

Rapid Prototyping Job Scheduling Optimization

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by

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ABSTRACT

Today's commercial rapid prototyping systems (i.e., solid freeform fabrication, layered manufacturing) rely on human intervention to load and unload build jobs. Hence, jobs are processed subject to both the machine's and the operator's schedules. In particular, first-in-first-out (FIFO) queuing of such systems will result in machine idle time whenever a build job has been completed and an operator is not available to unload that build job and start up the next one. These machine idle times can significantly affect the system throughput, and, hence, the effective cost rate.

This thesis addresses this problem by rearranging the job queue to minimizing the machine idle time, subject to the machine's and operator's schedules. This is achieved by employing a general branch-and-bound search method, that, for efficiency, reduces the search space by identifying contiguous sequences and avoiding reshuffling of those sequences during the branching procedure. The effectiveness of this job scheduling optimization has been demonstrated using a sequence of 30 jobs extracted from the usage log for the FDM 1600 rapid prototyping system in the Department of Mechanical Engineering at Virginia Tech.

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Chapter 1

INTRODUCTION

Rapid prototyping is an important component of the modern design process. With minimal human intervention, it translates virtual solid models into physical parts for improved visualization and understanding. Hence, by reducing the time and cost of each design-fabrication-redesign iteration, rapid prototyping enables designers to detect design errors earlier and at a lower cost.

Most rapid prototyping machines today fabricate parts by depositing thin layers of material, one cross section on top of another. This fabrication process is usually composed of two steps: a short period of manual job setup, followed by a relatively long period of automated part building. The setup requires a human operator to configure the machine, unload any previously finished parts, etc., and it is usually completed within the hour. The part building, on the other hand, is completely automated and does not require an operator to be present, but it can take days to complete.

Once the fabrication process is under way, a job generally cannot be preempted by another job without being cancelled. Hence, in most cases, a job must simply wait its turn. In most rapid prototyping operations, the human operator simply maintains an ad hoc queuing system in which the next job is manually selected, usually on a first-in-first-out (FIFO) basis. Bailey [Bailey95] facilitated this concept by enabling users to submit jobs over a local area network (LAN) via a FIFO print queue. FIFO print queues have since been commercialized for a number of the lower-cost rapid prototyping systems, including the Genisys (Stratasys, Inc.) and the ThermoJet (3D Systems, Inc.).

1.1 PROBLEM STATEMENT AND OBJECTIVES

The problem with using a FIFO queuing system to feed today's rapid prototyping systems, is that it will cause machine idle time whenever a machine operator is not at hand to perform a setup for the next job. This machine idle time can significantly impact the rapid prototyping systems' long-term throughput, and, hence, its effective cost rate.

Figure 1.1 illustrates this problem. A sequence of five jobs arrives and is processed FIFO subject to the operator's schedule. The result is several hours or days of machine idle time between jobs 2 and 3 due to the operator's not being available to start up job 3.

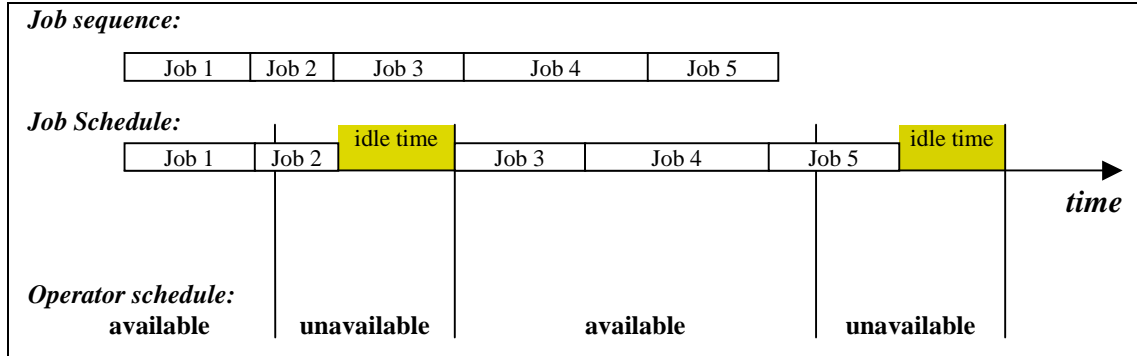


Figure 1.1 Example of how a FIFO queueing system can cause machine idle time for a given job sequence and operator schedule.

