.05	7.59	0.60	35538	16.4	5.82	9.64
SPT.T	0.75	31025	28.7	6.18	7.45	1.00	32486	37.6	6.46	7.99	0.58	30458	16.5	6.18	9.98
SPTR.T	1.21	51072	30.4	7.25	8.27	1.68	53975	40.8	7.56	9.04	1.04	51314	20.7	7.25	10.9

The fourth modification of the rules was expected to give priority to soon-to-finish orders. Depending on the problem its use, nevertheless, deteriorates the performance of the ATC and COVERT rules by 50-100% in weighted mean tardiness and maximum tardiness (Figure 4-15). Moreover, mean flow times and related holding costs increase slightly. Yet, it helps the ATC rule to decrease the portion of tardy jobs, while the impact on the COVERT rule is the opposite (Figure 4-16).

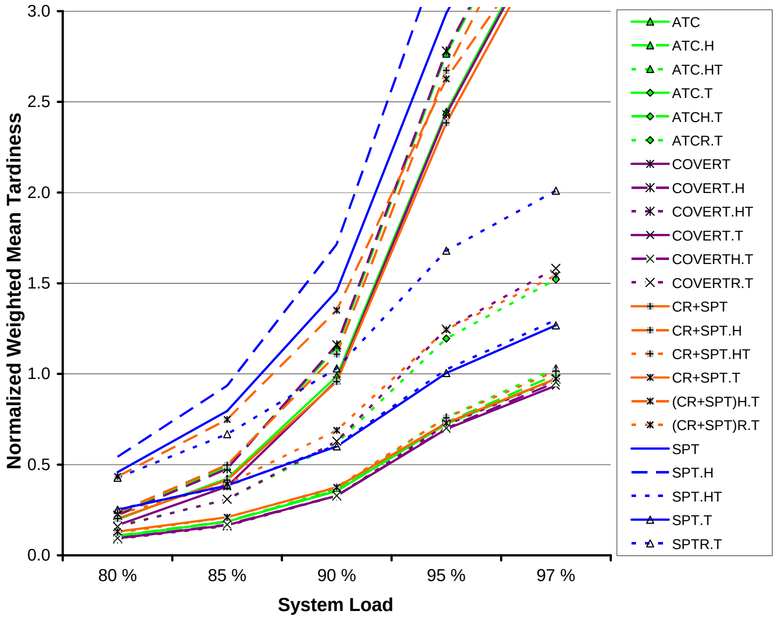

Figure 4-15 Weighted mean tardiness with the different versions of the ATC, COVERT, CR+SPT, and SPT rules in the base case (weighted job shop problem).

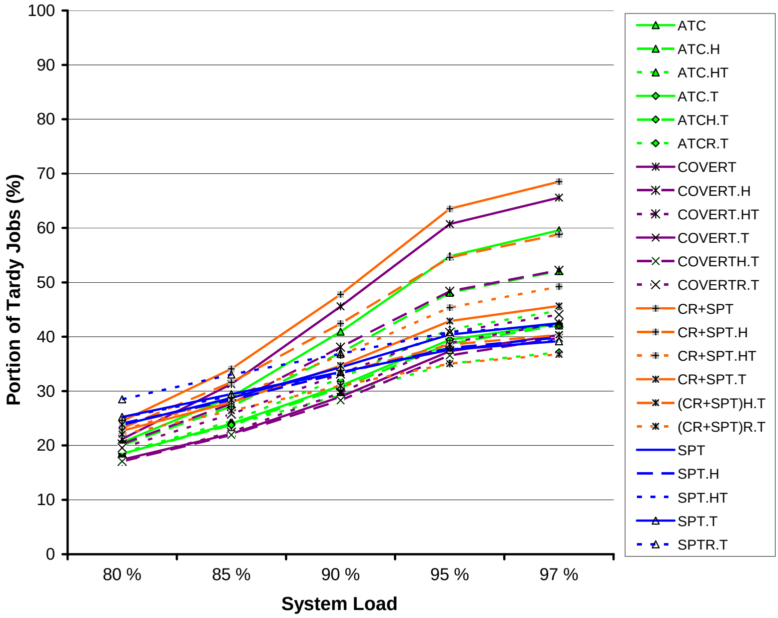

Figure 4-16 Portion of tardy jobs with the different versions of the ATC, COVERT, CR+SPT, and SPT rules in the base case (weighted job shop problem).

The similar performance of the three priority index rules (ATC, COVERT, and CR+SPT) is found to be explained by their underlying logic. Each of the rules uses a look-ahead: the ATC rule has an exponential look-ahead with local slack, while the COVERT and CR+SPT rules rely on a linear global look-ahead (Figure 4-17). The main difference between the COVERT and CR+SPT rules is that the CR+SPT rule does not include an internal release mechanism, and so its priority index values can increase infinitely without any reference point.

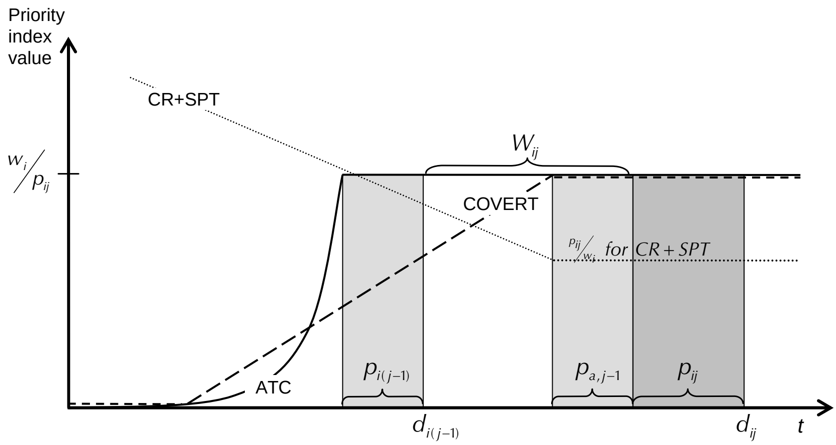

Figure 4-17 Illustration of priority index values for one order with two remaining operations using the three look-ahead rules (ATC.T, COVERT.T, and CR+SPT.T).

Also some other modifications of the look-ahead rules could be tested. For example, the remaining processing time of an order could be weighted depending on the number of remaining operations. The pitfall of such priority index rules can be that they may give too much priority to soon-to-finish orders over not-yet-started orders, which can lead to recurring decisions where almost finished orders are completed in advance and orders whose start was delayed are not finished on time.

4.6 Summary and Discussion

The large-scale simulations reported in this chapter demonstrated that there are priority index rules that consistently work best in the common types of job shop problems in priority scheduling research. Based on the analysis of the simulation results, the priority index rules with dominating performance are the ATC.T, COVERT.T, and CR+SPT.T rules. One SPT-based rule works slightly better in minimizing the holding costs of work-in-process inventories than the three look-ahead rules, but it gives higher tardiness costs. Moreover, if the total costs of tardiness and holding of work-in-process are used as the performance measure, the priority index rules together form an efficient frontier for each level of system load.

There is evidence that the differences among the best priority index rules and other candidates are statistically significant. Furthermore, the results of the special case where all orders are equally important imply that although there are some dispatching rules using global probing (e.g. RR and PT+WINQ) that work well in some problem incidences, the performance of the three look-ahead rules is never significantly worse than the performance of the probing rules. Global probing rules that require extensive computing and iteration of future process events cannot, in any case, be considered as the core of order scheduling protocols because they do provide the required form of coordination. Moreover, in the unweighted problems easier to solve than the weighted problems some push-based rules also give good results in the portion of tardy jobs and mean flow time. Finally, the testing of some potential modifications of the dominant priority index rules indicated their robustness to the type of information used.

Overall, based on the evidence of the extensive comparisons, there is an opportunity to agree on a family of priority index rules recommendable for job shop production, in which the decisions of order management are localized and distributed and customers accept the classification of their orders based on tardiness penalties. Nevertheless, further research is needed in order to assess according to what constraints the look-ahead priority rules could be employed as the core of standard order scheduling protocols. For implementation purposes, it is also important to test what are the tolerances of the different priority index rules to the detail and scope of information. Additionally, sensitivity to the potential different types of usage in order handling should be investigated.

5 Specifications and Tolerances for Look-ahead Protocols

This chapter analyzes the sensitivity of selected priority index rules to modifications in their technical specifications and in the information used. More specifically, it examines the implications of alternative lead time estimation methods, accuracy of processing time and cost data, crude classifications of orders based on their tardiness costs, and the scope and level of information on rule performances. While the simulations here add to the material collected in Chapter 4 for the benchmarking framework introduced in Section 2.4, some insights can be gained also for the design of open order scheduling protocols primarily relying on the look-ahead rules shown to perform robustly.

5.1 Open Protocols for Order Management and Scheduling

By definition a protocol is, for example, a set of guidelines, the code of current conduct, etiquette observed, or a convention not formally ratified. This research presumes protocols to be specified with the following three layers:

a. Technical specifications and tolerances,
b. Rules of scheduling behavior, and
c. Conventions of usage.

The first layer of protocols concerns technical specifications and tolerances for information and communication that is necessary for the use of scheduling rules. The second layer specifies the rules of scheduling behavior for given situations. These rules can be defined, for example, by priority index rules. The conventions of usage, third layer of a protocol, define how the selected scheduling rules are applied in the decisions of order handling in different production or supply chain contexts. They give the code-of-conduct, for example, by defining if all decision-makers should apply the same rule or would one from the same family suffice. Other guidelines include the use of screening mechanisms in controlling the release of orders to the shop floor. Furthermore, in addition to these three layers, the scope of implementation as well as structural optimization should be considered.

In the handling of customer orders, the purpose of a standard scheduling protocol shared by decision-makers is to coordinate distributed decision-making within one organization or across multiple organizations including sales and production units as well as independent players of production networks. The open protocols are intended to be accessible to all potential users, yet not customizable to the characteristics of each manufacturing system. Here it is assumed that the rules of scheduling behavior in non-delay job shop scheduling are specified by the priority index rules found robust earlier in this thesis. Next, a set of exact estimations and some approximate managerial relaxations to be used with the rules are examined, while some alternative scheduling conventions will be explored in Chapter 6.

5.2 Alternative Lead Time Estimation Methods

Our comparative analyses of priority index rules in weighted and unweighted job shop problems indicated that the rules that include a mechanism, even a simple one, for estimating the expected waiting time of each order perform better than the competing rules. Two of the best priority index rules, ATC and COVERT, use a look-ahead parameter to scale the slack, normally the sum of remaining operation waiting times, according to the expected number of competing orders as well as a lead time estimate to adjust the total remaining processing time to the level of shop congestion potentially causing long waiting times within the system. The limited use of this type of look-ahead rules in practice suggests that there are doubts concerning the sensitivity of the rule performance to parameter values and the selection of the estimation methods. Thus, different versions of lead time estimation methods are investigated to evaluate if poor choices or random decisions of decision-makers can have major effects on the performance.

5.2.1 Test Setting

Vepsalainen and Morton (1988) tested three alternative lead time estimation methods. The methods were standard flow time allowance (STD), priority-based lead time estimation (PRIO), and lead time iteration (ITER). The STD method estimates lead times on the basis of the work content of an order (Equation 5-1). The priority-based lead time estimation, the default method in this thesis, weights the work content of each order depending on its relative priority. Vepsalainen and Morton (1988) argued that the iterative search method with simulations (in Equation 5-1 k is the index of simulation) is simple compared to the iteration-based scheduling methods introduced earlier (e.g. Emery 1969; Holloway and Nelson 1974a). Their equilibrium-seeking heuristic approach, which cannot be proven to converge, repeats simulations to identify lead time estimates that better match a specific problem and system load. It uses a local rule to extract better global information and needs a stopping rule for finding an appropriate cutoff point.

$$
\begin{aligned}
STD:&\; W_{ij} = bp_{ij} \\
PRIO:&\; W_{ij} = bp_{ij}\frac{w_i}{\overline{w}} + l\overline{p} \\
ITER:&\; W_{ij}^{k+1} = (1-a)W_{ij}^{k} + aq_{ij}^{k+1}
\end{aligned}
\qquad (5\text{-}1)
$$

The lead time iteration method is shown to outperform the results of other estimation methods when used with the ATC and COVERT rules in flow shops (Vepsalainen and Morton 1988). It is, however, not realistic to expect that the iterative method would be implemented in practice. It is demanding in terms of data collection and processing, and it assumes that decision-makers know the processing times of future operations accurately. Moreover, one-pass scheduling heuristics are preferred when specifying a managerial protocol for order scheduling. Thus, the lead time iteration method, whose robustness is not known, is excluded from further analysis. Instead, different versions of both the standard and priority-based lead time estimations are tested (Table 5-1).

Table 5-1 Factorial design for the comparison of lead time and waiting time estimation methods.

Design parameter	Number of levels	Levels
Lead-time estimation method	2	Multiple of processing times (STD), Priority-based (PRIO)
Lead-time estimation parameter (b)	1	2.0
Load estimation parameter (k)	2	2.0, 3.0
Multiplier of mean processing time (l)	4	0.25, 0.50, 0.75, 1.00
Type of look-ahead (p)	3	Parameter (mean of operation-specific processing time), All jobs waiting, Other jobs waiting

The lead time estimation parameter, multiplier *b*, is assumed to be fixed in the experiment. The load estimation parameter, look-ahead *k*, is tested with two values only, since earlier results have recommended values of two and three for the COVERT and ATC rules, respectively (e.g. Vepsalainen 1984). The priority-based lead time estimation is tested with four different values of the multiplier *l* that defines what portion of the average operation-specific processing time is added to the lead time estimate. Additionally, the performance of the ATC rule is tested with three alternative techniques that estimate the average processing time at the current resource. These methods are 1) the mean processing time of orders at the current resource based on historical data, 2) the average operation-specific processing time of all orders waiting to be processed, and 3) the average operation-specific processing time of all other orders in the queue, which excludes the order for which the priority index is being calculated. The three alternatives as well as the different values of multiplier *l* have not been tested before. In total, the set of simulations includes 4,000 runs. It is carried out in the base case with tight randomly assigned due dates for three different due date setting methods.

5.2.2 Results and Observations

The results indicate that the shorter look-ahead (*k*=2) generally works better for the COVERT.T rule regardless of the due date setting method and system load (Table 5-2 and Table 5-3). It can lead to a higher weighted maximum tardiness and portion of tardy jobs, but it helps to reach lower weighted mean tardiness, especially with the priority-based lead time estimation. The priority-based lead time estimation also reduces tardiness and holding costs. For the ATC.T rule the superiority of the priority-based lead time estimation is not as evident. If normalized weighted mean tardiness is used as the ranking criterion, the STD method is efficient with medium system load. The priority-based lead time estimation method (the value of parameter *l* is 0.25 or 0.50), however, works more robustly in all performance measures. The most efficient method for estimating the average processing time at the current operation is the average of all orders currently waiting to be processed. However, it is not the best in all problem instances. The use of an estimate calculated on the basis of historical data (parameter) gives worse results especially when system load is high and due dates are not set using the TWK method.

The tardiness penalties and holding costs of the ATC.T rule (*k*=3) and the COVERT.T rule (*k*=2) with alternative lead time estimation methods with medium and high system load are illustrated in Figure 5-1. The COVERT.T rule performs consistently better than the ATC.T rule in normalized weighted mean tardiness, whereas the ATC.T rule gives lower normalized WIP holding costs. Furthermore, this analysis suggests that the priority-based lead time estimation is superior to the standard method when look-ahead is set correctly, and it improves the COVERT.T rule more than the ATC.T rule. Moreover, it is observed that the performance of the ATC.T and COVERT.T rules in weighted mean tardiness and WIP holding costs can be improved slightly, if the best available lead time estimation method were used instead of the default settings of this study (priority-based lead time estimation, *l*=0.5, parameter). In the portion of tardy jobs, differences among the estimation methods are larger especially with high system load (Figure 5-2).

Table 5-2 Lead time and waiting time estimation methods for the ATC.T and COVERT.T rules in a uniform job shop when system load is 85% and tight due dates are assigned with the TWK, RANSLK, or CONSLK method.

				System load 85%											
Rule	**Look-ahead**	**Lead time estimate**	**Estimation of average wait**	**TWK** (multiplier 3)				**RANSLK** (range 0-6)				**CONSLK** (3*avg p)			
				mWT	**TJ (%)**	**WIP**	**WIS**	**mWT**	**TJ (%)**	**WIP**	**WIS**	**mWT**	**TJ (%)**	**WIP**	**WIS**
COVERT.T	*k*=2	STD *b*=2	-	0.078	13.5	3.53	4.39	0.170	26.7	3.66	4.58	0.121	17.2	3.59	4.53
	k=2	PRIO *l*=0.25	-	0.098	14.0	3.49	4.49	0.163	23.2	3.61	4.57	0.111	12.8	3.54	4.52
	k=2	PRIO *l*=0.50	-	0.070	10.2	3.46	4.37	0.166	22.1	3.60	4.59	0.113	12.0	3.52	4.54
	k=2	PRIO *l*=0.75	-	0.075	9.5	3.45	4.40	0.172	22.2	3.59	4.61	0.119	12.1	3.51	4.56
	k=2	PRIO *l*=1.00	-	0.080	9.8	3.44	4.42	0.178	22.3	3.59	4.64	0.125	12.5	3.50	4.59
	k=3	STD *b*=2	-	0.085	10.2	3.42	4.45	0.188	25.5	3.64	4.66	0.141	16.3	3.56	4.63
	k=3	PRIO *l*=0.25	-	0.092	10.8	3.44	4.48	0.183	22.5	3.60	4.66	0.130	12.7	3.51	4.61
	k=3	PRIO *l*=0.50	-	0.101	11.2	3.43	4.52	0.194	22.5	3.60	4.71	0.139	12.8	3.49	4.65
	k=3	PRIO *l*=0.75	-	0.106	11.8	3.41	4.54	0.198	22.8	3.57	4.72	0.147	13.3	3.48	4.68
	k=3	PRIO *l*=1.00	-	0.111	12.2	3.40	4.56	0.207	23.2	3.56	4.75	0.153	13.7	3.46	4.70
ATC.T	*k*=2	STD *b*=2	Parameter	0.076	12.0	3.36	4.32	0.179	25.8	3.59	4.54	0.121	16.6	3.48	4.49
	k=2	STD *b*=2	All waiting	0.078	11.1	3.29	4.36	0.176	24.8	3.50	4.55	0.122	15.0	3.40	4.52
	k=2	STD *b*=2	Other waiting	0.078	11.3	3.34	4.37	0.179	25.0	3.59	4.57	0.123	15.2	3.47	4.52
	k=2	PRIO *l*=0.25	Parameter	0.076	12.1	3.36	4.33	0.178	25.1	3.56	4.54	0.119	15.5	3.46	4.48
	k=2	PRIO *l*=0.50	Parameter	0.078	12.4	3.37	4.34	0.181	25.2	3.57	4.56	0.123	15.5	3.46	4.50
	k=2	PRIO *l*=0.75	Parameter	0.083	13.1	3.39	4.36	0.188	25.3	3.58	4.58	0.127	15.8	3.47	4.52
	k=2	PRIO *l*=1.00	Parameter	0.087	13.4	3.40	4.38	0.191	25.5	3.58	4.59	0.131	16.0	3.48	4.53
	k=2	PRIO *l*=0.25	All waiting	0.076	11.1	3.28	4.36	0.177	23.8	3.50	4.57	0.119	14.1	3.38	4.52
	k=2	PRIO *l*=0.50	All waiting	0.081	11.4	3.30	4.38	0.182	24.1	3.52	4.59	0.126	14.4	3.40	4.54
	k=2	PRIO *l*=0.75	All waiting	0.086	12.0	3.33	4.40	0.185	24.2	3.51	4.59	0.126	14.5	3.39	4.55
	k=2	PRIO *l*=1.00	All waiting	0.092	12.8	3.35	4.42	0.190	24.5	3.51	4.60	0.131	14.9	3.40	4.56
	k=2	PRIO *l*=0.25	Other waiting	0.078	11.2	3.34	4.37	0.179	23.8	3.56	4.57	0.120	14.3	3.44	4.52
	k=2	PRIO *l*=0.50	Other waiting	0.083	11.6	3.37	4.39	0.183	24.2	3.57	4.59	0.122	14.3	3.43	4.53
	k=2	PRIO *l*=0.75	Other waiting	0.086	12.1	3.38	4.41	0.187	24.3	3.56	4.60	0.128	14.8	3.45	4.55
	k=2	PRIO *l*=1.00	Other waiting	0.092	12.6	3.39	4.42	0.189	24.3	3.56	4.60	0.130	15.0	3.45	4.55
	k=3	STD *b*=2	Parameter	0.080	11.5	3.33	4.38	0.180	24.5	3.54	4.58	0.123	14.4	3.34	4.60
	k=3	STD *b*=2	All waiting	0.088	11.4	3.26	4.44	0.185	23.8	3.47	4.63	0.132	14.4	3.34	4.60
	k=3	STD *b*=2	Other waiting	0.088	11.6	3.30	4.44	0.187	24.1	3.54	4.64	0.130	14.4	3.39	4.59
	k=3	PRIO *l*=0.25	Parameter	0.079	11.3	3.32	4.38	0.179	23.8	3.52	4.59	0.104	13.2	3.38	4.47
	k=3	PRIO *l*=0.50	Parameter	0.084	11.9	3.34	4.40	0.185	24.0	3.53	4.60	0.109	13.3	3.39	4.49
	k=3	PRIO *l*=0.75	Parameter	0.089	12.2	3.36	4.42	0.187	24.0	3.53	4.61	0.113	13.5	3.39	4.50
	k=3	PRIO *l*=1.00	Parameter	0.093	12.7	3.37	4.44	0.191	24.1	3.53	4.62	0.118	13.7	3.40	4.53
	k=3	PRIO *l*=0.25	All waiting	0.087	11.1	3.25	4.44	0.184	23.0	3.45	4.63	0.111	12.6	3.28	4.52
	k=3	PRIO *l*=0.50	All waiting	0.093	11.5	3.28	4.46	0.190	23.2	3.46	4.65	0.118	12.8	3.30	4.55
	k=3	PRIO *l*=0.75	All waiting	0.095	11.8	3.28	4.47	0.193	23.4	3.46	4.66	0.123	13.2	3.32	4.57
	k=3	PRIO *l*=1.00	All waiting	0.097	12.3	3.28	4.47	0.196	23.8	3.46	4.67	0.127	13.5	3.33	4.59
	k=3	PRIO *l*=0.25	Other waiting	0.087	11.0	3.30	4.45	0.184	23.0	3.50	4.63	0.113	12.6	3.36	4.54
	k=3	PRIO *l*=0.50	Other waiting	0.092	11.5	3.32	4.46	0.189	23.3	3.51	4.65	0.119	13.0	3.37	4.56
	k=3	PRIO *l*=0.75	Other waiting	0.096	11.9	3.33	4.47	0.193	23.6	3.52	4.66	0.121	13.1	3.37	4.56
	k=3	PRIO *l*=1.00	Other waiting	0.099	12.2	3.34	4.49	0.198	23.6	3.52	4.68	0.125	13.5	3.38	4.58

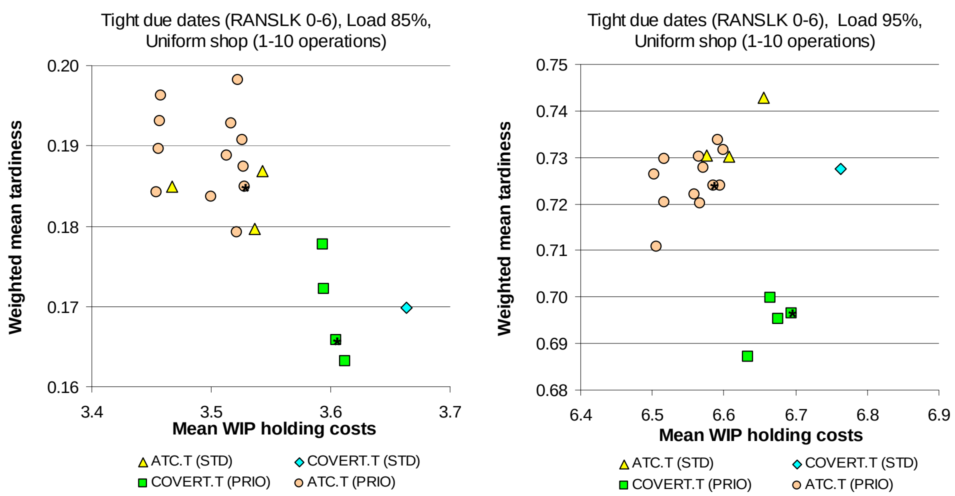

Figure 5-1 Tardiness and holding costs of the alternative lead time estimation methods when used by the ATC.T (*k*=3) and COVERT.T (*k*=2) rules in the base case (defaults marked with*).