There are three solutions to this problem. One solution is to compromise the operator's schedule to ensure that an operator is always available. However, this is not always possible, especially with single-shift operations. A second solution is to redesign the rapid prototyping system such that a manual operator is not needed, much like a conventional laser printer. Brockmeier et al. [Brockmeier99] demonstrated this solution for the fused deposition modeling (FDM) rapid prototyping systems. An automated job loading and unloading mechanism was built to replace the role of human operator. The third solution is to rearrange the job sequence in order to minimize the machine idle time.

The objective of this thesis is to demonstrate the third solution: namely, to develop a queueing system that is appropriate for rapid prototyping job scheduling. The queueing system should maximize the rapid-prototyping-machine utilization, subject to a given operator's schedule.

1.2 SOLUTION OUTLINE

The proposed solution for reducing machine idle time in rapid prototyping operations is based on the general branch-and-bound search method [Pinedo99] [French82]. With this enumerative method, all possible permutations of jobs are generated for a given set of jobs. Subject to a known operator's schedule, each of these job sequences represents a different job schedule with an associated amount of machine idle time. The optimal job

schedule is the one with minimum machine idle time. The algorithm presented here seeks to identify this optimal job schedule. To illustrate such a job schedule, consider the one depicted in Figure 1.2. It is a clear improvement on the one depicted in Figure 1.1: the idle time is reduced and the set of jobs is completed sooner.

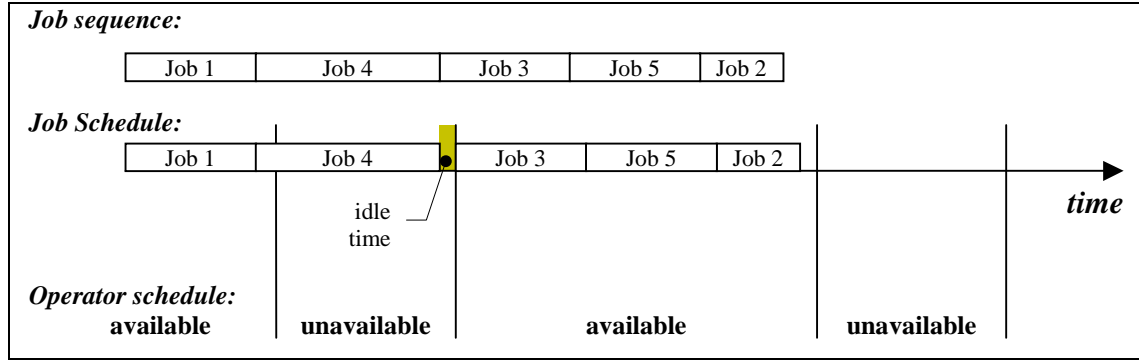
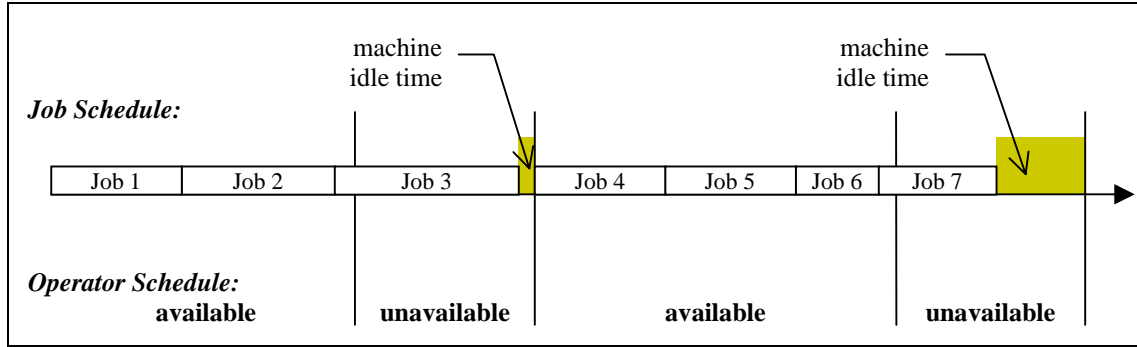