Table 5-3 Lead time and waiting time estimation methods for the ATC.T and COVERT.T rules in a uniform job shop when system load is 95% and due dates are assigned with the TWK, RANSLK or CONSLK method.

				System load 95%											
Rule	**Look-ahead**	**Lead time estimate**	**Estimation of avg wait**	**TWK** (multiplier 3)				**RANSLK** (range 0-6)				**CONSLK** (3*avg p)			
				mWT	**TJ (%)**	**WIP**	**WIS**	**mWT**	**TJ (%)**	**WIP**	**WIS**	**mWT**	**TJ (%)**	**WIP**	**WIS**
COVERT.T	*k*=2	STD *b*=2	-	0.519	29.5	6.31	6.70	0.728	44.6	6.76	7.14	0.611	33.9	6.42	6.86
	k=2	PRIO *l*=0.25	-	0.546	26.5	6.28	6.82	0.695	39.9	6.68	7.07	0.582	28.4	6.37	6.83
	k=2	PRIO *l*=0.50	-	0.497	24.3	6.26	6.67	0.696	37.3	6.69	7.12	0.589	25.9	6.38	6.88
	k=2	PRIO *l*=0.75	-	0.499	22.3	6.24	6.69	0.687	35.8	6.63	7.11	0.594	25.2	6.35	6.90
	k=2	PRIO *l*=1.00	-	0.509	21.7	6.24	6.74	0.700	35.2	6.66	7.17	0.597	25.0	6.31	6.90
	k=3	STD *b*=2	-	0.518	21.9	6.23	6.77	0.735	39.5	6.76	7.27	0.632	29.7	6.41	7.01
	k=3	PRIO *l*=0.25	-	0.530	21.7	6.28	6.84	0.706	34.4	6.71	7.24	0.606	24.4	6.38	6.99
	k=3	PRIO *l*=0.50	-	0.540	21.9	6.25	6.87	0.719	33.9	6.69	7.27	0.614	24.0	6.33	7.01
	k=3	PRIO *l*=0.75	-	0.554	22.4	6.24	6.90	0.732	34.0	6.72	7.35	0.628	24.0	6.33	7.06
	k=3	PRIO *l*=1.00	-	0.567	22.8	6.24	6.94	0.738	33.9	6.68	7.35	0.644	24.2	6.33	7.11
ATC.T	*k*=2	STD *b*=2	Parameter	0.543	32.2	6.18	6.58	0.755	45.3	6.68	7.08	0.631	35.9	6.34	6.80
	k=2	STD *b*=2	All waiting	0.528	27.6	6.12	6.64	0.739	41.9	6.62	7.10	0.613	31.8	6.25	6.84
	k=2	STD *b*=2	Other waiting	0.524	27.8	6.12	6.62	0.738	42.0	6.64	7.10	0.616	32.0	6.29	6.84
	k=2	PRIO *l*=0.25	Parameter	0.534	31.6	6.18	6.58	0.741	43.9	6.64	7.05	0.622	34.2	6.33	6.81
	k=2	PRIO *l*=0.50	Parameter	0.542	31.3	6.20	6.62	0.743	43.4	6.63	7.05	0.622	33.9	6.31	6.80
	k=2	PRIO *l*=0.75	Parameter	0.551	31.6	6.24	6.65	0.742	43.5	6.62	7.05	0.634	33.9	6.36	6.85
	k=2	PRIO *l*=1.00	Parameter	0.560	31.6	6.28	6.70	0.750	43.2	6.63	7.07	0.636	33.8	6.35	6.86
	k=2	PRIO *l*=0.25	All waiting	0.519	26.9	6.12	6.64	0.723	40.3	6.59	7.09	0.604	30.0	6.23	6.82
	k=2	PRIO *l*=0.50	All waiting	0.523	27.0	6.13	6.65	0.725	40.0	6.59	7.10	0.612	30.0	6.25	6.86
	k=2	PRIO *l*=0.75	All waiting	0.537	27.2	6.18	6.72	0.731	39.9	6.59	7.11	0.617	30.0	6.26	6.88
	k=2	PRIO *l*=1.00	All waiting	0.542	27.6	6.18	6.72	0.730	39.7	6.57	7.10	0.622	30.0	6.28	6.91
	k=2	PRIO *l*=0.25	Other waiting	0.521	26.8	6.16	6.66	0.729	40.5	6.64	7.11	0.612	30.2	6.30	6.86
	k=2	PRIO *l*=0.50	Other waiting	0.525	27.0	6.15	6.66	0.728	40.1	6.62	7.11	0.609	30.1	6.29	6.86
	k=2	PRIO *l*=0.75	Other waiting	0.534	27.3	6.17	6.69	0.727	40.0	6.59	7.08	0.618	30.1	6.29	6.87
	k=2	PRIO *l*=1.00	Other waiting	0.542	27.7	6.18	6.71	0.735	40.1	6.63	7.13	0.624	30.0	6.30	6.90
	k=3	STD *b*=2	Parameter	0.529	27.5	6.14	6.66	0.743	41.0	6.65	7.16	0.614	28.0	6.21	6.97
	k=3	STD *b*=2	All waiting	0.527	24.7	6.05	6.73	0.730	38.1	6.58	7.20	0.619	28.0	6.21	6.97
	k=3	STD *b*=2	Other waiting	0.529	24.6	6.10	6.75	0.730	38.2	6.61	7.20	0.618	27.8	6.26	6.99
	k=3	PRIO *l*=0.25	Parameter	0.526	26.9	6.15	6.67	0.724	39.5	6.60	7.11	0.590	30.6	6.24	6.79
	k=3	PRIO *l*=0.50	Parameter	0.533	26.9	6.18	6.71	0.724	39.4	6.59	7.11	0.601	30.0	6.28	6.84
	k=3	PRIO *l*=0.75	Parameter	0.544	27.2	6.21	6.75	0.732	39.2	6.60	7.13	0.600	29.7	6.24	6.82
	k=3	PRIO *l*=1.00	Parameter	0.549	27.7	6.20	6.75	0.734	39.2	6.59	7.14	0.611	29.6	6.27	6.87
	k=3	PRIO *l*=0.25	All waiting	0.526	23.9	6.08	6.75	0.711	36.8	6.51	7.15	0.586	27.1	6.13	6.84
	k=3	PRIO *l*=0.50	All waiting	0.531	24.1	6.09	6.77	0.720	36.6	6.52	7.17	0.592	26.9	6.17	6.89
	k=3	PRIO *l*=0.75	All waiting	0.540	24.5	6.11	6.80	0.726	36.8	6.50	7.17	0.598	26.8	6.18	6.93
	k=3	PRIO *l*=1.00	All waiting	0.546	25.0	6.12	6.82	0.730	36.8	6.52	7.19	0.604	26.8	6.15	6.92
	k=3	PRIO *l*=0.25	Other waiting	0.526	23.8	6.13	6.78	0.720	36.6	6.57	7.18	0.592	27.3	6.21	6.88
	k=3	PRIO *l*=0.50	Other waiting	0.536	24.3	6.15	6.81	0.722	36.8	6.56	7.18	0.598	27.0	6.21	6.90
	k=3	PRIO *l*=0.75	Other waiting	0.540	24.6	6.14	6.80	0.728	36.7	6.57	7.20	0.599	26.7	6.19	6.90
	k=3	PRIO *l*=1.00	Other waiting	0.547	25.0	6.15	6.82	0.730	36.8	6.57	7.21	0.610	26.8	6.23	6.95

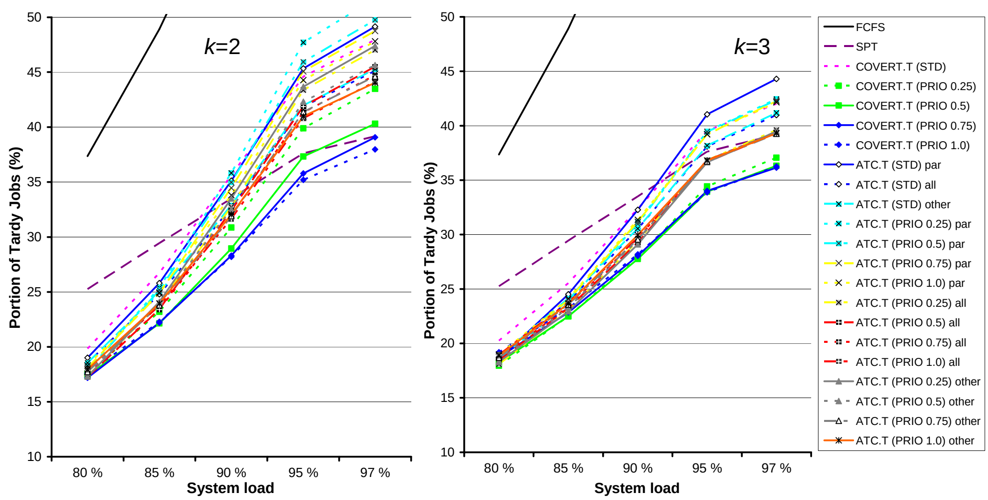

Figure 5-2 Portion of tardy jobs for the ATC.T and COVERT.T rules in the base case with two load estimation parameters (*k*=2 and *k*=3).

All tested versions of the ATC.T and COVERT.T rules perform well compared to the family of the next best dispatch priority rules regardless of the system load and the method used for due date setting. Additionally, the difference between the best and worst lead time estimation method tested for the two rules is only about 10% in weighted mean tardiness with high system load. This implies that the performance of the look-ahead rules is not highly sensitive to the choice of parameter values and/or estimation principles.

5.3 Errors in Processing Times and Tardiness Penalties

Inadequate quality of order information is often considered the cause of poor performance and less than adequate reliability of heuristic scheduling methods. It is argued that the power of scheduling heuristics reduces when, for instance, actual processing times differ significantly from the estimated values that have been used as the basis for planning and decision-making. There are some results on the effects of errors in the estimates of processing times (e.g. Conway *et al.* 1967; Muth and Thompson 1963; Vepsalainen 1984) in static small-scale problems. There are no studies that would have tested the impact of errors in both processing times and tardiness penalties (also called weights) in dynamic large-scale job shop problems.

5.3.1 Test Setting

Simulations of large-scale weighted job shop problems are carried out to examine the effects of estimation errors on the performance of priority index rules. The selected prominent rules are ATC.T, COVERT.T, CR+SPT.T, SPT.T, and S/RPT+SPT.T. Moreover, the performances of the unweighted EDD rule and the MOD.T rule, which is a good representative of composite priority index rules that consider due date and processing time information, are tested. The simulations are carried out according to the experimental design specified in Chapter 4 except for the reporting period. Here the standard performance statistics are calculated using the data of all processed orders, so the warm-up period is included. This experiment extends the standard simulation setup by two variables called the error in the estimate of processing time and the error in the estimate of tardiness penalty, which indicate how much the estimates used in decision-making can in maximum differ from their actual values. The absolute maximum errors can be up to 100% of the actual processing time and tardiness penalty (Table 5-4). The order-specific levels of error are derived independently for both of the variables from a uniform distribution.

Table 5-4 Level of estimation errors in the experiments.

Level of errors	Maximum absolute error	Processing times	Tardiness penalties / weights
None	0.0	$p^e_{ij} = p_{ij}$	$w^e_i = w_i$
Minor	0.2	p^e_{ij} ~U[0.8*p_{ij}, 1.2*p_{ij}]	w^e_i ~U[0.8*w_i, 1.2*w_i]
	0.4	p^e_{ij} ~U[0.6*p_{ij}, 1.4*p_{ij}]	w^e_i ~U[0.6*w_i, 1.4*w_i]
Moderate	0.6	p^e_{ij} ~U[0.4*p_{ij}, 1.6*p_{ij}]	w^e_i ~U[0.4*w_i, 1.6*w_i]
	0.8	p^e_{ij} ~U[0.2*p_{ij}, 1.8*p_{ij}]	w^e_i ~U[0.2*w_i, 1.8*w_i]
Major	1.0	p^e_{ij} ~U[0.001*p_{ij}, 2*p_{ij}]	w^e_i ~U[0.001*w_i, 2*w_i]

The estimates of processing times and tardiness penalties are used to calculate the values of order-specific priority indices and lead time estimates. On the basis of these values the decisions of priority scheduling are carried out. The actual values of job attributes are used to determine the rate of order arrivals and to calculate the statistics for performance indicators because they define the actual duration of order processing as well as the realized cost of delayed delivery. It follows that the system events, including loading, unloading and release of orders, are scheduled using the actual values of processing times.

5.3.2 Inaccurate Estimates of Processing Times

As a starting point the results of the small-scale experiment reported in Vepsalainen (1984) are summarized. There 20 jobs were sequenced within a static one-machine shop using three different priority index rules (SPT.T, EDD, ATC.T, and ATC.T with look-ahead adaptation). The weighted tardiness performance of the selected rules for three levels of erroneous processing time data was reported as an average of results with five levels of machine load (Table 5-5).

Table 5-5 Effects of errors in the estimates of processing times on the performance of four dispatch priority rules in normalized weighted mean tardiness (Vepsalainen 1984, 24).

	With maximum errors of:			
Rule	**0 %**	**30 %**	**60 %**	**90 %**
SPT.T	1.155	1.147	1.312	1.422
EDD	0.646	0.646	0.646	0.646
ATC.T	0.254	0.259	0.304	0.344
ATC.T w/ look-ahead adaptation	0.225	0.240	0.270	0.318

Vepsalainen (1984) concluded that the dispatching rules are relatively robust. The impact of the erroneous estimates of processing times on rule performance was relatively small. Another observation was that the ranking of the rules remained the same even for the highest level of errors, and the performance of the best rule, in his experiment the ATC.T rule, was significantly better than the performance of the EDD rule even with the highest level of errors (0.344 versus 0.646). This is different from the conclusion of Holloway and Nelson (1974a). They studied the capability of a multi-pass adjusting procedure to minimize average tardiness in static shops and observed that their heuristic search procedure outperformed the SPT, truncated SPT, S/OPN, and EDD rules in three deterministic problems. Interestingly, the erroneous estimates of processing times deteriorated the performance of their procedure, even below the levels of SPT and EDD rules in some cases.

According to the new experiments in a larger multi-machine system (uniform 10-machine shop), the order of magnitude in performance changes due to inaccurate processing time data depends on the dispatch priority rules and the performance measure. Naturally, the way how a priority index rule uses the data about handling requirements has an impact on the effect of errors. Inaccurate data does not change the order dispatching decisions produced by priority index rules, such as the EDD, which do not use processing time information in determining the value of order-specific priority indices. In general, the increasing variance of processing times caused by estimation errors influences most the weighted mean tardiness and maximum weighted tardiness regardless of system load and priority index rule. Figure 5-3 illustrates the changes in the normalized weighted mean tardiness for two levels of system load. With medium system load, for example, the EDD rule produces two times higher tardiness costs compared to the best rules.

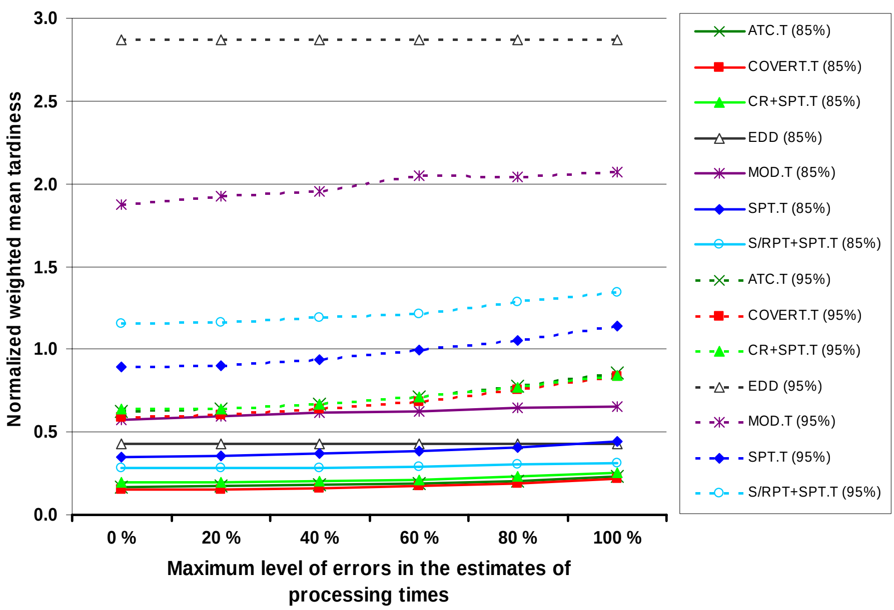

Figure 5-3 Effects of estimation errors in processing times on normalized weighted mean tardiness in a uniform job shop when system load is 85% or 95%.

The average effect of errors increases along with the system load. However, the three look-ahead rules (ATC.T, COVERT.T, and CR+SPT.T) give significantly lower weighted mean tardiness even with the highest possible level of errors than the next best rules with accurate data independent of the system load. Estimation errors in processing times increase also the portion of tardy jobs when either the ATC.T or COVERT.T rule is used. Other performance statistics of all tested rules are relatively insensitive to the inaccurate processing times.

5.3.3 Inaccurate Estimates of Tardiness Penalties

In addition to processing times it can, in practice, be difficult to determine accurate values for order-specific tardiness penalties. Thus, how inaccuracy in weights that are used as the indicators of order-specific delay penalties influences the system performance produced by different priority index rules is examined. The results of the experiments imply that minor estimation errors in the costs do not significantly change the level of weighted mean tardiness (Figure 5-4). However, if the absolute value for maximum deviation exceeds 60% of the actual tardiness penalty, the performance of some priority rules (ATC.T, COVERT.T, and CR+SPT.T, and SPT.T) deteriorates significantly. The resulting increase in the tardiness costs can be up to 100-190%, depending on the system load, compared to using accurate values of tardiness penalties as the basis of the dispatching decisions.

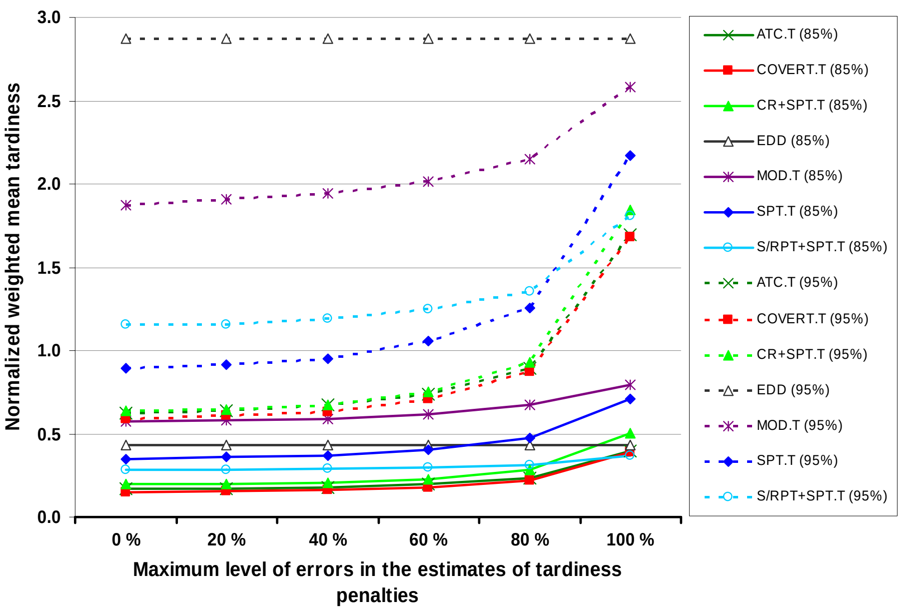

Figure 5-4 Effects of estimation errors in the tardiness penalties on normalized weighted mean tardiness in a uniform job shop when system load is 85% or 95%.

The errors in the estimated values of weights do not influence dispatching decisions made using priority index values calculated with the unweighted EDD rule. Thus, weighted mean tardiness remains the same for all levels of errors as illustrated above.

5.3.4 Combined Effects of Estimation Errors

The combined effects of errors in the estimates of processing times and tardiness penalties are also investigated (Table 5-6). The portion of tardy jobs increases up to 26% depending on the priority index rule and the level of system load. Only for the EDD and S/RPT+SPT.T rules the portion of tardy jobs does not increase. Mean flow times as well as work-in-process holding costs typically increase by 5%, whereas the maximum weighted tardiness can increase up to 9.7 times due to inaccurate estimates. Estimation errors also enlarge the tardiness costs of the best priority index rules by 100-200% depending on the system load (Figure 5-5). However, the three best performing rules (ATC.T, COVERT.T and CR+SPT.T) are better than the competing rules, if the maximum level of absolute errors does not exceed 60% of the actual values of the considered two job attributes. When the estimated values are more than 60% lower or more than 60% higher than the actual value the average tardiness performance of a production system worsens considerably more. This is logical because the look-ahead rules as well as the other weighted priority index rules seek for the best trade-offs between flow times and delivery accuracy.

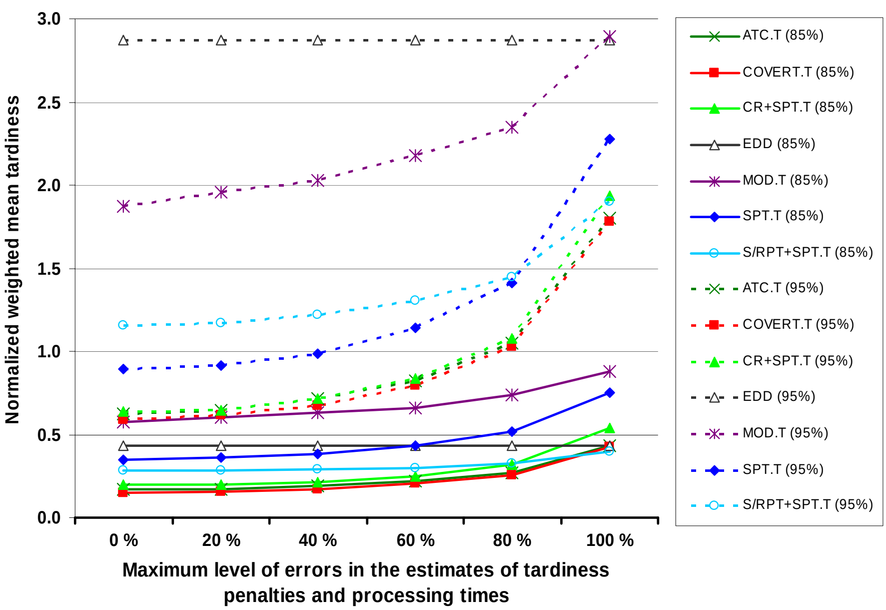

Figure 5-5 Effects of errors in the estimates of processing times and tardiness penalties on normalized weighted mean tardiness in a uniform shop when system load is 85% or 95%.

Table 5-6 Effects of errors in the estimates of processing times and tardiness penalties on four key performance measures in the base case when system load is 85% or 95%.

		Random slack method (range 0-6)													
Level of errors	**Priority index rule**	**System load 85%**							**System load 95%**						
		mWT	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**WIS**
No errors	ATC.T	0.17	9118	22.7	299	1.16	3.40	4.52	0.63	22936	37.3	534	1.17	6.06	6.63
	COVERT.T	0.15	8190	21.4	307	1.19	3.48	4.51	0.59	23185	35.4	538	1.18	6.12	6.60
	CR+SPT.T	0.20	8826	27.1	299	1.16	3.40	4.65	0.64	25362	41.0	535	1.17	6.07	6.77
	EDD	0.43	9289	44.5	315	1.22	3.58	4.43	2.87	22003	84.3	584	1.28	6.62	6.87
	MOD.T	0.57	48853	32.3	302	1.17	3.43	5.09	1.87	187264	43.2	544	1.20	6.16	7.52
	SPT.T	0.35	12528	28.3	286	1.11	3.25	5.04	0.89	26103	36.7	520	1.14	5.90	7.46
	S/RPT+SPT.T	0.28	6943	45.5	308	1.19	3.49	4.45	1.15	21700	80.7	560	1.23	6.35	6.67
max. +/- 20%	ATC.T	0.17	10001	23.0	300	1.16	3.41	4.53	0.65	26087	37.5	535	1.17	6.07	6.65
	COVERT.T	0.16	9074	21.5	307	1.19	3.48	4.51	0.61	25333	35.8	542	1.19	6.15	6.63
	CR+SPT.T	0.20	10077	27.1	299	1.16	3.39	4.65	0.65	25691	41.1	534	1.17	6.07	6.77
	EDD	0.43	9289	44.5	315	1.22	3.58	4.43	2.87	22003	84.3	584	1.28	6.62	6.87
	MOD.T	0.60	47655	32.5	305	1.18	3.47	5.13	1.96	201267	43.5	556	1.22	6.31	7.66
	SPT.T	0.36	12872	28.5	287	1.11	3.26	5.06	0.92	29565	36.9	520	1.14	5.91	7.46
	S/RPT+SPT.T	0.28	7779	45.7	307	1.19	3.49	4.44	1.17	23517	80.8	560	1.23	6.34	6.66
max. +/- 60%	ATC.T	0.22	14674	23.9	303	1.17	3.44	4.57	0.82	41723	38.9	541	1.19	6.14	6.74
	COVERT.T	0.20	15136	23.0	311	1.20	3.53	4.55	0.79	42173	37.9	549	1.21	6.24	6.72
	CR+SPT.T	0.25	14285	28.1	301	1.16	3.42	4.69	0.84	46488	42.2	545	1.20	6.19	6.92
	EDD	0.43	9289	44.5	315	1.22	3.58	4.43	2.87	22003	84.3	584	1.28	6.62	6.87
	MOD.T	0.66	54213	33.2	310	1.20	3.51	5.15	2.18	197900	44.2	567	1.24	6.44	7.77
	SPT.T	0.43	22312	29.4	291	1.13	3.31	5.07	1.14	52798	38.4	532	1.17	6.04	7.55
	S/RPT+SPT.T	0.30	10474	45.5	308	1.19	3.50	4.45	1.31	34494	80.2	563	1.24	6.38	6.70
max. +100%/-99%	ATC.T	0.44	64143	25.0	307	1.19	3.47	4.68	1.80	245724	38.9	562	1.23	6.37	7.06
	COVERT.T	0.42	59899	27.1	317	1.23	3.60	4.66	1.78	241702	43.0	572	1.26	6.49	7.02
	CR+SPT.T	0.54	69432	29.4	307	1.19	3.48	4.85	1.94	263894	42.0	563	1.24	6.39	7.28
	EDD	0.43	9289	44.5	315	1.22	3.58	4.43	2.87	22003	84.3	584	1.28	6.62	6.87
	MOD.T	0.88	63391	33.7	315	1.22	3.57	5.19	2.89	220205	44.7	582	1.28	6.59	7.90
	SPT.T	0.75	75333	30.6	304	1.18	3.45	5.17	2.27	258332	39.8	556	1.22	6.31	7.77
	S/RPT+SPT.T	0.39	43712	44.9	313	1.21	3.55	4.53	1.90	187219	76.2	572	1.26	6.49	6.85

Overall, the results of these experiments are comforting for decision-makers. The priority index rules are rather robust to estimation errors in both processing time and cost data. More importantly, the performance of the three look-ahead rules is significantly better than the performance of the competing rules in the key performance measures, even if there were reasonably large errors in the data used to calculate order-specific priority indices.

It would be interesting to examine, in detail, to what extent the performance changes observed here correlate with the structure of priority index rules and the way how they use information on processing times and costs. Moreover, the effects of due date assignment and accuracy of due date information on the robustness of the results could be investigated. In fact, on the basis of some preliminary tests, for example the performance of the priority index rules becomes slightly more sensitive to errors in data if due dates are set using the total work content method.

5.4 Priority Classes Based on Tardiness Costs

One of the main practical objections to the index-based priority rules examined in this thesis concerns the difficulty of determining order-specific costs. In practice, any categorization of orders based on customer importance may be perceived as being more pragmatic and better aligned with strategic goals of a firm. In a company-specific analysis, the benefits and drawbacks of customer-based order prioritization in comparison to order-based priority scheduling can be estimated using standard performance measures. Here, a more fundamental analysis on the use of order priority classes, which is a system expected to ease the work of production schedulers and dispatchers, is carried out. This experiment gives indications about the benefit of aggregating/disaggregating data as well as the cost of not being able to detail tardiness penalty, which exists for each order even though not always specified explicitly.

5.4.1 Test Setting

The systems of priority classification tested here categorize arriving orders into classes on the basis of their estimated tardiness penalties. A pre-defined tie-breaker rule is then used to select the next order to be processed from the priority class with the highest delay cost when a resource is freed. Each priority class includes customer orders with weight values that are within a pre-specified range. These ranges are equal in all the order priority classes and depend on the number of classes and the range of tardiness penalty values. For instance, if the number of priority classes is ten and order-specific tardiness penalties have values between 1 and 31, then customer orders with weights of 5, 12, and 27 are ranked into priority classes 2, 4, and 9, respectively. Order dispatching is carried out with the 'highest-priority-class-first' principle. It dispatches all orders of the class with the highest tardiness penalty first using the tie-breaker before selecting orders from the next priority class. This simulation experiment is carried out in the base case. It is tested how the number of priority classes and the choice of the tie-breaker rule influence the system performance. The number of priority classes is 1, 2, 5, 10, or 20, and within each class the FCFS, EDD, SPT, or SPT.T rule is applied as the queue discipline. Moreover, the performance of simple priority index rules is examined because the intention is to test systems and principles that are in all likelihood applied in practice. The different configurations of order priority class systems are benchmarked against the group of look-ahead rules (ATC.T, COVERT.T, and CR+SPT.T).

5.4.2 Results and Observations

The results of the simulations suggest that a high number of categories improve the performance of the priority class system, if the FCFS rule is the tie-breaker (Table 5-7). When the SPT.T rule is applied as the tie-breaker, the opposite is true: as the number of priority classes increases the system performance deteriorates in all performance measures. The a priori categorization of the orders seems to prevent the SPT.T rule from making the best possible trade-off between loading efficiency and the value of order, regardless of the system load and due date tightness. If the EDD rule is the tie-breaker, the influence of the number of categories depends on system load, performance measure, and due date setting procedure. For example, with medium load an order priority system with two classes is worse than a system with one or five priority classes in the weighted mean tardiness (Figure 5-6).

Table 5-7 Performance of the priority class systems with medium and high system load in a uniform job shop when tight due dates are assigned with the TWK, RANSLK, and CONSLK method.

	System load 85%											
	Uniform shop & RANSLK						**Proportionate shop & RANSLK**					
Rule	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**
IMM & ATC.T	0.18	9411	24.0	310	1.03	3.53	0.20	11366	23.9	294	1.07	3.56
IMM & COVERT.T	0.17	10036	22.1	317	1.05	3.60	0.18	11026	22.4	299	1.09	3.62
IMM & CR+SPT.T	0.21	10978	27.9	309	1.03	3.53	0.23	11171	28.1	293	1.07	3.55
IMM & EDD	0.49	9397	47.3	325	1.08	3.69	0.54	9700	48.7	311	1.13	3.76
IMM & FCFS	1.26	25697	48.9	367	1.22	4.17	1.25	25014	48.5	342	1.24	4.14
IMM & SPT.T	0.39	13577	29.4	300	1.00	3.42	0.38	15902	28.7	275	1.00	3.33
FIXED (FCFS) & FCFS	1.28	25153	49.6	366	1.22	4.21	1.26	25468	49.3	341	1.24	4.19
FIXED (FCFS) & EDD	0.51	9563	49.0	325	1.08	3.75	0.58	9777	50.5	310	1.13	3.82
FIXED (EDD) & FCFS	1.27	26118	49.5	365	1.22	4.21	1.26	24765	49.2	341	1.24	4.19
FIXED (EDD) & EDD	0.52	9602	49.0	325	1.08	3.75	0.57	9723	50.5	310	1.13	3.82
CONWIP (FCFS) & FCFS	1.26	25697	48.9	367	1.22	4.17	1.25	25014	48.5	342	1.24	4.14
CONWIP (FCFS) & EDD	0.49	9397	47.3	325	1.08	3.69	0.54	9700	48.7	311	1.13	3.76
CONWIP (EDD) & FCFS	1.26	25697	48.9	367	1.22	4.17	1.25	25014	48.5	342	1.24	4.14
CONWIP (EDD) & EDD	0.49	9397	47.3	325	1.08	3.69	0.54	9700	48.7	311	1.13	3.76
MWL (FCFS) & FCFS	1.51	26559	54.0	342	1.14	4.57	1.45	25455	52.7	322	1.17	4.47
MWL (FCFS) & EDD	0.55	9849	48.2	318	1.06	3.77	0.61	10239	49.6	302	1.10	3.85
MWL (EDD) & FCFS	1.40	23537	53.1	341	1.13	4.45	1.34	21920	51.8	321	1.17	4.35
MWL (EDD) & EDD	0.54	9692	48.3	320	1.06	3.77	0.59	10008	49.3	304	1.10	3.82

	System load 95%											
	Uniform shop & RANSLK						**Proportionate shop & RANSLK**					
Rule	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**
IMM & ATC.T	0.72	28927	39.4	578	1.46	6.59	0.72	31673	37.1	522	1.35	6.33
IMM & COVERT.T	0.70	30650	37.3	588	1.48	6.69	0.68	31896	35.7	527	1.36	6.38
IMM & CR+SPT.T	0.73	29845	42.9	580	1.46	6.61	0.72	32743	41.4	523	1.35	6.34
IMM & EDD	3.42	26093	87.1	637	1.60	7.24	3.33	24036	87.1	589	1.52	7.13
IMM & FCFS	5.10	59361	76.2	760	1.91	8.64	4.85	55625	75.6	691	1.79	8.37
IMM & SPT.T	1.00	32486	37.6	567	1.43	6.46	0.98	36774	36.3	498	1.29	6.03
FIXED (FCFS) & FCFS	5.13	58065	76.7	759	1.91	8.69	4.91	55984	76.2	692	1.79	8.45
FIXED (FCFS) & EDD	3.47	26358	87.4	635	1.60	7.29	3.38	24334	87.8	588	1.52	7.20
FIXED (EDD) & FCFS	5.16	58485	76.7	761	1.92	8.71	4.92	55443	76.2	693	1.79	8.47
FIXED (EDD) & EDD	3.48	26223	87.4	636	1.60	7.30	3.38	24376	87.8	589	1.52	7.20
CONWIP (FCFS) & FCFS	5.10	52757	77.7	706	1.78	8.68	4.82	49854	76.7	647	1.68	8.38
CONWIP (FCFS) & EDD	3.46	26319	87.2	620	1.56	7.27	3.36	24246	87.2	573	1.48	7.17
CONWIP (EDD) & FCFS	5.04	51881	77.5	705	1.77	8.62	4.79	48362	76.7	647	1.68	8.35
CONWIP (EDD) & EDD	3.46	26242	87.1	620	1.56	7.28	3.36	24239	87.2	573	1.48	7.17
MWL (FCFS) & FCFS	11.39	75046	92.4	397	1.00	15.27	10.41	66589	91.7	387	1.00	14.28
MWL (FCFS) & EDD	6.69	42575	91.4	422	1.06	10.59	6.26	38139	91.5	406	1.05	10.15
MWL (EDD) & FCFS	11.32	73610	92.1	398	1.00	15.23	9.79	62073	91.0	386	1.00	13.66
MWL (EDD) & EDD	6.27	40434	90.9	436	1.10	10.17	5.78	36328	90.9	428	1.11	9.67

Interestingly, the FCFS-based priority systems perform almost as well as the EDD-based systems when the number of priority classes is more than five. Moreover, even the best combinations of both priority systems give at least 80% higher weighted mean tardiness than the best look-ahead rules in the base case. Even the best priority class system, two classes with SPT.T as the tie-breaker, gives 15%-95% higher average weighted tardiness than the best look-ahead rule depending on the system load and due date setting method. If the portion of tardy jobs is the most important criterion, more of the tested priority systems are competitive (Figure 5-7).

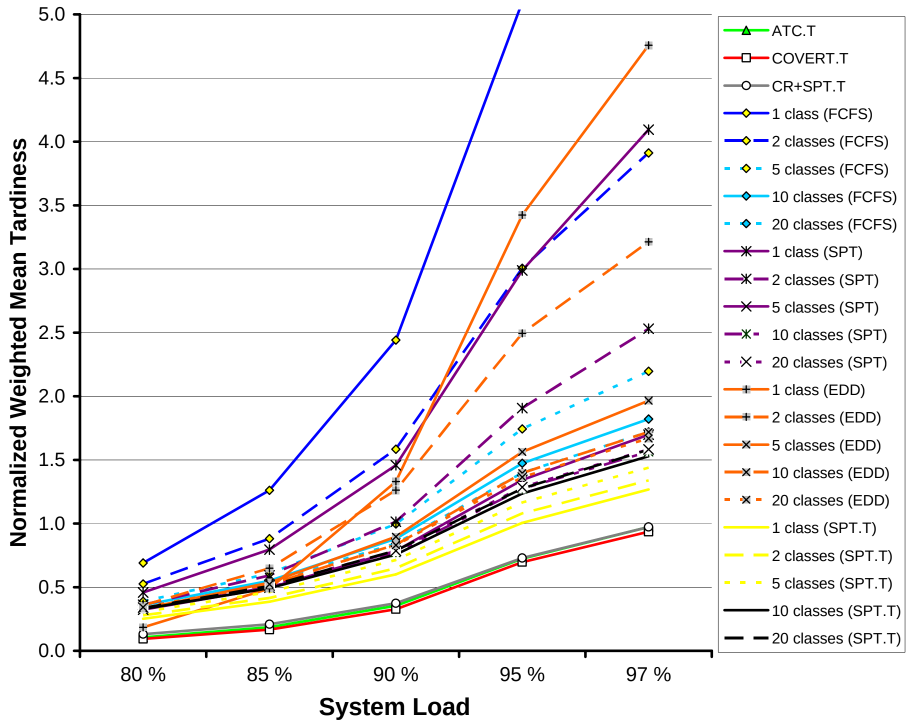

Figure 5-6 Normalized weighted mean tardiness for the priority class systems in comparison to the look-ahead priority rules in a uniform shop when tight due dates are assigned randomly.

In work-in-process holding costs the priority class systems with the SPT.T rule are viable (Figure 5-8), but on the basis of the work-in-system holding costs the benefits of the priority class systems can be questioned.

For the companies that hesitate with the use of order-specific tardiness penalties in order scheduling, the EDD-based systems may seem agreeable despite their poor performance compared to the best priority index rules. However, according to these results decision-makers who search for a simple priority scheduling system should try a system with a few classes and the SPT.T rule as the tie-breaker.

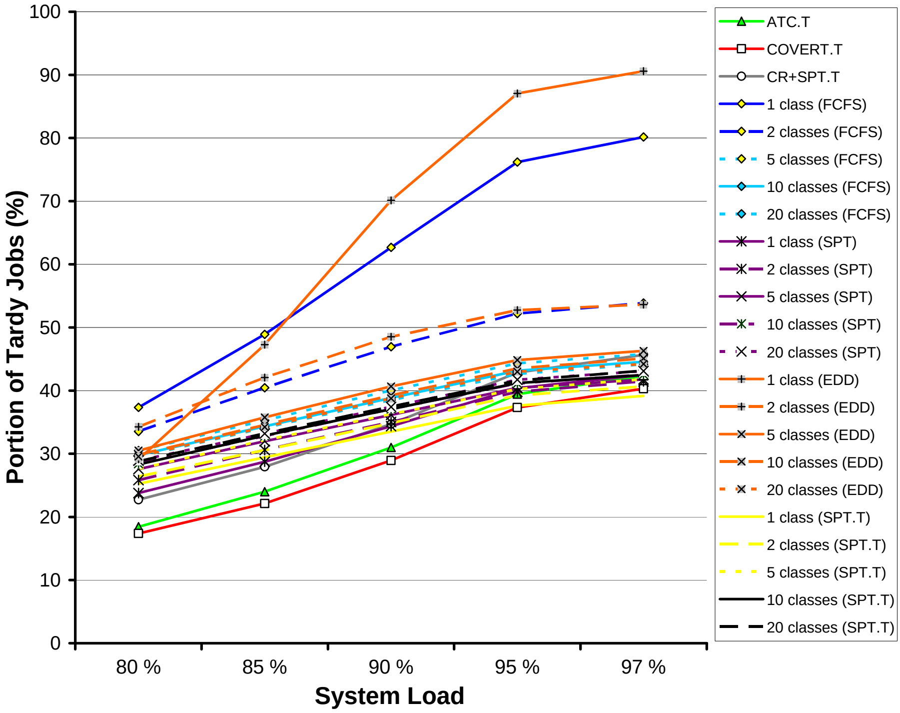

Figure 5-7 Portion of tardy jobs for the priority class systems in comparison to the look-ahead rules in a uniform shop when tight due dates are assigned randomly.