Figure 1.2 Example of improved job schedule in comparison to the schedule shown in Figure 1.1.

The branch-and-bound method, however, is known for its computational complexity. The time needed to find such an optimal schedule grows exponentially as the number of jobs increases. In addition, the difficulties of lower-bound evaluation for rapid prototyping job scheduling make it hard to implement an efficient branch-and-bound method. This thesis addresses this computational cost problem by exploiting certain underlying characteristics associated with the rapid prototyping job and operator schedules. Specifically, the proposed solution seeks to identify and maximize *contiguous sequences*.

Contiguous sequence is defined here as a sequence of jobs for which the corresponding schedule does not contain machine idle time. Figure 1.3 illustrates the formation of two contiguous sequences. For the given operator schedule and job sequence, the job schedule is broken into several pieces separated by machine idle time. Each of these pieces contains a subset of jobs that are processed contiguously in sequence; hence the term *contiguous sequence*.



**Figure 1.3 An example of two contiguous sequences:
(Job 1, Job 2, Job 3) and (Job 4, Job 5, Job 6, Job 7).**

Since there is no machine idle time within a contiguous sequence, it represents an optimal schedule for the jobs it contains during the period it has been allocated. Hence, it is unnecessary to attempt a reshuffling of jobs within a contiguous sequence. Job schedules I and II in Figure 1.4 illustrate a set of contiguous sequences that have been needlessly reshuffled. In the original job schedule, two contiguous sequences, (Job 1, Job 2, Job 3) and (Job 4, Job 5, Job 6, Job 7), are formed. Schedule I is the result of exchanging the positions of Job 1 and Job 2 in the first contiguous sequence, and it does not reduce the machine idle time relative to the original schedule. Schedule II is the result of exchanging the position of Job 2 and Job 3 in the first contiguous sequence. This change actually increases the machine idle time by forcing a shortening of the first contiguous sequence and delaying the end of it to spill over and impact the second contiguous sequence. Similarly, the same two situations will occur if the jobs within the second contiguous sequence are reshuffled.

The branch-and-bound method should therefore avoid branches that cause job reshuffling within contiguous sequences. Instead, it should attempt to maximize the lengths of the contiguous sequences to minimize the machine idle time and increase the probability of reducing the search space. This strategy of avoiding reshuffling branches significantly reduces the search space and hence the computation cost.