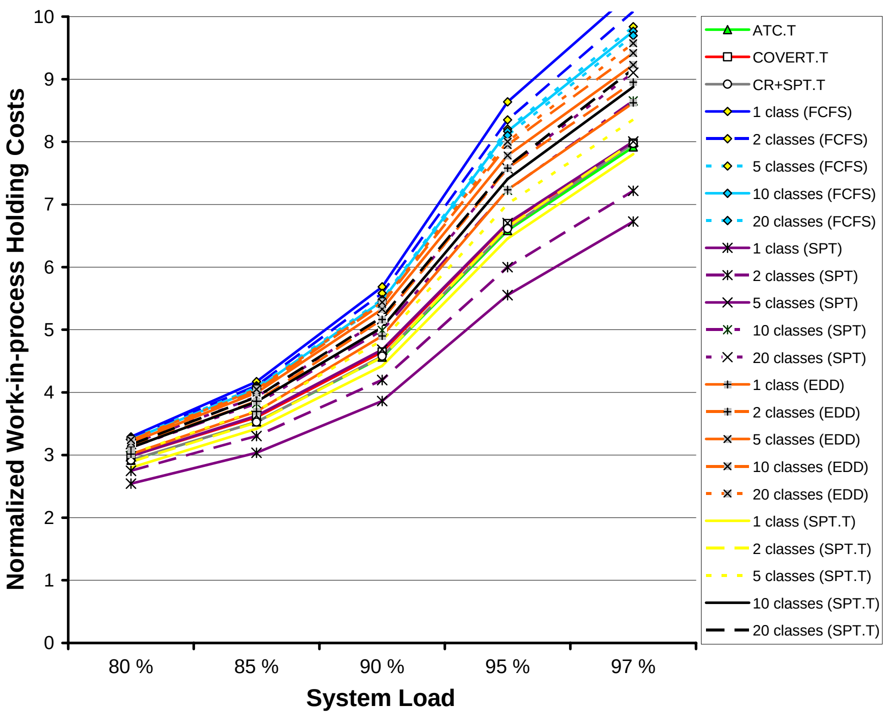

Figure 5-8 Normalized WIP holding costs for the priority class systems in comparison to the look-ahead rules in a uniform shop when tight due dates are assigned randomly.

Other similar kinds of managerial relaxations, which ease the task of priority scheduling in practice, could be examined. It would be interesting to estimate the effects of using a piece-wise linear look-ahead instead of the linear or exponential look-ahead now employed in the ATC and COVERT rules. Namely, a piece-wise linear look-ahead indicating the urgency of orders could be easier to understand and implement in practice. Hence, it could enhance the use of the look-ahead rules in order management and scheduling. Other options include hedging rules and weighting mechanisms that adjust tardiness penalties and remaining processing times depending on the number and type of operations remaining.

5.5 Operation- or Job-based Data

The use of global order information in addition to the detailed data on operations is considered as an approach that can result in order handling decisions which better meet customers' expectations on response times and delivery accuracy. When the aggregation of order data improves the system performance is a relevant question especially for multi-stage operations, since high process visibility and information sharing are not necessarily standard practices there.

In non-delay scheduling, it is relatively easy to assess at least the differences between the use of operation details and the use of order level data. There are some prior results of the effects of an aggregated process and order data on the quality of dispatching decisions. Kanet and Hayya (1982) as well as Baker and Kanet (1983) compared the performance of selected priority index rules such as EDD and CR with stage-specific data and standards/ targets specified for orders. Baker and Kanet (1983) confirmed that the operation-based rules are more efficient than their job-based counterparts. Their superiority, however, is not apparent when due dates are loose. Hence, the results of the prior studies are revisited. The effects of operation-specific data are estimated in comparison to the use of process-wide aggregated data in order dispatching to observe the responses of the look-ahead priority index rules in particular to the type of data.

5.5.1 Test Setting

It is examined how the level and scope of data impacts the performance of eight priority index rules that use order-specific tardiness penalties to coordinate distributed decisions. The selected priority index rules can use either aggregated or disaggregated information on processing times and/or due dates in the calculation of order-specific priority indices. The SPT.T(J)[10] rule, as an example, uses total processing time of all operations, while the standard version of SPT.T, here called SPT.T(O), uses operation-specific processing time. The AVPRO.T(J) rule considers a mean processing time, while the FDD.T(O) rule calculates the operation-specific milestones based on the work content of (preceding) operations (Rajendran and Jaymohan 2000b). For the ATC.T and COVERT.T rules the comparisons are done between the standard versions that use processing time of the current operation in the SPT.T index, which is an element of all look-ahead rules, and versions that use remaining processing time in the priority index. The EDD.T(J) rule uses the final order-specific due date, while the EDD.T(O) rule considers disaggregated due dates derived from the order-specific due date. The MDD.T(J) and MDD.T(O) rules are implemented according to Baker and Bertrand (1982), whereas the CR and SLK rules are specified based on Kutanoglu and Sabuncuoglu (1999). The simulation experiment is conducted in a uniform 10-machine job shop with various levels of system load. Order due dates are determined using the three different due date assignment methods (random slack RANSLK, total work content TWK, and constant CON) with one level of due date tightness (tight).

5.5.2 Results and Observations

In principle, the priority index rules using aggregated data could work well due to the coordination of order progress through a complex system. For example, orders close to completion would receive higher priority leading to a lower portion of late orders. Nevertheless, on the basis of the experiments aggregated order data is not valuable for most of the rules tested especially if the weighted mean tardiness and maximum tardiness are considered. There are two priority index rules, MDD.T and CR.T, which can improve their performance in weighted mean tardiness and maximum tardiness by using order-specific data regardless of the due date assignment method. However, at least for the CR.T rule the use of order-specific data seems to translate into higher portion of tardy jobs. Furthermore, the ATC.T, AVPRO.T, EDD.T, and MDD.T rules can, depending on the due date setting method, use aggregated order data to finish a higher portion of orders on-time, especially when the system load is high (Figure 5-9). In the flow-time based measures, the aggregated order data does not produce desirable coordination effects.

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[10] J for aggregated job data and O for operation-specific data

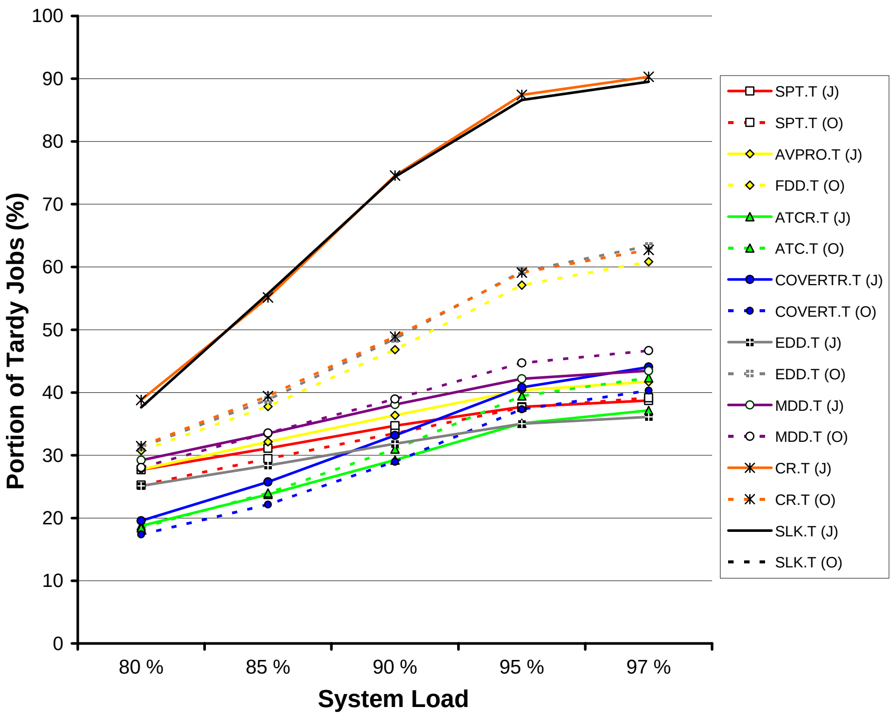

Figure 5-9 Portion of tardy jobs for the different system loads in a uniform shop when tight due dates are assingned randomly (comparison of operation- and job-based data in weighted problem).

Overall, the results indicate that the order-specific data helps to coordinate decisions and improves the rule performance only in some of the cases. Usually, the use of operation-specific data in greedy dispatching decisions gives better results, especially in the weighted mean tardiness. As a result, it would be interesting to examine further the benefits of process visibility in order to estimate the value of information sharing for priority-based order scheduling.

5.6 Summary and Discussion

This chapter explored issues linked to the implementation and use of open protocols in order management and scheduling. First, to estimate the robustness of two look-ahead rules, ATC.T and COVERT.T, alternative methods for estimating waiting times and lead times were compared. It was found that the priority-based lead time estimation clearly improves the performance of the COVERT.T rule, and its impact on the ATC.T rule is on average positive. The examination of tardiness and holding costs demonstrated that neither of the rules is superior but they form an efficient frontier in studied problem instances. In other words, there is a trade-off between the ATC.T and COVERT.T rules. This experiment also showed that the differences among the alternative lead time estimation methods are not significant in most of the important performance measures. Hence, the technical specifications of the estimation method are not critical for the success of the analyzed look-ahead rules. Furthermore, the results imply that the risks due to using managerial heuristics when setting the parameter values and selecting the estimation methods are relatively small. As already mentioned, the performance of the two look-ahead rules can, however, be improved a little by fine-tuning the way how lead times are estimated.

Second, the effects of estimation errors were estimated. The experiment focused on the estimates of processing times and tardiness penalties. The results showed that the look-ahead rules (ATC.T, COVERT.T, and CR+SPT.T) perform worse when the level of estimation errors increases. Inaccurate data increases the weighted mean tardiness especially for the priority rules that seek for a reasonable trade-off between loading efficiency and customer service. Importantly, this deterioration in the system performance does not change the relative rankings of the priority index rules tested even with high load. The best weighted rules using more order information perform better than the common benchmarks, even if the estimates were somewhat inaccurate. This result is expected to eliminate one of the main barriers for using priority scheduling in order management and scheduling. It encourages the assessment and use of detailed order-specific data because the results of look-ahead rules are not highly sensitive to estimation errors.

Third, it was explored how good results are achieved by using rough estimates on order-specific tardiness costs in order dispatching. The motivation for this experiment comes from practice. It is often suitable to design simple principles for sequencing customer orders instead of suggesting sophisticated methods. Thus, the performance of a set of order priority systems, which largely rely on rough tardiness cost information, was compared to the results given by three look-ahead rules. The results of the simulations showed that the order priority systems can outperform the common priority rules FCFS and EDD. Nevertheless, the methods perform significantly worse than the look-ahead rules (ATC.T, COVERT.T and CR+SPT.T) in the key performance measures. This implies that accurate order-specific priority indices should be used instead of managerial categorizations whenever possible.

Fourth, it was tested if job-specific data should be preferred to operation-specific data in order to improve coordination effects of priority dispatch rules. It was found that in most situations the use of aggregated order data for greedy and myopic dispatching decisions does not improve the performance of the tested priority index rules. The rules that rely on disaggregated information on operations provide better loading efficiency/service level. It is explained by the use of local information such as operational due dates which can be coordinated with global lead time estimates and targets. The results also imply that process visibility leading to expediting of some orders on the basis of their remaining operations may have an unfavorable impact on performance.

The results of the simulation experiments discussed in this chapter further support the benchmarking framework introduced for integrated order management in Section 2.4. According to the basic guideline of the framework priority indices have to be updated dynamically at each operation for tackling all but the easiest (level 1) scheduling tasks. However, the anticipation of the interference by other jobs by probing the load in the next queue, for instance, turned out to be too complex to contribute to the coordination except for a few unweighted criteria, as in the case of the RR rule. Furthermore, updating and disaggregating the rules by operation based data on due dates and slack improves the performance in terms of weighted tardiness and portion of tardy jobs in some easy cases. However, it basically is the economic rationale of trading off the loading efficiency against the longer slack in the three dynamic look-ahead rules that leads to consistently excellent performance in scheduling tasks of level 2 and even level 3. According to the stipulation of the benchmarking framework, achieving the potential for improvement in the complex problems requires the application of unbiased lead time estimates, as demonstrated by the robust performance of the COVERT rule with the priority-based lead time estimates in particular. Rational expectations work in terms of the lead time iteration method also (Vepsalainen and Morton 1988). The limits of complexity for the application of priority index rules may well be here, considering the previous unsuccessful attempts to incorporate adaptive probing along with the lead time iteration in the ATC and COVERT rules (Vepsalainen 1984). Furthermore, the rationale of the look-ahead rules is sound also in terms of immunity against incorrect data, as indicated by the remarkable results with persistent estimation errors in processing times and tardiness penalties. On the other hand, using crude classifications of the weights or job-based processing times inevitably deteriorates the performance of even the best rules in most of the cases. All in all, the benchmarking framework can be considered as a reliable guide for using simple, robust, and decomposable dispatch priority rules as a way to coordinate postponed and localized decision-making in different job shops.

6 Illustrations of Alternative Scheduling Conventions

Scheduling rules can be applied in many alternative ways. Their effects on the system performance depend not only on the way how the dispatch priority rules are used but also on the other methods of order handling. This chapter first examines the effects of order release mechanisms selected from the literature on system performance compared to applying priority index rules only. Second, the mixed use of priority index rules is explored in the context of job shops in order to recognize the effects of combining different types of priority rules. Third, order-specific lead times are studied by investigating how operation due dates hold from the perspective of individual orders. This new type of experiment is motivated, for example by the need to understand the key properties of look-ahead rules.

6.1 Screening with Order Release Policies

The prior research on order scheduling has offered different types of order review and input/output control mechanisms as practical tools for production planners and schedulers. The release mechanisms are argued not only to balance the WIP level but also to ease the task of scheduling so that sophisticated priority rules are no longer needed on the shop floor. Next, it is studied how the screening of arriving orders using order release mechanisms influences the performance of job shops compared to applying priority index rules only.

6.1.1 Combinations of Order Release Policies and Priority Rules

Three basic order release mechanisms are tested. These methods are fixed release rate (FIXED), constant number of orders on the shop floor (CONWIP), and maximum limit for workload pending on the shop floor (MWL). The release mechanisms are supplemented with release priority and dispatching rules that determine which orders are dispatched on idle resources (dispatching rule) and which orders are released to the shop floor (release priority). The selected three release methods are tested with the FCFS and EDD priority rules because the fundamental reasoning of formal screening, which is that they remove the need for sophisticated dispatch priority rules on the shop floor. As a result, the experimental design includes 12 alternative policies for releasing and sequencing customer orders. Additionally, six priority index rules (ATC.T, COVERT.T, CR+SPT.T, EDD, FCFS, and SPT.T) with immediate release of orders to the shop floor are considered as the benchmarks (Table 6-1).

All order release policies, 18 in total, are tested in a 10-machine job shop. In the experiments, tight due dates are assigned randomly and order-specific processing times are either uniform or proportionate over operations.

Table 6-1 Order release policies that combine the rules of release, release priority, and dispatching.

#	Combination	Release rule	Release priority	Dispatching
1	IMM & FCFS	Immediate release	-	FCFS
2	IMM & EDD	Immediate release	-	EDD
3	IMM & SPT	Immediate release	-	SPT.T
4	IMM & ATC	Immediate release	-	ATC.T
5	IMM & COVERT	Immediate release	-	COVERT.T
6	IMM & CR+SPT	Immediate release	-	CR+SPT.T
7	FIXED (FCFS) & FCFS	Standard rate (interval=6)	FCFS	FCFS
8	FIXED (FCFS) & EDD	Standard rate (interval=6)	FCFS	EDD
9	FIXED (EDD) & FCFS	Standard rate (interval=6)	EDD	FCFS
10	FIXED (EDD) & EDD	Standard rate (interval=6)	EDD	EDD
11	CONWIP (FCFS) & FCFS	Constant work-in-process (max WIP=50)	FCFS	FCFS
12	CONWIP (FCFS) & EDD	Constant work-in-process (max WIP=50)	FCFS	EDD
13	CONWIP (EDD) & FCFS	Constant work-in-process (max WIP=50)	EDD	FCFS
14	CONWIP (EDD) & EDD	Constant work-in-process (max WIP=50)	EDD	EDD
15	MWL (FCFS) & FCFS	Maximum workload (max WL=5000)	FCFS	FCFS
16	MWL (FCFS) & EDD	Maximum workload (max WL=5000)	FCFS	EDD
17	MWL (EDD) & FCFS	Maximum workload (max WL=5000)	EDD	FCFS
18	MWL (EDD) & EDD	Maximum workload (max WL=5000)	EDD	EDD

The parameters of the screening mechanisms are set on the basis of logical reasoning that is expected to be applied by practitioners. The average arrival rate of orders to the system varies between 9 and 11 depending on the load. Hence, the standard release rate imposed by the FIXED policy is defined to be more frequent, six in this case. In the CONWIP policy, the maximum number of orders pending or being worked on on the shop floor is limited to 50 orders. Consequently, there are on average four orders in each resource-specific queue. The maximum amount of work released by the MWL policy is determined using statistical data on the average processing times of orders, and therefore the workload limit is set to 5,000 work units. Some tests were run to ascertain that these selected parameter values are appropriate.

6.1.2 Results and Observations

The comparison of the order release mechanisms to the dispatch priority rules, some of which have an internal mechanism for adjusting the release of each order depending on its work content and current system load, reveals the advantages of order release in large job shop environments. Especially with high system load, dispatchers can reduce mean flow time, work-in-system holding costs, and maximum tardiness by controlling order releases. The impact of a controlled order flow on relative mean flow times demonstrates that workload-based mechanisms are indeed superior in shortening and standardizing relative mean flow times as reported in the prior research (Figure 6-1).

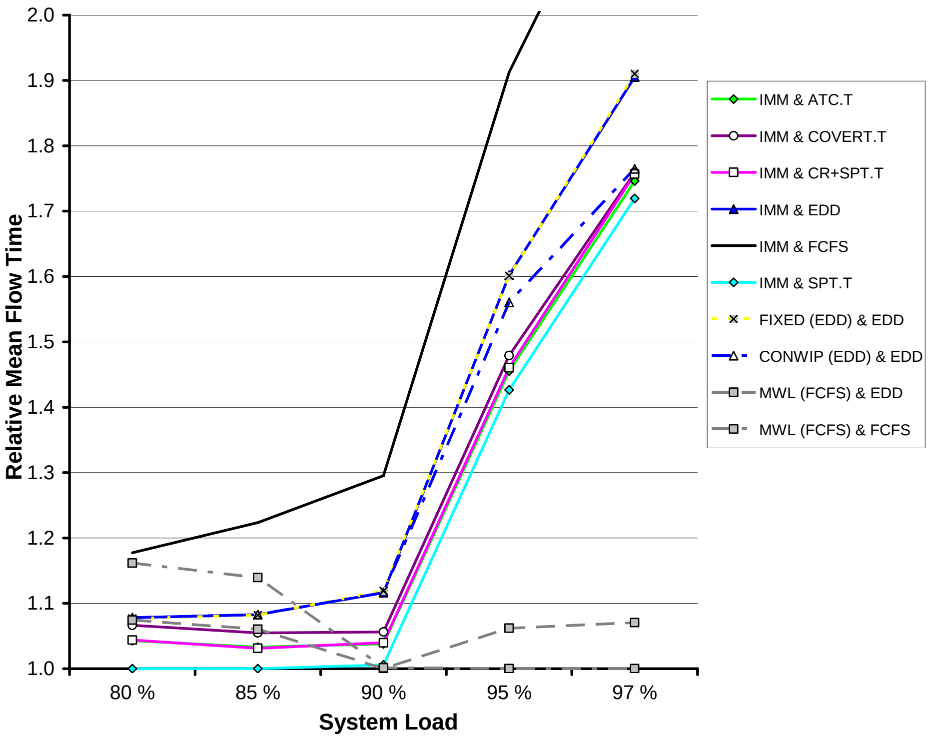

Figure 6-1 Relative mean flow times for selected release policies in the base case (weighted job shop problem with 1-10 operations per order and tight randomly assigned due dates).

The comparison of the best order screening methods to the average performance of the three look-ahead rules (ATC.T, COVERT.T and CR+SPT.T with immediate release) brings out the following. Depending on the system load, the best order release mechanism gives 0.7-4 times higher weighted average tardiness, 50-100% higher portion of tardy jobs, and up to 10% higher WIP holding costs than the average of the three look-ahead rules (Table 6-2). The best release policy is more efficient in reducing mean flow times, WIS holding costs, and maximum tardiness, especially when the system load is high. The effects of the queue discipline applied in release and dispatching of orders depends on the release policy, performance measure, and system load. The choice of the release priority has an impact when the MWL method is used: the EDD rule gives lower weighted mean and maximum tardiness, whereas the FCFS rule produces shorter mean flow times especially with high system load. In dispatching, the EDD rule gives better results for all three order release mechanisms in weighted mean and maximum tardiness, especially when system load is moderate (80%-

85%). Furthermore, if the system load is high, the use of the EDD rule increases the portion of tardy jobs for the FIXED and CONWIP policies. The EDD rule as dispatch priority rule deteriorates also the results of the MWL policy in mean flow time and WIS holding costs.

Table 6-2 Performance of all order release policies in proportionate and uniform shops when the system load is 85% or 95% and tight due dates are assigned randomly.

	System load 85%											
	Uniform shop & RANSLK						**Proportionate shop & RANSLK**					
Rule	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**
IMM & ATC.T	0.18	9411	24.0	310	1.03	3.53	0.20	11366	23.9	294	1.07	3.56
IMM & COVERT.T	0.17	10036	22.1	317	1.05	3.60	0.18	11026	22.4	299	1.09	3.62
IMM & CR+SPT.T	0.21	10978	27.9	309	1.03	3.53	0.23	11171	28.1	293	1.07	3.55
IMM & EDD	0.49	9397	47.3	325	1.08	3.69	0.54	9700	48.7	311	1.13	3.76
IMM & FCFS	1.26	25697	48.9	367	1.22	4.17	1.25	25014	48.5	342	1.24	4.14
IMM & SPT.T	0.39	13577	29.4	300	1.00	3.42	0.38	15902	28.7	275	1.00	3.33
FIXED (FCFS) & FCFS	1.28	25153	49.6	366	1.22	4.21	1.26	25468	49.3	341	1.24	4.19
FIXED (FCFS) & EDD	0.51	9563	49.0	325	1.08	3.75	0.58	9777	50.5	310	1.13	3.82
FIXED (EDD) & FCFS	1.27	26118	49.5	365	1.22	4.21	1.26	24765	49.2	341	1.24	4.19
FIXED (EDD) & EDD	0.52	9602	49.0	325	1.08	3.75	0.57	9723	50.5	310	1.13	3.82
CONWIP (FCFS) & FCFS	1.26	25697	48.9	367	1.22	4.17	1.25	25014	48.5	342	1.24	4.14
CONWIP (FCFS) & EDD	0.49	9397	47.3	325	1.08	3.69	0.54	9700	48.7	311	1.13	3.76
CONWIP (EDD) & FCFS	1.26	25697	48.9	367	1.22	4.17	1.25	25014	48.5	342	1.24	4.14
CONWIP (EDD) & EDD	0.49	9397	47.3	325	1.08	3.69	0.54	9700	48.7	311	1.13	3.76
MWL (FCFS) & FCFS	1.51	26559	54.0	342	1.14	4.57	1.45	25455	52.7	322	1.17	4.47
MWL (FCFS) & EDD	0.55	9849	48.2	318	1.06	3.77	0.61	10239	49.6	302	1.10	3.85
MWL (EDD) & FCFS	1.40	23537	53.1	341	1.13	4.45	1.34	21920	51.8	321	1.17	4.35
MWL (EDD) & EDD	0.54	9692	48.3	320	1.06	3.77	0.59	10008	49.3	304	1.10	3.82

	System load 95%											
	Uniform shop & RANSLK						**Proportionate shop & RANSLK**					
Rule	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**	**mWT**	**maxWT**	**TJ (%)**	**mFT**	**rFT**	**WIP**
IMM & ATC.T	0.72	28927	39.4	578	1.46	6.59	0.72	31673	37.1	522	1.35	6.33
IMM & COVERT.T	0.70	30650	37.3	588	1.48	6.69	0.68	31896	35.7	527	1.36	6.38
IMM & CR+SPT.T	0.73	29845	42.9	580	1.46	6.61	0.72	32743	41.4	523	1.35	6.34
IMM & EDD	3.42	26093	87.1	637	1.60	7.24	3.33	24036	87.1	589	1.52	7.13
IMM & FCFS	5.10	59361	76.2	760	1.91	8.64	4.85	55625	75.6	691	1.79	8.37
IMM & SPT.T	1.00	32486	37.6	567	1.43	6.46	0.98	36774	36.3	498	1.29	6.03
FIXED (FCFS) & FCFS	5.13	58065	76.7	759	1.91	8.69	4.91	55984	76.2	692	1.79	8.45
FIXED (FCFS) & EDD	3.47	26358	87.4	635	1.60	7.29	3.38	24334	87.8	588	1.52	7.20
FIXED (EDD) & FCFS	5.16	58485	76.7	761	1.92	8.71	4.92	55443	76.2	693	1.79	8.47
FIXED (EDD) & EDD	3.48	26223	87.4	636	1.60	7.30	3.38	24376	87.8	589	1.52	7.20
CONWIP (FCFS) & FCFS	5.10	52757	77.7	706	1.78	8.68	4.82	49854	76.7	647	1.68	8.38
CONWIP (FCFS) & EDD	3.46	26319	87.2	620	1.56	7.27	3.36	24246	87.2	573	1.48	7.17
CONWIP (EDD) & FCFS	5.04	51881	77.5	705	1.77	8.62	4.79	48362	76.7	647	1.68	8.35
CONWIP (EDD) & EDD	3.46	26242	87.1	620	1.56	7.28	3.36	24239	87.2	573	1.48	7.17
MWL (FCFS) & FCFS	11.39	75046	92.4	397	1.00	15.27	10.41	66589	91.7	387	1.00	14.28
MWL (FCFS) & EDD	6.69	42575	91.4	422	1.06	10.59	6.26	38139	91.5	406	1.05	10.15
MWL (EDD) & FCFS	11.32	73610	92.1	398	1.00	15.23	9.79	62073	91.0	386	1.00	13.66
MWL (EDD) & EDD	6.27	40434	90.9	436	1.10	10.17	5.78	36328	90.9	428	1.11	9.67

The actual cost differences among the order release policies are not significant. This is confirmed in Figure 6-2, which illustrates the work-in-process holding costs of selected order release policies compared to the priority index rules. In weighted mean tardiness (Figure 6-3) as well as in the portion of tardy jobs (Figure 6-4) the look-ahead rules work significantly better than the release policies tested. Overall, the results of these experiments indicate that the use of order screening can prove beneficial especially when the utilization of resources is low, since otherwise early order releases give rise to high system-level holding costs.

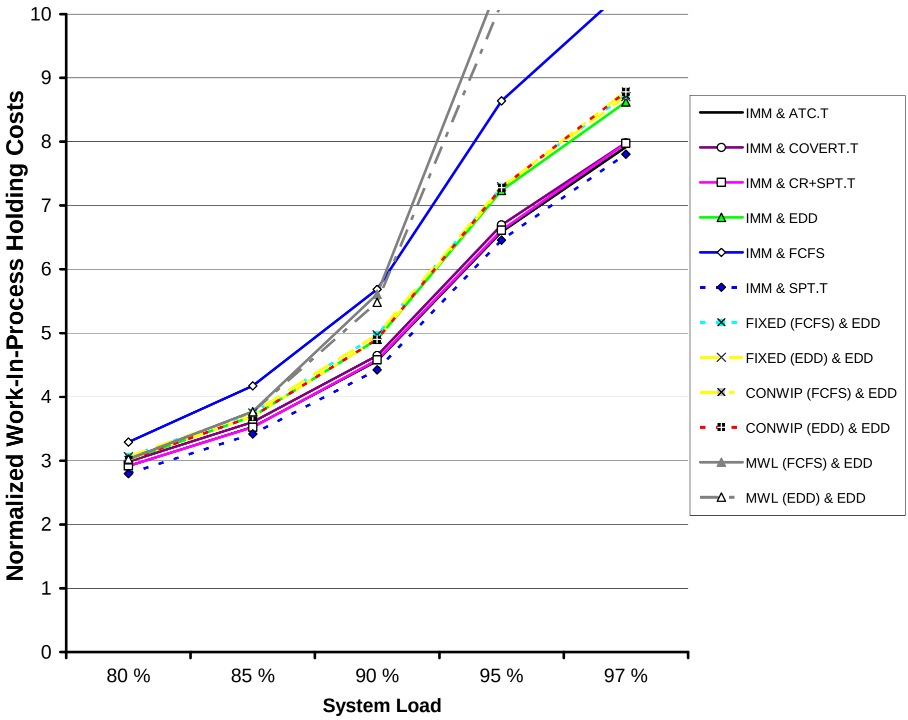

Figure 6-2 Normalized WIP holding costs for selected order release policies in the base case.

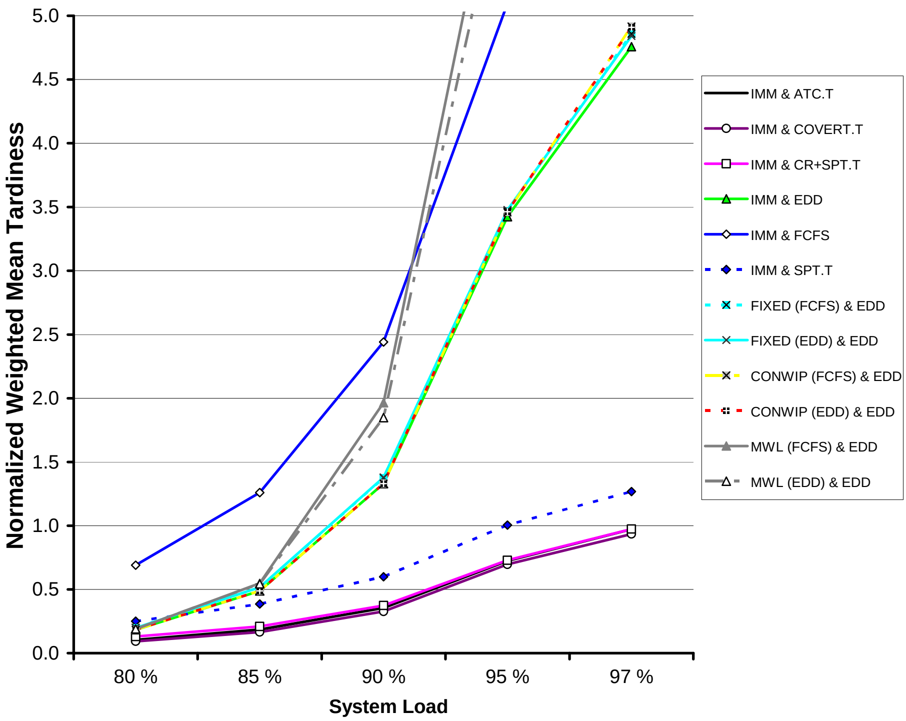

Figure 6-3 Weighted mean tardiness for selected order release policies in the base case.

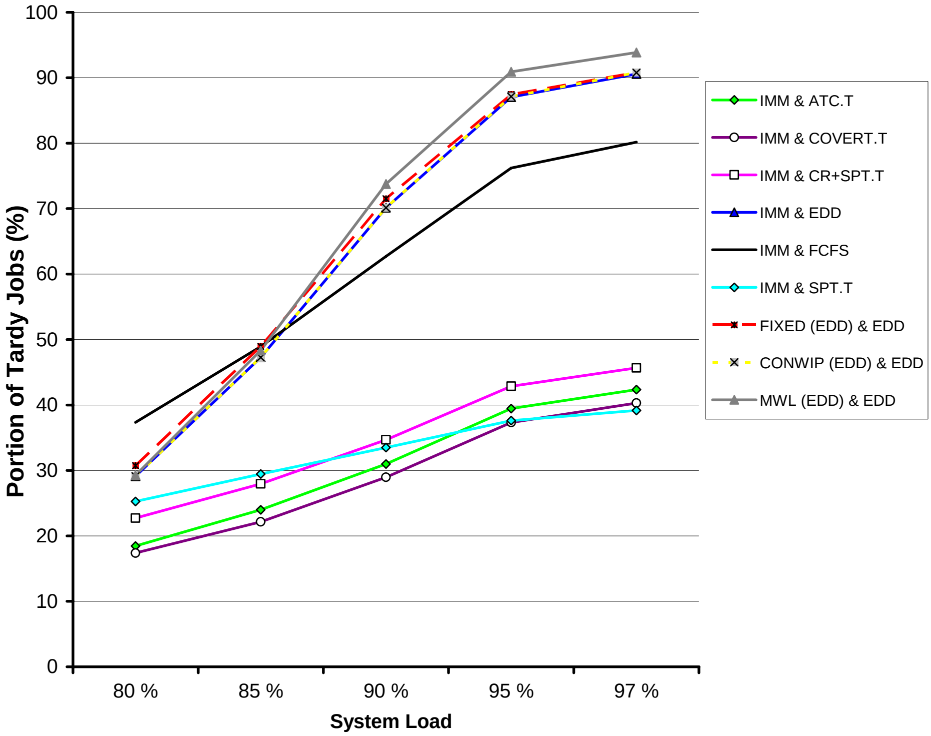

Figure 6-4 Portion of tardy jobs for selected order release policies in the base case.

When analyzing the results of these experiments it has to be remembered that this research studies the performance of alternative conventions of order management and scheduling in production systems where the response time requests of customers have variability and manufacturers readjust to the lead time requirements. Naturally, the effects of order release mechanisms would be different if the congestion on the shop floor could be converted into longer lead times, i.e. manufacturers could quote lead times calculated by adding the expected waiting time before order release to the standard throughput time including also waiting during the process.

6.2 Mixed Use of Priority Index Rules at Different Operations

Reaching consensus on the priority index rule can be challenging even within one organization. In flow shops, the effect of combining simple priority rules has been examined. Mahmoodi *et al.* (1996) and Barman (1998) concluded that combined strategies work better than the pure forms of EDD, SPT, SLK, and SI^x rules[11], especially with multiple objectives.

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[11] The SI^x rule is a modification of the SPT rule combining job slacks and their processing times.

The ramifications of not being able to control that every decision-maker in a job shop uses the same priority index rule are not known. The previous experiments have shown that there are three look-ahead rules that succeed in making trade-offs between loading efficiency and customer service better than other rules in job shops, similarly as the rule combinations recommended for flow-dominant shops in Barman (1997, 1998). Hence, it is worthwhile to investigate, particularly with these look-ahead rules, how important it is that all decision-makers in a job shop agree on using the same priority index rule.

6.2.1 Rule Mixes in Five-Machine Job Shop

The effects of mixing more than one priority index rule are studied within a 5-machine job shop. The benchmarks for estimating the performance impact of the hybrid strategies is provided by cases in which every decision-maker uses the same priority index rule. The main interest is to identify if there are rule combinations that should be avoided or favored to gain better system performance especially in normalized weighted mean tardiness and portion of tardy jobs. Six priority index rules are included in this experiment: three benchmark rules (EDD, FCFS, and SPT.T) and the suggested family of look-ahead rules (ATC.T, COVERT.T, and CR+SPT.T). For each of the rules two alternative hybrid strategies (i.e. mixed use) are tested. In the first mix, four of the resources apply the same rule and one resource uses a different rule, which is one of the other five priority rules included in this experiment. In the second mix, three resources apply the same rule and two resources use a different priority index rule. Simulations are carried out in the base case, i.e. tight due dates are assigned randomly in the uniform shop. There are, however, only five machines in the job shop, and it follows that the number of operations per order varies between one and five.

6.2.2 Results and Observations

Performances of the benchmarks, i.e. the results given by the pure strategies, are reported in raw values in Table 6-3. Other numbers show, per each level of system load, the relative changes from the rule-specific benchmarks due to the mixed use of priority rules. If two resources apply a different priority rule, the effects on performance are as indicated in Table 6-4. Typically, the changes are larger when the utilization of resources is higher. For example, the negative impact of the EDD rule on the weighted mean tardiness increases as the system load increases for all other priority index rules except for the FCFS rule. The SPT.T rule illustrates an exception. It increases the weighted mean tardiness and portion of tardy jobs when used with any of the three look-ahead rules, but the effect is smaller when the system load is higher.

Table 6-3 Effects of the mixed use of priority index rules in a 5-machine job shop in weighted mean tardiness and portion of tardy jobs when one resources uses a different rule.

Difference in normalized weighted mean tardiness

Rule at 4 machines	System load	Priority index rule applied at 1 machine					
		ATC.T	COVERT.T	CR+SPT.T	EDD	FCFS	SPT.T
	80 %	***0.16***	-2 %	3 %	28 %	62 %	15 %
	85 %	***0.27***	0 %	1 %	37 %	66 %	11 %
ATC.T	90 %	***0.49***	3 %	0 %	57 %	73 %	7 %
	95 %	***0.97***	3 %	0 %	82 %	90 %	5 %
	97 %	***1.32***	3 %	0 %	94 %	93 %	3 %
	80 %	2 %	***0.15***	4 %	32 %	70 %	17 %
	85 %	1 %	***0.26***	3 %	43 %	75 %	13 %
COVERT.T	90 %	1 %	***0.47***	2 %	61 %	78 %	8 %
	95 %	1 %	***0.95***	2 %	87 %	93 %	5 %
	97 %	0 %	***1.30***	1 %	99 %	96 %	4 %
	80 %	-1 %	-3 %	***0.18***	21 %	54 %	12 %
	85 %	-2 %	-2 %	***0.29***	30 %	58 %	9 %
CR+SPT.T	90 %	-1 %	1 %	***0.49***	49 %	68 %	8 %
	95 %	1 %	5 %	***0.97***	79 %	84 %	5 %
	97 %	1 %	4 %	***1.30***	90 %	92 %	4 %
	80 %	-12 %	-11 %	-13 %	***0.37***	21 %	-8 %
	85 %	-14 %	-10 %	-14 %	***0.80***	15 %	-10 %
EDD	90 %	-14 %	-11 %	-14 %	***1.91***	12 %	-13 %
	95 %	-14 %	-11 %	-14 %	***5.03***	7 %	-13 %
	97 %	-11 %	-10 %	-12 %	***7.30***	6 %	-10 %
	80 %	-19 %	-17 %	-19 %	-10 %	***0.80***	-16 %
	85 %	-20 %	-17 %	-20 %	-9 %	***1.44***	-18 %
FCFS	90 %	-19 %	-16 %	-19 %	-6 %	***2.84***	-18 %
	95 %	-17 %	-15 %	-17 %	-5 %	***6.45***	-17 %
	97 %	-16 %	-14 %	-16 %	-3 %	***9.09***	-16 %
	80 %	-11 %	-13 %	-8 %	4 %	24 %	***0.29***
	85 %	-9 %	-10 %	-8 %	14 %	29 %	***0.44***
SPT.T	90 %	-8 %	-8 %	-6 %	30 %	43 %	***0.70***
	95 %	-5 %	-3 %	-4 %	61 %	61 %	***1.21***
	97 %	-4 %	-3 %	-4 %	70 %	73 %	***1.58***

Difference in portion of tardy jobs

Rule at 4 machines	System load	Priority index rule applied at 1 machine					
		ATC.T	COVERT.T	CR+SPT.T	EDD	FCFS	SPT.T
	80 %	***20.0***	2 %	4 %	15 %	23 %	5 %
	85 %	***24.7***	4 %	3 %	21 %	26 %	2 %
ATC.T	90 %	***30.7***	7 %	3 %	31 %	31 %	0 %
	95 %	***37.8***	9 %	2 %	41 %	41 %	-2 %
	97 %	***40.3***	12 %	3 %	47 %	44 %	-1 %
	80 %	2 %	***18.8***	4 %	18 %	26 %	6 %
	85 %	1 %	***23.4***	5 %	25 %	31 %	4 %
COVERT.T	90 %	0 %	***29.4***	5 %	34 %	36 %	1 %
	95 %	2 %	***35.9***	5 %	47 %	45 %	0 %
	97 %	1 %	***38.7***	4 %	51 %	47 %	0 %
	80 %	-2 %	-1 %	***23.1***	9 %	15 %	1 %
	85 %	-4 %	1 %	***28.5***	13 %	18 %	-1 %
CR+SPT.T	90 %	-3 %	4 %	***34.8***	23 %	24 %	-2 %
	95 %	-2 %	8 %	***42.1***	33 %	32 %	-3 %
	97 %	-2 %	8 %	***45.3***	37 %	34 %	-4 %
	80 %	-7 %	-5 %	-5 %	***32.6***	6 %	-5 %
	85 %	-7 %	-4 %	-6 %	***47.3***	3 %	-7 %
EDD	90 %	-7 %	-5 %	-6 %	***66.8***	1 %	-8 %
	95 %	-6 %	-4 %	-6 %	***85.5***	-1 %	-7 %
	97 %	-4 %	-3 %	-4 %	***89.9***	-1 %	-5 %
	80 %	-7 %	-4 %	-6 %	0 %	***37.5***	-7 %
	85 %	-6 %	-3 %	-6 %	1 %	***49.0***	-7 %
FCFS	90 %	-6 %	-2 %	-5 %	3 %	***62.8***	-7 %
	95 %	-5 %	-2 %	-4 %	2 %	***78.3***	-6 %
	97 %	-4 %	-2 %	-3 %	2 %	***83.1***	-5 %
	80 %	-3 %	-2 %	0 %	8 %	13 %	***23.8***
	85 %	-2 %	3 %	1 %	16 %	18 %	***27.5***
SPT.T	90 %	-2 %	6 %	2 %	27 %	26 %	***31.7***
	95 %	1 %	12 %	4 %	44 %	39 %	***35.7***
	97 %	2 %	14 %	4 %	50 %	45 %	***37.3***

Table 6-4 Effects of the mixed use of priority index rules in a 5-machine job shop in weighted mean tardiness and portion of tardy jobs when two resources use a different rule.