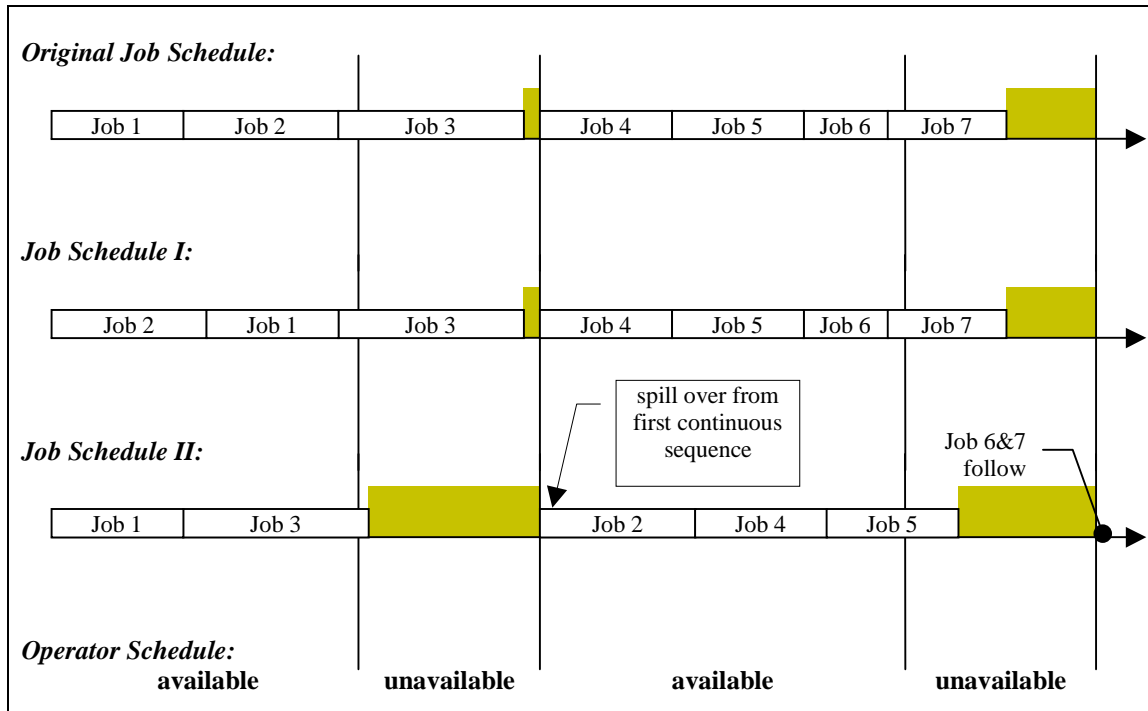


Figure 1.4 Reshuffling the jobs within the contiguous sequence (Job 1, Job 2, Job 3) may result in either no improvement (Schedule I) or worse performance (Schedule II). Reshuffling within a contiguous sequence should therefore be avoided.

1.3 THESIS ORGANIZATION

The remainder of this thesis details the new rapid-prototyping job-scheduling algorithm. It consists of the following:

Chapter 2 provides some background information on rapid prototyping technologies and, in particular, the Fused Deposition Modeling 1600 system, which is used as the test bed for this thesis. It reviews the research on remote manufacturing as it relates to rapid prototyping systems, job dispatching rules, and the general branch-and-bound method.

Chapter 3 discusses the proposed scheduling algorithm in detail. It looks at the attributes of rapid-prototyping job queues and the influence of the operator's schedule. It then lays out the strategy for decomposing the scheduling problem and eliminating unnecessary searching space for the branch-and-bound method.

Chapter 4 examines the results of the proposed scheduling method when applied to a FDM 1600 system. Two sample sets of job sequences are used to test the new scheduling method. The results are compared with conventional First-In-First-Out (FIFO) schedule.

Chapter 5 presents conclusions, outlines contributions, and gives suggestions for future work.

Chapter 2

LITERATURE REVIEW

Rapid prototyping (RP) is an important technology for the design process. It enables fabrication of complex geometric parts directly from computer aided design (CAD) models. Compared to traditional fabrication systems, RP systems require fewer operating procedures, and most of these procedures are automated. This enables fast design-fabrication-redesign iterations at a lower cost. Because the CAD models used by RP systems are in electronic forms, they can be easily transmitted across the Internet. Hence, there has been an interest in facilitating remote RP fabrication of three-dimensional parts across the Internet, similar to two-dimensional image printing using network-connected printers.

This chapter provides a brief introduction to RP fabrication technologies, using the FDM 1600 rapid prototyping system as an example. It reviews past efforts in remote fabrication using RP systems, job dispatching rules and scheduling methods, and their potential to facilitate remote RP fabrication.

2.1 RAPID PROTOTYPING AND FUSED DEPOSITION MODELING

Rapid prototyping refers to fabrication technologies that build 3D solid models directly from a computer-based design model [Burns93]. Unlike traditional manufacturing systems, which generally require constant human supervision and instructions during the fabrication process, RP systems control fabrication operations using numerical control (NC) toolpath files generated directly from the CAD model. Human intervention is only needed when loading materials, mounting support structures, or removing finished parts. The operating procedures of RP systems are hence simple and mostly automated.

Fused deposition modeling (FDM) is one of the more widely used RP technologies. FDM systems can build complex geometric parts from various thermoplastic materials including ABS plastic, investment casting wax, or elastomer. During the fabrication process, material is heated into a semi-liquid state and deposited layer by layer onto a

foam foundation through the FDM head. The FDM head is controlled by the NC tool-path file generated from the CAD model. After completing the material deposition in one layer, the foam foundation moves down to allow the FDM head to deposit another layer of material. These successive layers of material fuse together and solidify to grow an accurate three-dimensional model of the design [Stratasys95].

Figure 2.1 shows the basic configuration of the FDM 1600 rapid prototyping system. It consists of a workstation and an FDM 1600 rapid prototyping machine. During the fabrication process, the workstation continuously uploads NC commands to the FDM machine, which in turn deposits material according to these NC commands. These NC commands can either be generated by the CAD software in the workstation, or be uploaded to the workstation from elsewhere.

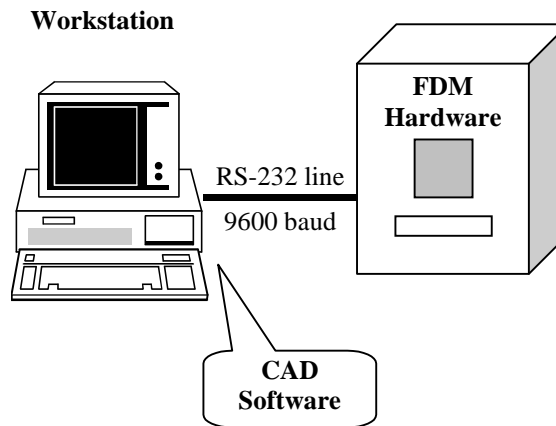


Figure 2.1 Basic configuration of FDM system

For most RP systems, the standard operating procedure consists of the following three steps [Stratasys95]:

1. Make the NC codes available. For the FDM 1600 rapid prototyping system, NC codes need to be stored on the workstation.
2. Ready the RP machine. For the FDM 1600 rapid prototyping system, this operation includes loading material, unloading the finished parts, if any, and then loading a new foam foundation where the material is to be deposited.
3. Start the part building process. For the FDM 1600 rapid prototyping system, a start command is issued from the workstation to start building a part. After the

start command is issued, NC codes are uploaded to the controller of the FDM machine, and the fabrication process is performed automatically until it is completed or interrupted.

These three steps require an operator to be present in order to start a fabrication job. Some commercial RP systems simplify the operation by performing step 1 and step 3 using software, while the machine preparation procedure is still performed manually. To improve the automation level of the FDM 1600 system, Brockmeier et al. [Brockmeier99] built a fully automated system to load and unload the foam foundation. However, none of today's commercial RP systems is equipped with such an automated loading mechanism and therefore human intervention is required. Their uses are hence significantly affected by operator's schedules.

In addition, because of limitations in the standard FDM control software, an FDM job should not be preempted. The FDM control software does not store the information about the current position of the FDM head or the foam foundation when an FDM job is interrupted and preempted by other jobs. Hence, when the preempted job is to be resumed, it will be practically impossible to return the FDM head back to the position at which it was interrupted, for further material deposition without negatively affecting the precision and finish of the part. This lack of preemptive capability applies to most of the current RP systems.

2.2 REMOTE RAPID PROTOTYPING

Remote rapid prototyping refers to the situation where the product model, which is designed at one geographic location, is transferred across the Internet to an RP system at another location for fabrication. The purpose of remote RP systems is to share the RP device among a larger community of engineers to dilute the cost of investment, similar to the network-connected printers that are shared by multiple users.