Difference in normalized weighted mean tardiness

Rule at 3 machines	System load	Priority index rule applied at 2 machines					
		ATC.T	COVERT.T	CR+SPT.T	EDD	FCFS	SPT.T
	80 %	***0.16***	-3 %	4 %	48 %	129 %	29 %
	85 %	***0.27***	-1 %	2 %	76 %	142 %	22 %
ATC.T	90 %	***0.49***	3 %	0 %	115 %	164 %	15 %
	95 %	***0.97***	7 %	0 %	183 %	211 %	10 %
	97 %	***1.32***	6 %	-1 %	213 %	237 %	7 %
	80 %	4 %	***0.15***	7 %	57 %	144 %	35 %
	85 %	3 %	***0.26***	6 %	87 %	159 %	26 %
COVERT.T	90 %	2 %	***0.47***	3 %	121 %	179 %	17 %
	95 %	1 %	***0.95***	1 %	191 %	221 %	10 %
	97 %	1 %	***1.30***	1 %	224 %	248 %	8 %
	80 %	-2 %	-5 %	***0.18***	37 %	115 %	25 %
	85 %	-3 %	-4 %	***0.29***	64 %	129 %	20 %
CR+SPT.T	90 %	-1 %	-1 %	***0.49***	110 %	161 %	16 %
	95 %	0 %	1 %	***0.97***	181 %	211 %	12 %
	97 %	1 %	1 %	***1.30***	214 %	236 %	8 %
	80 %	-23 %	-23 %	-23 %	***0.37***	45 %	-12 %
	85 %	-27 %	-26 %	-26 %	***0.80***	34 %	-18 %
EDD	90 %	-30 %	-29 %	-30 %	***1.91***	21 %	-26 %
	95 %	-32 %	-31 %	-33 %	***5.03***	13 %	-30 %
	97 %	-31 %	-31 %	-32 %	***7.30***	11 %	-30 %
	80 %	-37 %	-37 %	-37 %	-21 %	***0.80***	-31 %
	85 %	-38 %	-37 %	-37 %	-19 %	***1.44***	-34 %
FCFS	90 %	-38 %	-38 %	-39 %	-13 %	***2.84***	-36 %
	95 %	-39 %	-38 %	-39 %	-8 %	***6.45***	-38 %
	97 %	-38 %	-37 %	-38 %	-7 %	***9.09***	-37 %
	80 %	-19 %	-21 %	-16 %	6 %	53 %	***0.29***
	85 %	-18 %	-19 %	-16 %	26 %	69 %	***0.44***
SPT.T	90 %	-14 %	-15 %	-13 %	67 %	101 %	***0.70***
	95 %	-8 %	-9 %	-9 %	138 %	160 %	***1.21***
	97 %	-8 %	-8 %	-7 %	170 %	188 %	***1.58***

Difference in portion of tardy jobs

Rule at 3 machines	System load	Priority index rule applied at 2 machines					
		ATC.T	COVERT.T	CR+SPT.T	EDD	FCFS	SPT.T
	80 %	***20.0***	5 %	7 %	29 %	42 %	8 %
	85 %	***24.7***	9 %	6 %	42 %	49 %	5 %
ATC.T	90 %	***30.7***	14 %	6 %	59 %	59 %	0 %
	95 %	***37.8***	20 %	4 %	74 %	69 %	-3 %
	97 %	***40.3***	23 %	5 %	79 %	73 %	-4 %
	80 %	3 %	***18.8***	10 %	34 %	48 %	11 %
	85 %	3 %	***23.4***	11 %	49 %	56 %	7 %
COVERT.T	90 %	2 %	***29.4***	8 %	65 %	66 %	3 %
	95 %	2 %	***35.9***	9 %	82 %	77 %	0 %
	97 %	2 %	***38.7***	8 %	85 %	79 %	-1 %
	80 %	-5 %	-7 %	***23.1***	18 %	30 %	1 %
	85 %	-6 %	-7 %	***28.5***	28 %	34 %	-2 %
CR+SPT.T	90 %	-4 %	-5 %	***34.8***	46 %	45 %	-4 %
	95 %	-4 %	-5 %	***42.1***	61 %	55 %	-6 %
	97 %	-4 %	-5 %	***45.3***	63 %	57 %	-8 %
	80 %	-15 %	-16 %	-11 %	***32.6***	9 %	-11 %
	85 %	-17 %	-18 %	-15 %	***47.3***	5 %	-16 %
EDD	90 %	-17 %	-18 %	-16 %	***66.8***	-1 %	-19 %
	95 %	-15 %	-15 %	-13 %	***85.5***	-3 %	-16 %
	97 %	-12 %	-12 %	-11 %	***89.9***	-3 %	-14 %
	80 %	-16 %	-16 %	-13 %	-2 %	***37.5***	-13 %
	85 %	-15 %	-15 %	-13 %	1 %	***49.0***	-15 %
FCFS	90 %	-14 %	-14 %	-13 %	5 %	***62.8***	-17 %
	95 %	-12 %	-11 %	-11 %	4 %	***78.3***	-15 %
	97 %	-10 %	-10 %	-9 %	3 %	***83.1***	-13 %
	80 %	-6 %	-8 %	-1 %	17 %	25 %	***23.8***
	85 %	-4 %	-6 %	2 %	32 %	35 %	***27.5***
SPT.T	90 %	-2 %	-3 %	4 %	55 %	51 %	***31.7***
	95 %	2 %	1 %	8 %	81 %	72 %	***35.7***
	97 %	4 %	3 %	9 %	88 %	78 %	***37.3***

Noteworthy observations on the performance of the look-ahead rules include:

- The look-ahead rules generally have a positive effect on the indicators also when applied at one or two of resources only.
- The benefits of the look-ahead rules increase when applied at more resources.
- The performance of the look-ahead rules deteriorates clearly if another priority index rule (not a look-ahead rule) is applied at any of the resources.
- The use of the look-ahead rules at some of the resources cannot significantly improve the poor system performance initiated by other priority index rules.

The positive impact of the look-ahead rules (ATC.T, COVERT.T, and CR+SPT.T) on the weighted mean tardiness is intuitive. Even one resource can arrange orders into a good sequence for remaining operations. Furthermore, the effect of applying one of the look-ahead rules at a single resource only is typically positive, when measured in the weighted mean tardiness and the portion of tardy jobs. The look-ahead rules still cannot improve the performance of the hybrid strategies using FCFS, EDD or SPT.T as the dominant rule to the level of the best performing rule combinations. Additionally, most of the possible mixes of the look-ahead rules result in robust performance. This indicates that allowing each decision-maker to select the most suitable rule from the family of look-ahead rules is reasonable.

6.3 Predictability of Tardiness Behavior of Orders over Operations

There are many ways to estimate lead times and assign due dates as discussed in Chapter 4. Typically, the power of the methods that use job-specific attributes and/or knowledge on the system load has been estimated, for example, with average tardiness and standard deviation of lateness, since from the perspective of orders and customers it is relevant to investigate the accuracy of lead time estimates. In non-delay scheduling, nevertheless, it is not a valid objective for an analysis because delaying of orders to meet their estimated lead times and waiting for soon-to-arrive higher priority orders is not reasonable or feasible. Thus, the keeping of operation due dates, i.e. the signaling value of job progress through the system, is explored. New ways are suggested for investigating the predictability of the on-time progress of orders through the shop and for assessing to what extent the system performance is linked to the type of priority rules used.

6.3.1 Type of Analysis in Four-Machine Job Shop

In this experiment the job shop consists of 4 machines. The common set of 10,000 orders is generated statistically using the standard assumptions on processing times, costs, sizes, and routings so that each order can have from one to four operations. Moreover, tight due dates are set using either the random slack or the total work content method. The system performance is monitored with two levels of load that are medium (85%) and high (95%). Two standard benchmarks (EDD and SPT.T) and four priority index rules (ATC.T, COVERT.T, CR+SPT.T, and S/RPT+SPT) were considered. The ATC.T and COVERT.T rules are tested with both the priority-based lead time estimates (PRIO) and the standard lead time estimates (STD). Hence, in total 8 rules are considered. Data on the sequence and timing of all orders is recorded during one replication for each of the test settings.

It would be useful for practitioners to know what customer orders are typically not completed by given due dates, and to what extent the explanatory properties, if at all, are linked to the order scheduling policies imposed within the production system. Furthermore, it is increasingly important due to advanced tracking systems to be able to anticipate what type of orders are exposed to the risk of being late in the process and what type of orders have more potential to attain their estimated stage-specific flow times and operation due dates. Thus, for this analysis the completed orders are classified into four groups using two criteria: their final status at the end of the process (tardy/on-time) and status before their last operation (tardy/on-time)[12].

6.3.2 Key Findings

First it is evaluated how much the level of system load and the type of due date assignment method influence the rule performance. It is observed that the EDD and S/RPT+SPT rules work worse when the system load is high with both due date methods (Figure 6-5). The use of priority-based lead time estimation helps both the ATC.T and COVERT.T rules to finish more jobs on-time. This means that they find the most urgent orders for processing better. Furthermore, the CR+SPT rule seems to delay more of the orders that were still on-time before their last operation (Job type 3) than the other priority index rules considered. An interesting finding on order tardiness behavior of the COVERT.T (PRIO) rule is that it succeeds in attaining the planned schedule of more orders over the last operation than the other priority index rules. Further comparison of the characteristics of job types with the different look-ahead priority rules shows that Type 2 orders are somewhat different for the COVERT.T rule than for the other two look-ahead rules. For the COVERT.T rule, Type 2 orders are on average smaller, their first operation is shorter, and their tardiness penalty is higher. The statistics also report that these orders are typically tardier at their first or second operation with the COVERT.T rule than with the other rules, which is explained by the internal order release mechanism. Moreover, Type 2 and Type 4 jobs have on average a higher number of operations than other job types regardless of the priority rule considered.

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[12] Job Type 1 = Order is on-time before its last operation and is finished on-time, Job Type 2= Order is tardy before its last operation but is finished on-time, Job Type 3 = Order is on-time before its last operation but is finished late, Job Type 4 = Order is tardy before its last operation and it is finished tardy.

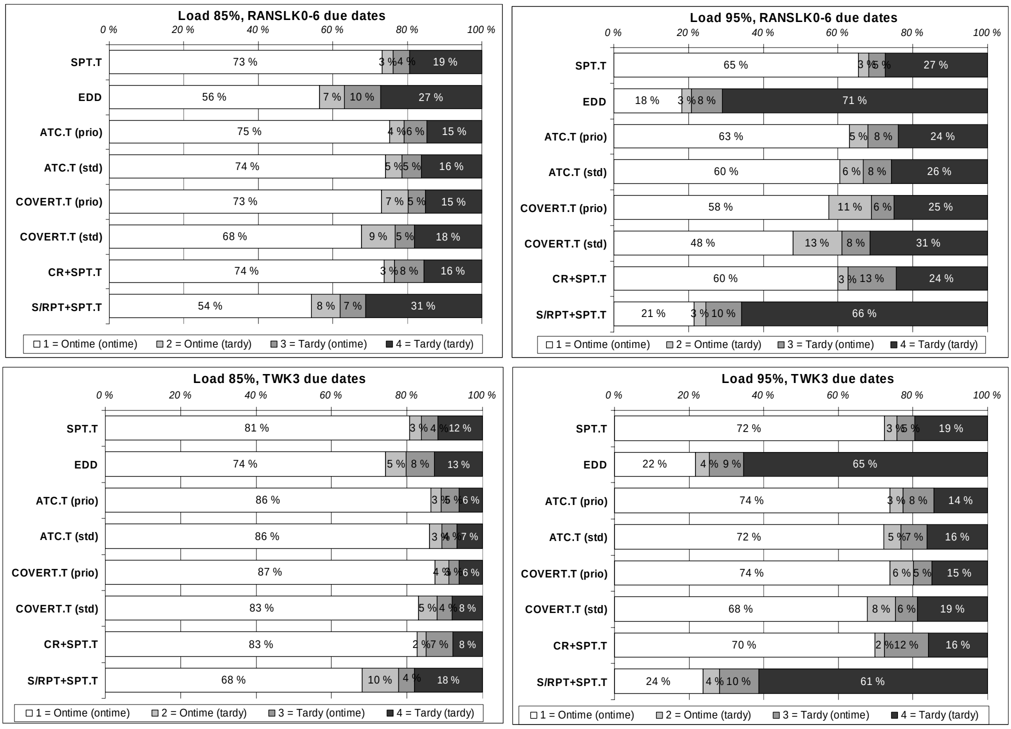

Figure 6-5 Portions of four job types in a 4-machine shop for the priority index rules when system load is 85% or 95% and tight due dates are assigned with the TWK or RANSLK method.

It is also examined what characterizes the orders that are completed after their due dates and if there are differences among the alternative priority rules. The relative portions of each job type with different values of tardiness penalties, 'weight per order size', and 'order per weight' index were compared, and it was observed that the use of tardiness penalty information in dispatching has a coordinating effect. The unweighted EDD rule differs from the other priority index rules examined not only by leaving significantly more orders late but also by leaving late orders that have high tardiness penalties. Based on the weight per order size index, the tardiness behavior for the three look-ahead rules as well as the SPT.T rule is pretty much alike (Figure 6-6). Especially the portion and type of orders that are late throughout the process are about the same across the rules. The COVERT.T(PRIO) rule differs from the two other look-ahead rules by the fact that the portion of Type 2 orders is higher with it. This is caused by the global look-ahead of the COVERT rule due to which orders can be started late compared to the operation-specific due dates, but yet attain the planned schedule at the last operation. The CR+SPT.T rule, which similarly as the COVERT rule considers the global slack, has significantly less of Type 2 orders. This is explained by the lack of waiting time estimation method. In other words, the CR+SPT.T rule includes only the trade-off of factors. It lacks the lead time estimation property, which would ease the anticipation of what happens between the release date and the due date of an order.

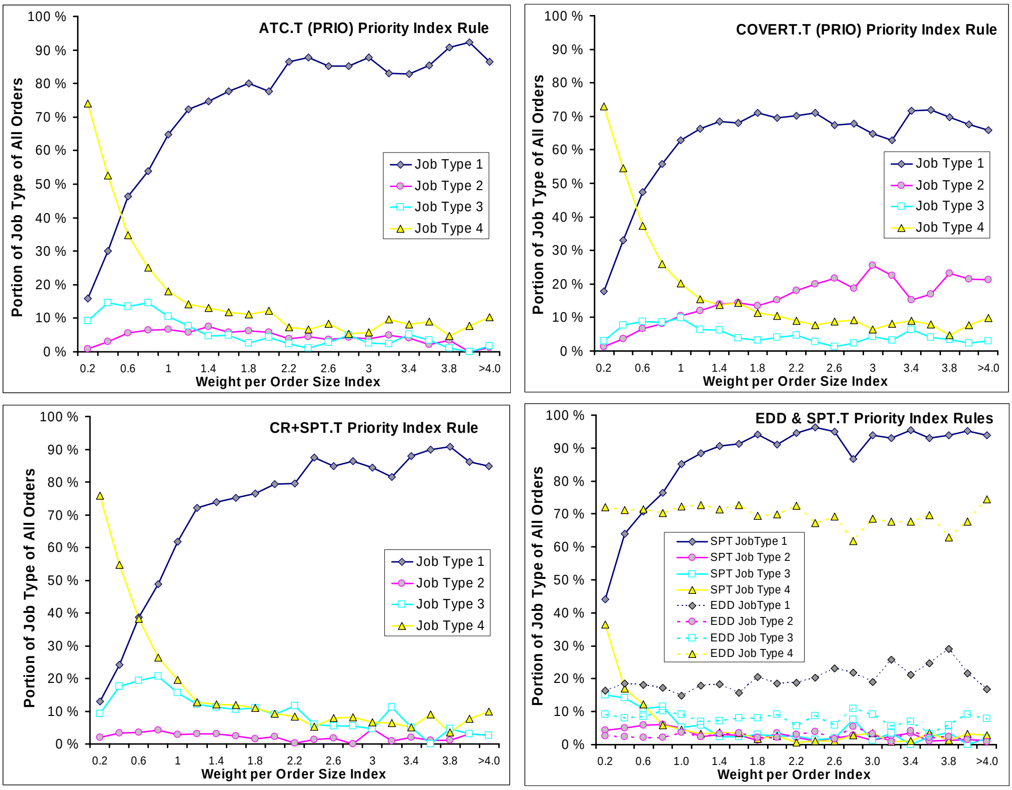

Figure 6-6 Portions of four job types with different values of 'weight per order size' index in a proportionate 4-machine job shop (RANSLK 0-6) with ATC.T(PRIO), COVERT.T(PRIO), CR+SPT.T, EDD, and SPT.T rules.

The observations discussed above give some indications on how the properties and behavior of priority index rules can be investigated in a way that gives decision-makers new information on order flow times and tardiness. The insights on what kinds of orders clear quickly through the shop with different types of priority index rules support lead time estimation and anticipation of order tardiness. Nevertheless, further analysis is needed to determine the implications of these findings, for example on pricing principles.

6.4 Summary and Discussion

This chapter demonstrated and compared some alternative principles for order management and scheduling in non-delay job shop scheduling. The first experiment investigated the effects of order release policies on the system performance. It revealed that the screening mechanisms tested perform worse than the priority index rules with the immediate release of accepted orders. The differences in the weighted tardiness and the portion of tardy jobs, in favor of the priority index rules, are largest when the system load is high. The prior research has offered order release mechanisms as a viable option, for example, for controlling material flows in congested production systems. The results imply that if a supplier with job shop production has no possibilities to influence the different lead time requests of customers, a separate mechanism for order releases is justified merely due to its positive effect on flow times. If the supplier can specify order-specific lead times and insert an appropriate amount of slack into the estimate, the benefits of order release would be higher. The second experiment examined the impact of applying different priority rules within a single job shop. The test was motivated by the fact that, in practice, it may be difficult to agree on the use of one priority index rule even within one organization. The results of the simulations imply that the look-ahead rules (ATC.T, COVERT.T and CR+SPT.T) produce consistent improvement if applied at some of the machines in the shops. The third investigation demonstrated the keeping of operation due dates and tardiness behavior of priority index rules. Some differences were found among the rules tested in the predictability of the on-time progress of orders through the shop. All in all, the simulation results imply that the selection of a priority index rule within the family of the look-ahead rules should be done on the basis of implementation aspects, in which the different properties of the rules make a difference, instead of focusing on computational results only.

This chapter is concluded by summarizing some features of a standard protocol for priority scheduling. First, the differences of the economic rationale and managerial interpretations of the ATC.T, COVERT.T, and CR+SPT.T rules, which are the prime candidates for the engine in the complex weighted job shop problems, needs to be specified (Table 6-5). The ATC.T and COVERT.T rules both use a lead time estimation method, whereas the CR+SPT.T rule does not anticipate how long orders are expected to wait before their completion. The ATC.T uses more up-to-date information when it estimates order-specific lead times compared to the COVERT.T rule, which calculates a relatively pessimistic estimation using information on remaining operations. Both the COVERT.T and CR+SPT.T rules calculate the global slack for each order by using information on remaining time and remaining operations. The ATC.T rule designates a portion of slack time per each remaining operation, and so determines the look-ahead using operation-specific due dates. Its look-ahead has also a different form, since order-specific priority index values do not increase linearly but exponentially, finally reaching the level of SPT.T index (see also Figure 4-17).

Table 6-5 Properties of the ATC.T, COVERT.T and CR+SPT.T rules.

Property	ATC.T	COVERT.T	CR+SPT.T
Lead time estimation*	Unbiased (1)	Worst case (1)	No estimation (0)
Type of look-ahead*	Local (1)	Global (0)	Global (0)
Form of look-ahead	Exponential	Linear	Linear
Key feature of the rule	Decomposable	Robust	Simple
Managerial interpretation	Direct cost index	Indirect cost index	Technical index

* Numbers in parentheses indicate the number of parameters in use.

For schedulers and decision-makers the most notable difference among these three priority index rules is linked to their complexity. The CR+SPT.T rule is the simplest. It considers less than five information elements and the total number of operations required for calculating the index is typically less than ten. The complexity of the ATC.T and COVERT.T rules increases significantly as the number of operations per order increases, and so their use can require more computing. They also use more information than the CR+SPT.T rule. On the basis of the simulation results reported earlier in this thesis, the key advantage of the COVERT.T rule is its robustness across relevant performance measures and test settings. The key property of the ATC.T rule is its decomposability, which enables the determination of operation due dates based on local slack information. The COVERT.T and CR+SPT.T rules are both more integrated due to the element of global slack. It should also be noted that the ATC.T and COVERT.T rules specify order-specific priority indices in a way that allows a managerial interpretation, while the values given by the CR+SPT.T rule should be considered only as technical indices.

Second, based on the simulation experiments, the specification of the priority index and the tolerances for the accuracy of data have been shown to be rather robust and easy to adapt to a practical situation. Managerial advice for the first layer of the protocol can be summarized tentatively by stating that any reasonable implementation of a look-ahead rule will work in practice. This means that the unbiased estimates of processing times, delay penalties, lead times and other parameters of the rules should be used, even if there are known to be errors in the estimates. Systematic use of the rules and feedback from the shop floor helps improving the accuracy of estimation, whereas crude predetermined classifications are rather difficult to build into the priority index without severe deterioration of performance. Third, some alternative conventions of usage of the dominant scheduling rules have been tested in the simulations. The guidelines of the third layer of the suggested protocol turn out to be rather straightforward including the exclusion of release control other than the application of the priority rule used. In a multi-stage process, the look-ahead rules should be used at as many stages as possible. The need for other conventions can be tested in further studies.

7 Conclusions

Despite the long traditions of job shop scheduling research and its rigorous quantitative treatment of practically-motivated problems, the impact of scheduling theory on real-world applications appears to be limited. As a consequence, schedulers all over the world make dispatching decisions that are against the well-known principles of priority scheduling by giving precedence to the longest job, to the most important customer, or to an order identified critical on the basis of some managerial beliefs such as the 'tons per day' thinking or the democracy of the FCFS principle. The primary cause may well be the lack of sound economic rationale for, or managerial interpretation of, scheduling rules. Even though some researchers have investigated the alternative ways to combine scheduling rules with resource pricing (e.g. Lawrence and Morton 1993, Morton *et al.* 1995), we still miss approaches and tools that would encourage and empower production planners and schedulers across organizations to utilize a tested and consistent discipline for order management and scheduling decisions.

What kind of practical tools are we looking for? Almost a century ago Harris (1913) introduced the economic order quantity (EOQ) model for inventory management and experienced the challenge of getting managers to accept the relatively simple method. It was argued that the EOQ model could not be applied due to its simplifying assumptions and the impossibility of collecting accurate data. Later, it was realized that due to the robustness of the rule even approximate and standardized statistics sufficed for improved performance. It looks as if order scheduling would be going through a similar phase with vocal objectors arguing that dispatching rules, so myopic in nature, do not qualify for the coordination of activities in manufacturing systems, let alone in the multifaceted supply networks. This study suggests, however, that there are dominant priority index rules that combine the relevant information on orders and system status intelligently enough to accomplish the double duty of coordination: schedulers get advice as to the most efficient immediate course of action, and production planners can engage in proactive dialogue with sales people on fulfilling customer promises instead of fighting fires upon every contingency of order management.

7.1 Summary

This thesis first described the state-of-the-art of priority scheduling. Practical applications of scheduling rules were discussed based on the prior published research and an exploratory small-scale study of Finnish manufacturing companies. The findings of the many case studies and surveys as well as the new study confirmed that the systematic use of scheduling rules in the key decisions of order handling is limited. Within the sample of 16 manufacturing companies it was, nevertheless, possible to recognize some companies expected to benefit from the use of order-based scheduling rules in coordination of order handling decisions. To synthesize and analyze what methods are offered to practitioners, an extensive number of studies in index-based scheduling heuristics were reviewed. In addition to order dispatching, the tools designed for due date assignment, order acceptance, and order release decisions were surveyed. The results and recommendations of prior priority scheduling research were examined with focus on research settings, rule benchmarking, reporting format, and customer perspective in problem definitions. On the basis of the published results any single priority index rule has not been found superior in dynamic job shop problems with tardiness-related criteria. Yet, some promising alternatives as well as conflicting results published in prestigious journals were found. These observations alone motivated the re-examination of the performance of different priority index rules in relevant job shop test settings.

As for the revisit to the priority scheduling literature, the validity of the earlier results was first examined via simulation experiments. The large set of tests in statistically generated job shops, forming the first experimental part of this thesis, revealed that there is a group of priority index rules called look-ahead rules including the ATC, COVER, and CR+SPT rules that performs better than any other rule suggested when judged by the performance measures which consider order-specific costs such as holding costs, tardiness penalties, and expediting charges. Furthermore, the robustness and behavior of the look-ahead rules was analyzed via various modifications. The second experimental part elaborated some details critical for the implementation of the priority index rules. The focus was on the rules that are competent due to their coordinating effect in a single production system and their potential use as the core of standard order scheduling protocol, possibly extending across sales and production organizations. Especially the sensitivity of the selected priority index rules to the accuracy and detail of information and communication used was assessed. In addition to these technical specifications and tolerances for the priority index rules, the performance effects of some alternative types of order handling procedures were demonstrated.