PARES [Hansen93] is an example of an early form of prototyping service on the Internet. To utilize the manufacturing service of this system, users need to convert their CAD models into a standard format and mail them over the Internet to the manufacturing facility. Human intervention is then required at the manufacturing site to pick up the

jobs, setup the manufacturing system and perform job planning. This system does not provide an automated job queuing system, and it is up to the machine operators to decide the job processing order.

The CyberCut project [Smith96] is a continuation of the PARES project [Hansen93]. Focusing on providing a complete CAD/CAM environment via the World Wide Web (WWW), the CyberCut system is implemented with three sets of agents: design agents, planning agents, and fabrication agents. Design agents provide users with design options that are accepted by the planning agents according to the capabilities of fabrication agents. The user makes design choices and sends them to the planning agents for process planning, cost estimation, feasibility evaluation, and estimation of time to manufacture. After the user is satisfied, the process plan is sent to a fabrication agent and placed in a fabrication queue. The fabrication of this job is initiated once the previously ordered jobs are completed. In essence, the jobs in this system are simply scheduled on a first-in-first-out (FIFO) basis.

The Tele-Manufacturing Facility (TMF) [Bailey95] is probably the first system that provides users with direct access to a rapid prototyping facility over the Internet. This system uses client-server software to handle the communication between the user and the prototyping facility. The user uploads CAD models through a WWW browser to the server. Upon receiving a CAD model, the server automatically performs error checking for the model file. It then puts the fabrication job into a queue of jobs waiting to be processed by a Helisys 1015 Laminated Object Manufacturing (LOM) rapid prototyping system. A similar system has been demonstrated by Luo et al. [Luo99].

TMF also manages its fabrication jobs on a FIFO basis. The queuing mechanism in TMF is built on top of the standard UNIX line printer spooler *lpr* (Figure 2.2). Incoming jobs are sequenced by the UNIX print spooling system according to their arrival times and thus form a FIFO queue. This project did not address machine utilization problems caused by the FIFO job schedule.

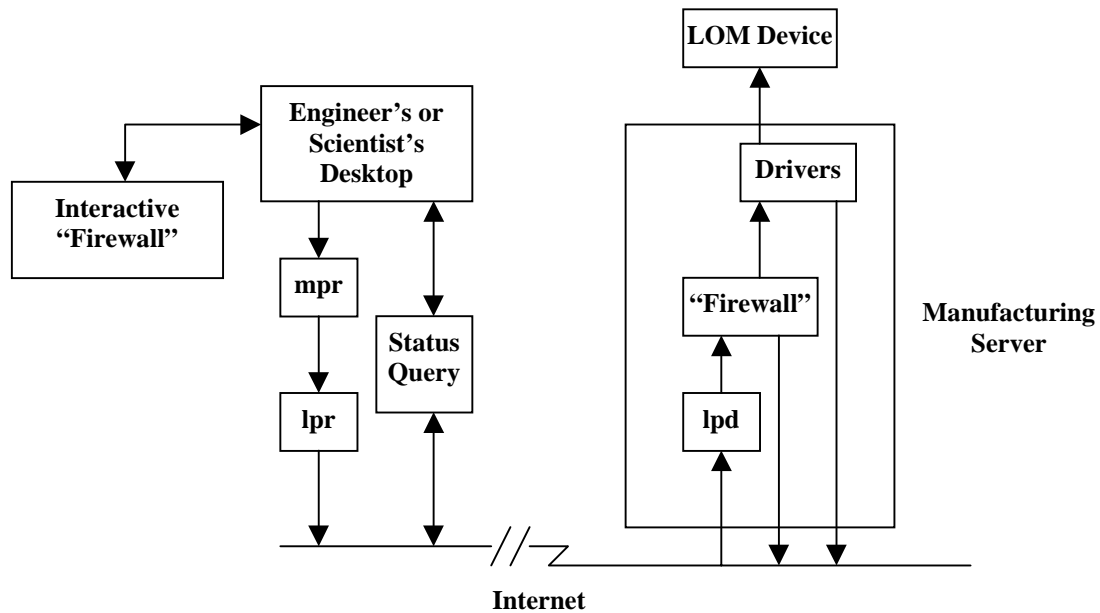


Figure 2.2 Tele-manufacturing Facility builds its network-accessible queuing mechanism on top of the UNIX print spooling system [Bailey95].