7.2 Results and Implications

The contribution of this thesis emerges from the systematic and thorough examination of the inherently complex scheduling problems. It provides a remarkably simple yet novel platform for evaluating the conditions for efficient coordination of priority index rules. The results are reported in three areas of priority scheduling: 1) the current state of index-based scheduling heuristics, 2) comparisons of priority index rules in job shops, and 3) standardization of order scheduling practices. Both the state-of-the-art review and the comparative analysis focused on job shops because they are considered as a good illustration of complex operations with high uncertainty due to interferences of orders that are not easy to predict. The managerial implications are elaborated in the form of open protocols for order management and scheduling within one company or along inter-organizational processes.

The current state of theoretical development and practical applications of priority scheduling was defined on the basis of published research primarily. Moreover, several classifications were developed in order to give a clear and comprehensive description. The process of order management and scheduling was illustrated by linking key decisions of order handling to the framework introduced by Pinedo (1995). The resulting OMPPOS process, which covers the scheduling of customer orders from order acceptance to dispatching, was used as the frame for identifying prior empirical and theoretical studies on scheduling rules. Classifications were introduced also to give structure to the problem of order scheduling in production systems. The scheduling disciplines matrix, which practitioners can use when trying to find the most appropriate approach for their scheduling task environment, was suggested. Grounded on the scheduling discipline matrix and the OMPPOS process description different types of order handling procedures were illustrated. Furthermore, the matrix was used as a tool when analyzing the methods of order management and scheduling used in 16 Finnish manufacturing companies that rely on the MTO strategy or apply a hybrid MTS/MTO strategy in their production planning and scheduling. A majority of these progressive companies did not systematically use the procedures of priority scheduling even in contingencies. However, in combination with the investigation of the flow of order handling decisions, the results of the exploratory study imply that some of the companies could benefit from using scheduling rules for coordinating their order handling decisions distributed to separate teams or organizations.

In addition to the findings in Finnish manufacturing companies the current published evidence on the use of scheduling heuristics, more specifically dispatching rules, was summarized on the basis of the published case studies and surveys. The differences in the type of dispatch priority rules actually in use were defined with a classification that considers the order information used by rule and the type of priority index. This classification, which promotes the analysis of the informational efficiency of priority index rules, was used and further demonstrated when analyzing the high number of dispatching rules found based on the extensive and thorough review of priority scheduling research. On the basis of the resulting classification, the type of rules that could be considered as potential candidates for the extensions of priority scheduling to order handling and supply chain management were specified. The global probing rules were excluded from the set of prominent priority index rules for three reasons: they use information that is uncertain due to the stochastic nature of job shops, they require extensive computing, and they are not decomposable, which undermines the motivation of standard order scheduling protocols.

The review of index-based scheduling heuristics was summarized in dominance charts. They give the rankings of alternative due date assignment, order release, order acceptance, and selected type of weighted dispatching rules on the basis of the results reported for the objective functions used in each of the publications. The literature review also specified why the revisitation of priority scheduling research is called for. A major shortcoming in the prior research is the shortage of clear recommendations for the selection and use of priority index rules. This is apparently due to the limited number of consistent and comprehensive comparisons of alternative scheduling rules. Kutanoglu and Sabuncuoglu (1999) reported the results of an exemplary study that compared dispatching rules in job shops. Nevertheless, their findings and other earlier results were later questioned by Jaymohan and Rajendran (2004). The contradictory evidence strongly illustrated the importance of developing standardized problems and experimental designs for the benchmarking of index-based scheduling rules. Additionally, the observed difficulty of comparing the reported results of simulation studies pointed out the importance of using normalized performance measures, which are comparable across test settings regardless of assumptions used in the generation of synthetic order and production system data. It was also discovered that the relevance of simulation-based priority scheduling research would be higher if problem definitions would consider expected customer requirements in due date assignment as well as in the specification of order properties better.

A set of simulation experiments was designed on the basis of the conclusions of the state-of-the-art review. The comparative analysis examined the performance of a large number of priority index rules in statistically generated job shop settings using the simulation software designed for the purposes of this thesis. The experimental design for the weighted job shop problems consisted of two shop types, two types of orders, five levels of system load, three due date setting methods, and two levels of due date tightness. Different due date setting methods were considered, firstly, to enable comparison of these results to the earlier publications, and secondly, to demonstrate the impact of customers' ordering behavior on the need and benefit of priority scheduling. In addition to the weighted job shop problems, which assume that customers have heterogeneous order-specific costs and lead time requests, the performance of unweighted priority index rules was analyzed in a special case, in which all customer orders are assumed to have equal weights, i.e. same penalties for late deliveries and costs of holding work-in-process inventory. This was motivated by the fact that many earlier studies have focused on developing dispatching rules for the special case solely. It should be noted that all these experiments used the normalized versions of the key performance measures to provide comparability across the problem instances.

Based on the analysis of the simulation results conclusions can be drawn on the performance of the candidate rules in terms of their level and robustness of performance using weighted mean tardiness, portion of tardy jobs, and WIP holding costs as the primary indicators. Especially in the analysis of the performance of the tested rules in weighted mean tardiness and WIP holding costs, the group of three look-ahead rules (ATC.T, COVERT.T, and CR+SPT.T) and the SPT-based rule form an efficient frontier for each level of system load. As for tardiness related criteria, the look-ahead rules are the most prominent candidates. When tardiness penalties and holding costs are equal for all jobs, the experiments indicated that the unweighted versions of the look-ahead rules performed well in this special case also. In unweighted problems probing is easier. It is supported by the finding that the global probing rule called RR performed very well compared to the look-ahead rules with moderate system load but was just mediocre with higher load. Moreover, also some push-based rules such as the PT+PW and PT+PW+FDD gave promising results, especially in the portion of tardy jobs.

The effects of incorporating holding costs or other combinations of order information as a part of the look-ahead rules were tested also. While one may expect this and other rule modifications checked to give advantage to the jobs in their last operations, and thereby possibly to avoid tardiness at completion, the dismal results proved the net effect to be negative. However, when the remaining processing time was used instead of the operation-specific processing time, an exception was the ATCR.T rule that decreased the number of tardy jobs. In all, the comprehensive evidence of the rule comparisons proved the three different look-ahead rules to be superior candidates for use in job shop scheduling. Even though some single problem instance may favor one of them, the choice of the rule should emphasize the implementation issues such as decomposability and managerial interpretation more than the simulation results.

It should be noticed that both the state-of-the-art review of priority scheduling research and the simulation experiments discussed above have some limitations. The review cannot cover all articles published in the area of priority scheduling, and so the simulation study may not include every prominent rule suggested and/or each experimental design used in the prior research. However, the fact that the results of the simulations are consistent across a large number of test settings removes most of the unfavorable implications of these two limitations.

The second experimental part of this thesis was constructive in nature. It studied potential practical barriers for the use of priority index rules by investigating specifications and tolerances for the identified group of look-ahead rules, in particular. Further, it demonstrated the impact of selected scheduling conventions on the system performance. The key finding was that the look-ahead rules work robustly and well compared to the alternative approaches tested. More specifically, the sensitivity of the rule functioning was examined via testing the impact of data accuracy and detail, and the type of lead time estimation methods. These experiments showed that minor errors in information or slightly different ways to estimate waiting times do not impair the performance of the look-ahead rules significantly. In some cases, in fact, another choice of the estimation method could have slightly improved their performance. Additional insights on the performance of the look-ahead rules include:

- Most of the alternative ways to estimate lead times give good results. Hence, it is reasonable to prefer the simplest approaches when possible.
- Moderate errors in the estimates of processing times and delay penalties do not change the rankings of the dispatch priority rules. Nevertheless, major estimation errors are observed to increase primarily weighted mean tardiness.
- The use of crude priority classifications defined on the basis of order-specific tardiness penalties improves the system performance in comparison to a hypothetical base case with no priority index rules in use. The results are, nevertheless, significantly worse than with the best priority index rules.
- The effects of aggregating data on due dates and processing times depend on the type of priority index rule. Yet, only little evidence for benefits of process visibility was observed.

Finally, some selected order management and scheduling methods were tested to measure their effects on the system performance:

- The look-ahead rules that also determine the release of orders proved efficient when compared to selected separate order release mechanisms suggested in the literature.
- The use of look-ahead rules improves the tardiness performance of a whole job shop, even if applied in some of the stages.
- When monitoring the on-time progress of orders through the shop, all look-ahead rules indicated predictable behavior. Compared to other alternatives these priority index rules make it easier to anticipate the tardiness of individual orders on the basis of their key properties such as processing time and tardiness penalty.

The managerial implications of the experimental results have been summarized in two ways: 1) a benchmarking framework for evaluating the potential efficiency of the coordination principles incorporated into the most promising priority rules, and 2) as a standard specification of a protocol for priority scheduling. The benchmarking framework helps managers to evaluate the compatibility of the technical properties of the rule, the associated economic principles of coordination, and the challenge of the scheduling problem, and maybe even predict the efficiency of coordination. The major results of the literature surveys and the empirical simulations of this thesis underline the importance of the economic rationale of the rule in terms of the look-ahead feature and unbiased lead time estimates. The dominant look-ahead rules, ATC, COVERT and CR+SPT, work well in both easy and difficult job shop problems with tardiness-related objectives. All three rules exhibit remarkable robustness in terms of different specifications of the shop, load and priority index and even with less than perfect quality of data. The formal specification of the scheduling protocol guides the implementation of the coordination principles in manufacturing and service organizations. The three layers of the recommended order scheduling protocol turn out to be rather straightforward despite the multitude of studies, complex settings of simulations, and somewhat confusing results. In short, the protocol stipulates that the dominant priority index rules should be applied consistently, yet there are rather generous tolerances for errors in the data and shortcuts in the conventions adopted. An indirect benefit from the systematic use of order-specific cost data comes from the close monitoring of the accuracy and correctness of estimates leading to improved estimation.

Overall, the results of the various new types of analyses discussed provide a deeper understanding of the mechanisms of dispatching – instead of widening the field of rule candidates – to facilitate the interaction between managers and scholars. Real-life applications of the findings are, nevertheless, expected to require education and training of both current and future decision-makers which would be easier if there were supporting learning tools available. Thus, it should be evaluated if the simulation software specified for this thesis could be further developed to demonstrate the interactions of different order management and scheduling decisions in some illustrative order scheduling environments. The availability of the program as an open source software would also definitely contribute to the development of priority scheduling research towards more standardized test settings, rule benchmarking, and reporting.

7.3 Topics for Future Research

While this thesis has exhaustively synthesized the traditional research on priority scheduling in dynamic job shops to a practical conclusion in the form of a scheduling protocol, it has opened several interesting avenues for future research. The immediate questions rise in four areas: 1) the potential extensions of priority scheduling towards applications in production networks and supply chains, 2) further development and quantitative modeling of the benchmarking frameworks of scheduling, 3) the design and testing of open protocols for scheduling in a variety of simulated and experimental settings, and 4) in-depth case studies and surveys of order management and priority scheduling.

First, the revisitation of priority scheduling research and applications alluded to the standard manufacturing environments and test settings for job shops. A natural extension would be, building on the findings, to conduct a series of simulations focusing on the special characteristics of inter-organizational and service processes. By the means of simulation it would be possible to assess how the performance of the scheduling rules suggested as the core of open scheduling protocols would change if implemented in different types of decision-making environments. The specification of appropriate test settings and standard practices as such are expected to be more demanding due to the potential sub-optimization. Besides the standard statistically generated job shop problems, test settings should be extended to cover entirely different structures and layouts of supply networks.

Second, the managerial implications of scheduling research and coordination theory will be made accessible in the form of the benchmarking framework also in the case of the extended problems discussed above. In order to build the confidence among potential users as well as scholars, further development and quantitative modeling of the evaluation process seems necessary to complement the rather qualitative analyses suggested in this thesis.

Third, the design of order scheduling protocols calls for further investigation in a variety of simulated and experimental settings. This thesis illustrated some alternative conventions of usage but there are also others that could be investigated. For instance, the possibilities to integrate information on product margins, order profits, and customer profitability in the rules of order management and scheduling in a way that eases the use of order-specific priority indices in pricing and order acceptance could be examined.

Finally, empirical case studies and surveys of order management and priority scheduling, both evaluating alternative coordination methods and testing applications of different order scheduling protocols, should be carried out. Also pilot studies are needed before recommending the use of any standard protocol. Linked to the pilots it would be useful to examine what types of incentive systems would encourage the decision-makers in systems with distributed control to make rational decisions on order prioritization, what type of protocols are compatible with planning and scheduling software, and how the calculation and communication of priority indices and related statistics can be implemented in information systems perhaps even as a standard element of order data. The automation of routine operations could enhance the actual use of priority scheduling whenever it is called for. It sure would ease the study of net coordination effects achieved by using order-specific priorities in practice. An intriguing question relates to the need for information sharing among decision-makers: can a high level of predictability be achieved via consensual use of priorities and lead time estimates determined based on rational expectations instead of collaborative planning and continuous monitoring of order progress.

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Appendices

Appendix 1 Descriptions of the selected Finnish manufacturing units

Case company	Industry	Share of exports	Manufacturing and logistics strategy	Type of products	Production strategy	Production process type	MPC approach
A	Electronics	98 %	Cost / Service	Standard & Customized	ATO	Assembly/ Batch	TOC
B	Electronics	80 %	Service / Innovation	Standard & Customized	MTO	Assembly/ Batch	MRP
C	Electronics	n/a	Service	Standard	MTO	Assembly/ Batch	JIT
D	Machinery	80 %	Cost / Service	Standard & Customized	Mixed	Batch/ Job shop	MRP & JIT
E	Machinery	96 %	Cost / Service	Standard & Customized	MTO	Batch/ Job shop	MRP
F	Machinery	98 %	Cost	Standard & Modular	MTO	Batch/ Job shop	MRP
G	Machinery	50 %	Service	Standard & Customized	MTO	Batch/ Job shop	MRP & TOC
H	Machinery	92 %	Service / Innovation	Modular	MTO	Job shop	JIT
I	Metal	83 %	Cost / Service	Standard	MTO	Batch	JIT
J	Metal	90 %	Cost / Service	Standard	Mixed	Batch	TOC & JIT
K	Metal	96 %	Cost	Standard & Customized	Mixed	Batch	MRP
L	Metal	95 %	Cost / Service	Standard	MTO	Batch	JIT
M	Paper	98 %	Cost/ Service/ Innovation	Standard	MTO	Continuous	JIT
N	Paper	~90 %	Service	Standard	MTO	Continuous	JIT
O	Paper	91 %	Cost / Service	Standard	MTO	Continuous	MRP
P	Paper	95 %	Service / Innovation	Standard	MTO	Continuous	JIT

Case company	Capacity allocation	Order acceptance criterion	Lead time estimation method	Order release	Basis of scheduling
A	(not used)	Capacity availability	Order-specific (load-dependent)	No slack	Rough schedule
B	Per customer	Customer importance	Standards (load-dependent)	No slack	Fixed schedules
C	Per customer	Customer importance	Order-specific (load-dependent)	Some slack	Rough schedule
D	(not used)	Customer importance	Standards (load-dependent)	Scheduled slack	Flexible schedules
E	(not used)	Customer importance	Standards (history data)	Scheduled slack	Flexible schedules
F	(not used)	Customer importance	Standards (history data)	Scheduled slack	Flexible schedules
G	(not used)	Customer importance	Order-specific (load-dependent)	Some slack	Flexible schedules
H	(not used)	Customer importance	Order-specific (load-dependent)	Some slack	Rough schedule
I	Per market	Capacity availability	Standards (load-dependent)	No slack	Fixed schedules
J	Per market / customer	Order profitability	Standards (load-dependent)	Scheduled slack	Rough schedule
K	Per customer	Customer importance	Order-specific (load-dependent)	Scheduled slack	Fixed schedules
L	Per market / customer	Customer importance	Order-specific (load-dependent)	Scheduled slack	Flexible schedules
M	Per market	Capacity availability	Standards (load-dependent)	Scheduled slack	Fixed schedules
N	(not used)	Order profitability	Standards (load-dependent)	Scheduled slack	Rough schedule
O	Per market / customer	Capacity availability	Standards (load-dependent)	Some slack	Rough schedule
P	(not used)	Capacity availability	Standards (history)	Some slack	Rough schedule

Case company	Order ranking method	Customer classifications	Order-specific priority indices	Delay penalties	Use of delay penalties
A	Case-by-case	Rare	Implicit indices	Common	Occasional
B	Case-by-case	Not used	Not used	Rare	Not used
C	Case-by-case	Not used	Not used	Not specified	Not used
D	Rough categories	Rare	Rare	Common	Occasional
E	Specific rules	Rare	Not used	Common	Occasional
F	Case-by-case	Not used	Not used	Common	Not used
G	Rough categories	Rare	Not used	Common	Not used
H	Case-by-case	Actively used	Not used	Standard practice	Occasional
I	Specific rules	Rare	Not used	Not specified	Not used
J	Rough categories	Actively used	Rare	Not specified	Not used
K	Rough categories	Actively used	Rare	Rare	Occasional
L	Case-by-case	Not used	Rare	Rare	Occasional
M	Specific rules	Not used	Not used	Not specified	Not used
N	Rough categories	Actively used	Not used	Not specified	Not used
O	Rough categories	Actively used	Not used	Not specified	Not used
P	Case-by-case	Not used	Not used	Not specified	Not used

Appendix 2 Abbreviations of priority index rules

Abbreviation	Definition	Other abbreviations
ATC	Apparent tardiness cost	AU, MRV, R&M
AVPRO	Shortest average processing time	RTIMOP
BD	Bottleneck dynamics	-
COST	Composite cost-based rule	C.R.
COVERT	Cost over time	Carroll's C/T rule, CVT
CR	Critical ratio	CRR, CRRAT, R/OPN, SCR
CR+SPT	Combination rule: CR+SPT	-
EDD	Earliest due date	DD, DDATE, DUEDA, E, EDDATE, JDD, SADD
EFD	Earliest finish time	ECT, FDD
Emery's rule	Emery's rule	
ERD	Earliest release date	ESD, EST
EXP-ET	Exponential early/tardy rule	
FCFS	First-come-first-served	AT, FIFO, FIQ, LCLS
LPT	Longest processing time	GTPT, LIO, LRPT, LSO, SL
MAXPEN	Maximum penalty	.
MDD	Modified due date	WI, PSK
MF	Multi-factor rule	-
MOD	Modified operation due date	MODD
MXPROF	Most profitable job	PRF/TOPT
NOP	Number of operations	NOPR
ODD	Operational due date	OPNDD, OSD
P/TWK	Relative length of next processing time	PDJT, PDRW, SDT
PT+PW	Process time and waiting time	-
PT+WINQ	Process time plus work in next queue	-
RAN	Random order	SIRO
RR	Raghu and Rajendran rule	NEW*
S/OPN	Slack time per operation	Job slack ratio, SLK/NOP, SLK/OP
S/RAT	Slack per remaining allowable time	JSR, QR (Queue ratio)
S/RPT	Slack per remaining processing time	JSPRP, SLACK/RP, SRT, S/RW, S/RMWK, SRPT, S/TWR
S/RPT+SPT	Combination rule: S/RPT+SPT	-
SLK	Least slack remaining	MINSLACK, MST, OSL, OSF, SL, SLACK
SPT	Shortest operation processing time	SI, SIO, SOT, LTPT, STPT, SS, SSO, SJPT, SOPT, MINIM, SP, TJT
SST	Shortest setup time rule	MNSTUP
TWKR	Least total remaining work content	LRT, LTWK, LWR, LWKR, RWK, RJT, SRM, SR, SREMTM, TWORK, TWK
VALADD	Value added	IPDOL
WINQ	Work in next queue	SNQ