Several commercial RP systems with a FIFO job queue have appeared since the TMF project, including the Prodigy (Stratasys, Inc.), the Genisys (Stratasys, Inc.), and the ThermoJet (3D Systems, Inc.). These systems require a network connection and can operate in an office environment as networked peripheral devices while accommodating multiple-user access. Users simply submit the prototyping job as a usual print job, and the job data is automatically sent via the local area network (LAN) to the print queue for fabrication on a FIFO basis.

All of these networked RP systems face the machine utilization problem that is caused by conflicts between the operator and job schedules. As mentioned in the previous section, none of these networked RP systems can handle fabrication job change-over without human intervention. That is, although the fabrication process itself may not require operator attendance, the completed part still needs to be unloaded manually before the next job in the queue can be started: when a job is completed, the machine simply waits in an idle state until an operator is available to execute the change-over. Hence, improved scheduling becomes increasingly important to the effective utilization of the RP systems as the number of queued jobs grows large.

2.3 JOB SEQUENCING AND SCHEDULING

Sequencing and Scheduling

Sequencing is the process that determines the order in which various operations are performed, while scheduling is the process that determines when each of these operations starts and finishes [French82]. The scheduling process is usually composed of two processes: a sequencing process and a timetabling process. The latter is the process that simply derives a schedule from a sequence.

Criteria in Scheduling

Every scheduling process uses certain criteria to measure the success of the schedule. Based on different scheduling objectives, various kinds of criteria exist. The most frequently used criteria are based on completion times, due dates, or inventory and utilization costs [French82].

Criteria based on completion times include the maximum completion time C_{max} , the maximum flow time F_{max} , the average flow time F_{avg} , and the average completion time C_{avg} [French82]. C_{max} is also called the total production time or the make-span. Minimizing C_{max} means that the cost of the schedule depends on how long the processing system is devoted to the entire set of jobs, while minimizing F_{max} implies that a schedule's cost is directly related to its longest job. It should be noted that F_{max} and C_{avg} are identical when all the job ready times are zero.

In rapid prototyping job scheduling it makes sense to select the maximum completion time as the scheduling criterion. The object of rapid prototyping job scheduling is to reduce machine idle time and hence increase system production. Machine idle time is computed as:

$$I = C_{max} - \sum_{i=1}^n p_i, \text{ where } p_i \text{ is the processing time of job } i \text{ [French82].}$$

For the rapid prototyping job-scheduling problem, each job's processing time is assumed to be a fixed value. Hence, machine idle time is proportional to the total completion time for the entire set of jobs in the queue. As a consequence, the total completion time, C_{max} ,

of the entire job set should be selected as the criterion of rapid prototyping job scheduling.

Job Dispatching Rule

Many job dispatching rules have been developed to help in deciding the order in which jobs are dispatched to the machine for processing. This thesis reviews three frequently used job dispatching rules: FIFO, SPT (Shortest Processing Time), and LPT (Longest Processing Time).

FIFO, also called first come first serve (FCFS), is the rule used in most print spooling systems and in some remote rapid prototyping systems. The advantage of FIFO is the simplicity of implementation. In the fact, no scheduling operation is needed because jobs are simply processed based on their arriving order. The disadvantage is that the schedule generated can be very bad based on performance measures, as illustrated in Chapter 1. This thesis uses the FIFO schedule as a benchmark to evaluate schedules generated by the proposed scheduling method.