Appendix 3 Descriptions of generic dispatch priority rules

Rule	Description (i.e how the rules selects the next job)	Developers	Rule modifications introduced and tested
ATC	Selects the job with the highest value of index that bases on weighted processing time and expected remaining slack scaled using a look-ahead.	Vepsalainen (1984), Vepsalainen & Morton (1987, 1988)	AU-COVERT, MAU, KATC (ATC with fixed value of k), LATC (ATC defined by Lee et al.), NATC (neural network ATC), RATC (Raman's ATC), X-RM
AVPRO	Selects the job with the least value of total processing time per number of operations.	Hausman and Scudder (1982), Jaymohan and Rajendran (2000b)	MD
BD	Selects the job with the largest activity price. The rule trades off an activity price, which is a reflection of the current scheduling decision to the weighted tardiness, with total remaining resource usage.	Morton and Pentico (1993), Kutanoglu and Sabuncuoglu (1999)	BD-Bot, BD-DynSt, BD-DynKZ, BD-Myp, BD-Stat, BD-Unif, X-BD-Bot, X-BD-DynSt, X-BD-DynKZ, X-BD-Myp, X-BD-Stat, X-BD-Unif
COST	Selects the job with the highest costs that are calculated based on four cost indices: in-process inventory, facilities utilization, lateness and mean setup time costs.	Aggarwal et al. (1973), Aggarwal and McCarl (1974)	DCR, DUR, DVR, UVR
COVERT	Selects the job with the highest cost per unit delay per current processing time.	Carroll (1965)	COVERT-LAJD, COVERT (DDWT), COVERT (DAWT), MCOVERT, OPCOVERT
CR	Selects the job with least slack available per remaining processing time.	Berry and Rao (1975)	CR/SPT, Method 41, OCR, OPCR, Two-class rules (MXPCRT, VLADCRT, CRRATP)
CR+SPT	Selects the job with the earliest operation due date based on equation that equals the MOD rule when jobs are on schedule.	Anderson and Nyirenda (1990)	-
EDD	Selects the job with the earliest due date.	Conway (1965a), Kim and Yano (1994)	Best Effort policy, DMMF, DOMF, EDD*, JDD;ODD, JDD;RAN
EFD	Selects the job with the earliest finish time which equals the release time plus processing time.	Baker and Bertrand (1981)	ECT;OSD, LFT, MIDDS, MIDSC, TS;DUAL
Emery's rule	Identifies critical jobs applying six screening criteria (external priority class, COVERT rule, waiting time, remaining work per processing time of current operation, processing time and size of queue) and then selects the job with the highest value of the weighted function.	Emery (1969)	-
ERD	Selects the job with the earliest release date.	Baker and Bertrand (1981)	-
EXP-ET	Selects the job with the highest value of function that considers weighted value of COVERT and early cost information with an exponential look-ahead.	Morton et al. (1988), Ow and Morton (1989)	LIN-ET (similar to ATC)
FCFS	Selects the job that has arrived at the queue or the system first.	Conway (1965a)	AT-RPT, FASFO, FAFS, FASFS, FISFS, SPTINV
LPT	Selects the job with the longest (imminent) operation processing time.	Baker and Dzielinski (1960), Conway (1965a)	LPT with large bottleneck jobs first, LPT.TWK, LPT.TWKR, LPT/TWK, LPT+LSO, PCF
MAXPEN	Selects the job with the highest penalty.	Kurtulus and Davis (1982), Lawrence and Morton (1993)	-
MDD	Selects the job with the smallest modified due date. Note! WI rule is a heuristic rule that bases on the local optimality condition for an adjacent pairwise interchange .	Baker and Bertrand (1982), Wilkerson and Irwin (1971)	-
MF	Combines four factors (tardiness cost, process time, due date and job routing) and selects the job with the highest index value so that jobs with longer expected waiting time, shorter slack time and higher ratio of tardiness cost over processing time are given priority.	Chen and Lin (1999)	-
MOD	Selects the job with the smallest modified operation due date.	Baker and Bertrand (1982)	CR+SPT
MXPROF	Selects the job with the highest profit of the jobs in the queue.	Hoffman and Scudder (1983), Scudder and Hoffman (1985a)	DOLSHP, truncated version of MXPRFTRN, PRF/OPT, VMOD
NOP	Selects the job with the largest number of operations remaining.	Baker and Dzielinski (1960), Conway (1965a), Rochette and Sadowski (1976)	BS+ROPT2, FOPR, FOPNR, FRO, IR, LNOR, LOPNR, LP+ROPT2, LRO, MNOR, MOPNR, MOPR, MRO, MTS, $RNOP^2$, $ROPT^2$+SC
ODD	Selects the job with the earliest operation due date (equally spaced due dates are assigned to each operation when a job arrives).	Conway (1965a), Jaymohan and Rajendran (2000b)	FDD , OPFSLK/PT; FDD, OPSLK/PT; ODD
P/TWK	Selects the job with the smallest ratio of next processing time to total work.	Conway (1965a)	-
PT+PW	Selects the job with the least value of the sum of waiting and processing time at the current operation.	Jaymohan and Rajendran (2000b)	PT+PW+FDD, PT+PW+ODD
PT+WINQ	Selects the job with the smallest sum of process time and work in next queue.	Conway (1965a), Holthaus and Rajendran (1997, 2000)	P+WQ(a), P+XWQ(a), PT+WINQ+AT, PT+WINQ+NPT+WSL, PT+WINQ+SL, PT+WINQ+SL+AT, 2PT+WINQ+NPT, (PT+WINQ)/TIS
RAN	Selects the job with the smallest value of a random priority, assigned at the time of arrival to queue.	Baker and Dzielinski (1960)	RAND-SPT/WINQ by Holthaus and Rajendran (1997)
RR	Selects the job with the least value of function that combines SRPT, SPT and WINQ depending on the system utilization rate.	Raghu and Rajendran (1993)	-
S/OPN	Selects the job with the least slack per the number of operations remaining.	Conway (1965a), Bulkin et al. (1966)	ASMS/OPN, CMS/OPN, DRO,KMS/OPN, P+S/OPN, SSLACK/RO, STSLACK/OP, STSLACK/ROP, SPT-SLK/NOP (ii), SPT-SLK/NOP (iii), SPT-SLK/NOP (iv), "Modified" slack incl. expected delay on next machines
S/RAT	Selects the job with the least slack per remaining allowable time.	Mizayaki (1981), Philipoom et al. (1989)	Sequential rule, STSLACK/TWK, STSLACK/TWKR
S/RPT	Selects the job with the least slack per total remaining processing time.	Bulkin et al. (1966)	DRT, MDSPRO
S/RPT+SPT	Selects the job with the earliest operation due date by considering due date tightness using SRPT and SPT rules.	Anderson and Nyirenda (1990)	-
SLK	Selects the job with the least slack remaining.	Conway (1965b), Grabot and Geneste (1994), etc.	BS, DS, JLS, MS-IR, MS-TWK, Modified job SLK ratio, SIO-job SLK ratio, SIXRUL, SMF, SLACK/TP, SLK/DUE, SLK/TWK, SLK/TWKR, SLK/RW, SMMF, SOF, SOMF, SSLACK, SS, STSLACK, SLK/Importance combinations
SPT	Selects the job with the shortest (imminent) operation processing time.	Baker and Dzielinski (1960), Gere (1966)	Truncated versions of SPT: CEXSPT, SIx, TSPT, SPT-T, SPTRUN(T), SPTTRN, SPT-SLK/NOP and CMF, CMMF, COF, COMF, OUF, LMT, PMJT, PMRW, PTF, PT/TIS, SASP, SMT, SEPT, SOT*TOT, SPT/TOT, SPT.TWK, SPT/TWK, SPT/TWKR, SPT/SLK, SPT+SSO, Weighted rule
SST	Selects the job with the shortest setup.	Aggarwal et al. (1973)	-
TWKR	Selects the job with the least total work for all uncompleted operations on its routing.	Conway (1965a), Eilon and Cotterill (1968)	MTWK, MWKR, MAXTWK, RWK+SC, TWK-RRO, TWK-FIFO, TWK-IR, TWKR;ODD; TWKR;OSD, TWKR;RRP, INVTST
VALADD	Selects the job with the greatest value added in the previous operations.	Hoffman and Scudder (1983), Scudder and Hoffman (1985a)	VLADRAT
WINQ	Selects the job that will go on for its next operation to the queue with the least work waiting.	Conway (1965a), Jones (1973)	NINQ, XWINQ

Appendix 4 Notation and symbols

i = job index
j,q = operation indices
$j(i)$ = operation j of job i
k = machine index
$k(q)$ = the machine required for operation q of the job under consideration
t = current time
w_i = weight, delay penalty of job i
h_i = weight, earliness penalty of job i
c_{ijk} = cost of jth operation of job i at machine k
m_i = number of operations of job i
m_{ij} = remaining number of operations of job i from operation j
r_i = release date of job i
d_i = due date of job i
d_{ij} = operation due date of operation j of job i to the current machine
a_{ij} = arrival time of job i for operation j
C_i = completion time of job i
$p_{ij(k)}$ = processing time of jth operation of job i (on machine k)
$\overline{p}_{ik}$ = mean processing time through the kth machine
$\overline{p}$ = average processing time of jobs
$p_{\min k}$ = minimum processing time of operations waiting for machine k
$A_i(t)$ = flow allowance of job i at time $t = d_i - t$
T_i = tardiness of job $i = \max\{0, C_i - d_i\}$
s_{ijK} = setup time required per operation j of job i at machine k
$\overline{s}_{2k}$ = mean setup time per operation at machine k
$S_{ij}(t)$ = slack of job i waiting for operation j at time t
$SS_{ij}(t)$ = local resource constrained slack of operation j of job i at time t
$U_{ij}(t)$ = urgency factor of operation j of job i at time t
$AP_{ij}(t)$ = activity price of operation j of job i at time t
$R_k(t)$ = resource price of machine k at time t
$L_k(t)$ = queue length of machine k at time t
ρ = utilization of machine on which the job is to be loaded
$\overline{\rho}$ = average utilization of the shop
TL_{ij} = estimated tail lead time for operation j of job i
W_{ij} = estimated waiting time for operation j of job i
W_{next} = estimated waiting time for job i at the machine of its next operation
$Y_{i,j+1}(t)$ = total work content of jobs in the queue of the next operation of job i at time t
$Y_{ij-1}(t)$ = total work content of jobs being processed in their preceding operation $j-1$ at time t
n = number of jobs in a specific planning horizon or in a simulation run
$N_{ij}(t)$ = number of jobs in the queue corresponding to operation j of job i at time t
b = waiting time estimation multiplier
h,K = look ahead parameters
β = inserted idleness parameter
B = parameter, $1.6 \leq B \leq 2.4$
e = processing time factor incorporating job shop status, $0 < e \leq 1$
δ_{ij} = operations status indicator (integer: 1=operation j of job i has not started)
l_i = total number of levels in job i (product complexity measure by M&M 1968)
pm_i = profit margin of job i
sp_i = selling price of job i
C_1 = daily inventory cost per dollar unit of inventory
C_{2k} = cost per processing hour at machine k
C_3 = daily cost of lateness cost per dollar value of jobs
C_{4k} = mean setup cost per hour for machine k
V_{ij} = value-added of job i in the previous operations (by operation j)
V_i = estimated mean dollar value of job i

Appendix 5 Abbreviations of due date assignment methods

Abbreviation	**Definition**
AT+a*PT+b*WIQ	Arrival time+a*processing time+b*work-in-queue
CON	Constant
DYN	Dynamic
δ	2-step methodology based on the regression approach
E[Sk,t]	Allowance proportional to the conditional sojourn time
JIQ	Jobs in queue
JIS	Jobs in system
NOP	Number of operations
PPW	Processing time plus waiting time
RAN	Random
REQ	Regression-based method for an assembly shop
RMR	Response mapping rule
σ[Sk,t]	Allowance proportional to the expected conditional sojourn time and sojourn time
SEQ	Sequential rule
SLK	Slack
TWK	Total work content
TWKCP	Total work on the critical path in an assembly shop
WEEKS	Weeks' version of jobs in system
WIQ	Work in queue

f

Appendix 6 Abbreviations of order release and review procedures

Abbreviation	Definition
Adjustment	Combination of order release mechanism and due date adjustment models
AGGWNQ	Aggregate workload trigger and work in next queue order selection
BIL	Backward infinite loading
BOTTLE	Bottleneck strategy
CMS	Critical machine selection
CONWIP	Constant work-in-process
DLR	Due date and load-based release
FFL	Forward finite loading
FIXED	Fixed quantity release strategy
IMM	Immediate release
INOUT	Global input/output strategy
IR	Interval release
JSSWC	Job trigger shortest slack and work center workload order selection
LAGS	Linear programming formulation with processing time as a transfer lag
LOMC	Load-oriented manufacturing control
MIL	Modified infinite loading
MSL	Maximum shop load
NORM	New order release mechanism
ORM	Order release mechanism
PAGG	Periodic aggregate loading
PBB	Path-based bottleneck
PFBB	Pull from both bottlenecks
PPB	Path-based bottleneck (modifications: PFB1/2)
Probabilistic	Method focusing on the probability that a job is produced during the first period
PSPTP	Integer programming formulation accounting for processing time
SA	Starvation avoidance
TB	Time-bucketing approach
WCEDD	Workcenter work load trigger and EDD selection
WB	Workload balancing
WR	Workload regulating policy
WT	Waiting time

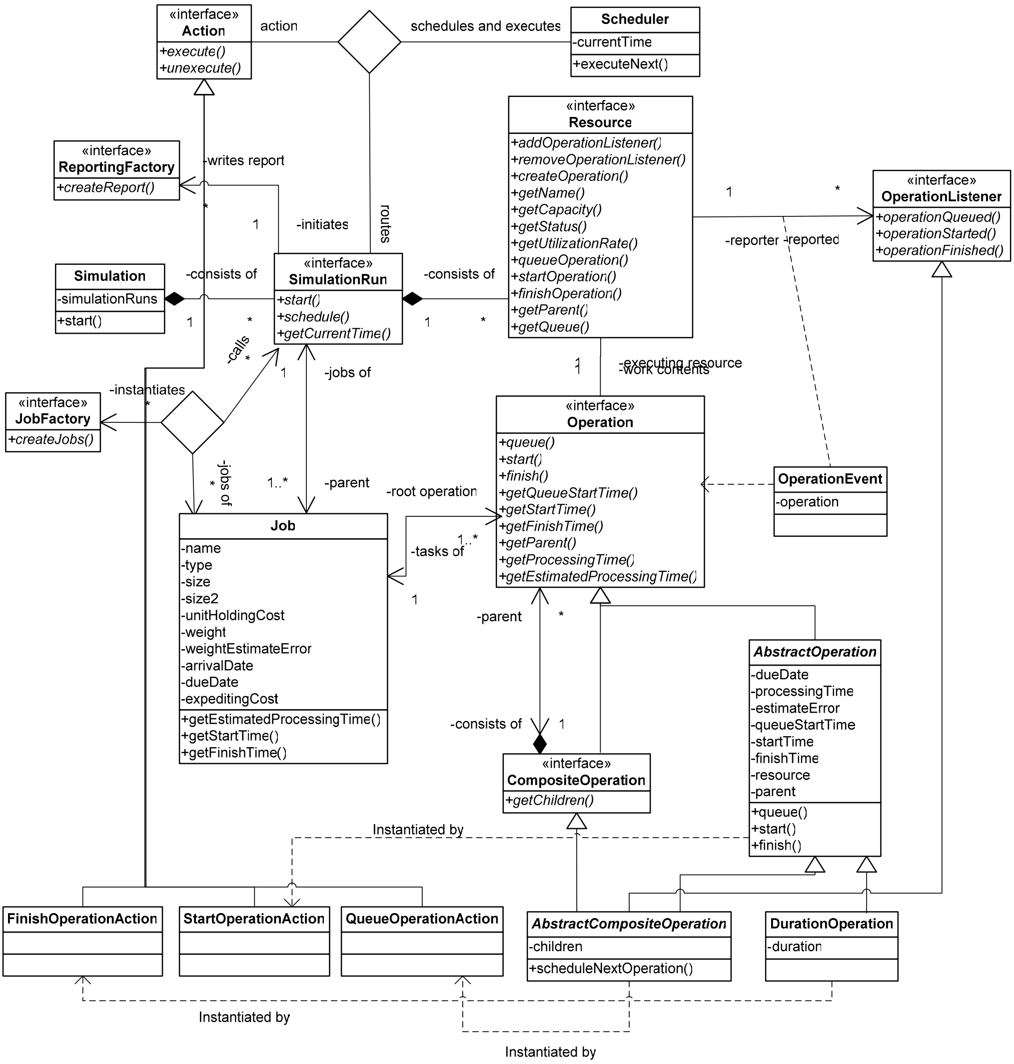
Appendix 7 Example of configuration templates used in the simulations

```
<?xml version="1.0" encoding="UTF-8" ?>
<simulation>
  <simulationRuns>

<%
        import fi.hse.jobshop.util.ConfigurableRandomizer;

List rules = [

 '<dispatchRule classname="ATC_TRule" k="3">\n' +
 ' <leadTimeEstimate classname="fi.hse.jobshop.math.PRIOLeadTimeEstimate" p="16" b="2" v="16" l="0.50"/>\n' +
 ' <pFunction classname="ATCRule$ParameterPFunction" p="16" />\n' +
 '</dispatchRule>',
 '<dispatchRule classname="COVERT_TRule" k="2">\n' +
 ' <leadTimeEstimate classname="fi.hse.jobshop.math.PRIOLeadTimeEstimate" p="16" b="2" v="16" l="0.50"/>\n' +
 '</dispatchRule>',
 '<dispatchRule classname="CRSPT_TRule" />'
];

        List ruleNames = [
                "ATC_T",
                "COVERT_T",
                "CRSPT_T",
                "SPT_T"
        ];

        List ddMultipliers = ["3"];
        List loads = ["0.80", "0.85", "0.90", "0.95", "0.97"];
        int numReplications = 20;

        int ddMultiplierCounter = 0;
        for (ddMultiplier in ddMultipliers) {

                int ruleCounter = 0;
                for (rule in rules) {
                        String activeRuleName = ruleNames[ruleCounter];
                        int loadCounter = 0;

                        for (load in loads) {

                                ConfigurableRandomizer rand = new ConfigurableRandomizer();
                                rand.floor = 0;
                                rand.ceil = Integer.MAX_VALUE;
                                rand.seed = 1;
                                rand.distribution = "UNIFORM";
                                randCheckValue = rand.randomInteger();

                                for (replications in 1..numReplications) {
                                        randCheckValue = rand.randomInteger();

%>
    <simulationRun>
          <scheduler currentTime="0"/>
      <compositeResource classname="fi.hse.jobshop.simulation.resources.JobShop2" name="Job shop2">
        <randomizer classname="fi.hse.jobshop.util.ConfigurableRandomizer"
         distribution="UNIFORM" seed="<%=rand.randomInteger()%>" floor="1" ceil="10"/>
         <queueStrategy classname="fi.hse.jobshop.simulation.queues.InstantDispatchQueueStrategy"/>
        <dispatchRule classname="FCFSRule"/>
        <resources>

<%
                        for (m in 1..10) {
%>
          <resource classname="fi.hse.jobshop.simulation.resources.RandomWeightMachine" capacity="1"
                        name="Machine <%=m%>">
            <randomizer classname="fi.hse.jobshop.util.ConfigurableRandomizer"
                  distribution="UNIFORM" seed="<%=rand.randomInteger()%>" floor="1" ceil="31"/>
            <%=rule%>
          </resource>
<%
                                        }
%>
        </resources>
      </compositeResource>

       <jobFactories>
        <jobFactory classname="fi.hse.jobshop.jobs.JobFactoryImpl" numJobs="3000" type="test1">

          <weight classname="fi.hse.jobshop.jobs.RandomValueObject">
            <randomizer classname="fi.hse.jobshop.util.ConfigurableRandomizer"
              distribution="UNIFORM" floor="1" ceil="31" seed="<%=rand.randomInteger()%>"/>
          </weight>
          <size classname="fi.hse.jobshop.jobs.RandomValueObject">
            <randomizer classname="fi.hse.jobshop.util.ConfigurableRandomizer"
              distribution="UNIFORM" floor="1" ceil="1" seed="<%=rand.randomInteger()%>"/>
          </size>
          <size2 classname="fi.hse.jobshop.jobs.RandomValueObject">
```

h

```
            <randomizer classname="fi.hse.jobshop.util.ConfigurableRandomizer"
              distribution="UNIFORM" floor="15" ceil="15" seed="<%=rand.randomInteger()%>"/>
          </size2>
          <unitHoldingCost classname="fi.hse.jobshop.jobs.RandomValueObject">
            <randomizer classname="fi.hse.jobshop.util.ConfigurableRandomizer"
              distribution="UNIFORM" floor="1" ceil="3" seed="<%=rand.randomInteger()%>"/>
          </unitHoldingCost>
          <expeditingCost classname="fi.hse.jobshop.jobs.RandomValueObject">
            <randomizer classname="fi.hse.jobshop.util.ConfigurableRandomizer"
              distribution="UNIFORM" floor="10" ceil="100" seed="<%=rand.randomInteger()%>"/>
          </expeditingCost>
          <arrivalDateFactory classname="fi.hse.jobshop.jobs.RandomMTBAFactory" multiplier="1"
             distribution="EXPONENTIAL" seed="<%=rand.randomInteger()%>"minOperations="1"
             maxOperations="10" numMachines="10"/>
          <dueDateFactory classname="fi.hse.jobshop.jobs.RandomTWKFactory" operationDueDateScalar="TPT">
            <cRandomizer classname="fi.hse.jobshop.util.ConfigurableRandomizer"
              distribution="UNIFORM" floor="0" ceil="0" seed="<%=rand.randomInteger()%>"/>
            <mRandomizer classname="fi.hse.jobshop.util.ConfigurableRandomizer"
              distribution="UNIFORM" floor="<%=ddMultiplier%>" ceil="<%=ddMultiplier%>"
             seed="<%=rand.randomInteger()%>"/>
          </dueDateFactory>
        </jobFactory>
      </jobFactories>

      <reportingFactories>
        <reportingFactory classname="fi.hse.jobshop.reporting.ExcelReportingFactory"
        fileName="weighted_UNIF_1-10_TWK3.xls" worksheet="<%= activeRuleName%>"
        row="<%=(loadCounter*34+1)%>" column="<%=(replications)%>" startFrom="750" endTo="2750"/>
        <reportingFactory classname="fi.hse.jobshop.reporting.ColumnReportingFactory"
        fileName="SPSS_weighted_UNIF_1-10_TWK3.xls" worksheet="Results"
        row="<%=(ruleCounter*loads.size()*ddMultipliers.size()*numReplications) +
        (loadCounter*numReplications*ddMultipliers.size()) + (ddMultiplierCounter*numReplications) +
        replications%>" column="1" startFrom="750" endTo="2750">
          <columns>
            <column value="<%=activeRuleName%>"
                 classname="fi.hse.jobshop.reporting.StaticValueColumn" />
                    <column value="<%=ruleCounter%>"
                          classname="fi.hse.jobshop.reporting.StaticValueColumn"/>
                    <column value="<%=load%>"
                          classname="fi.hse.jobshop.reporting.StaticValueColumn"/>
                    <column value="<%=ddMultiplier%>"
                          classname="fi.hse.jobshop.reporting.StaticValueColumn"/>
                    <column value="<%=replications%>"
                          classname="fi.hse.jobshop.reporting.StaticValueColumn"/>
                    <column property="meanFlowTime"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="maxFlowTime"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="varFlowTime"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="meanTardiness"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="maxTardiness"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="varTardiness"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="weightedMeanFlowTime"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="weightedMaxFlowTime"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="weightedVarFlowTime"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="weightedMeanTardiness"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="weightedMaxTardiness"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="weightedVarTardiness"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="percentageTardyJobs"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="weightedLateness"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="weightedTardiness"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="workInProcessHoldingCost"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="workInShopHoldingCost"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                    <column property="expeditingCost"
                          classname="fi.hse.jobshop.reporting.ReportingFactoryColumn"/>
                  </columns>
        </reportingFactory>
      </reportingFactories>
    </simulationRun>
<%
                                  };
                                  loadCounter++;
                          };
                          ruleCounter++;
                  };
                  ddMultiplierCounter++;
          };
%>
  </simulationRuns>
</simulation>
```

Appendix 8 Static structure of the simulation-application program interface (API) describing public methods and attributes as configurable properties (Svan 2005)



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