The SPT rule processes the shortest job first, while LPT prioritizes the longest one [French82]. Both rules have been tested for rapid prototyping job scheduling, and neither of them can consistently produce a good schedule with respect to minimizing the total completion time. Figure 2.3 shows two cases where SPT and LPT can even create schedules that are worse than the FIFO schedule.

Branch-and-bound Method

The branch-and-bound method is a widely used enumerative technique to solve combinatorial optimization problems and has been applied to many scheduling problems [French82][Ibaraki87][Pinedo95][Pinedo99]. The basic strategy of the branch-and-bound method is to decompose a given problem into sub-problems of smaller size and then solve the original problem by solving all of its sub-problems. This strategy is recursively applied to the sub-problems and results in an enumerative algorithm.

A hierarchical branching tree structure describes the process of the branch-and-bound method [French82]. Starting from the original problem, which is represented as the root of the tree, the branch-and-bound method first generates a set of nodes that represent

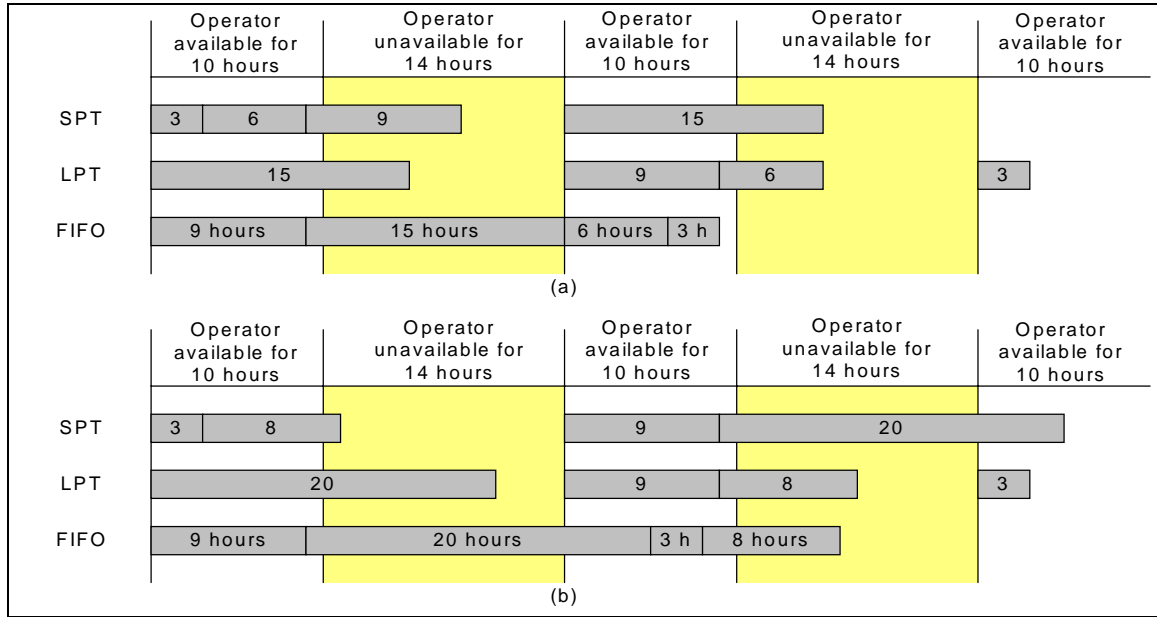


Figure 2.3. Two cases show that SPT and LPT can generate schedules worse than the FIFO schedules. The numbers in the shaded areas represent the job processing time for that particular job.

sub-problems in lower level. It then evaluates the lower bound of the objective function for each node at that level. For nodes whose lower bound passes the elimination criteria, the search will continue from those nodes by branching into the next level. If a node fails the elimination criteria, it will then be removed from the searching tree and the search is bounded back to other nodes at the same or higher levels.

For the RP job scheduling problem, the branch-and-bound method can be used to generate all the possible job sequences, evaluate the schedule for each sequence, and then select a shortest job schedule. The nodes in the branching tree will represent the sequences that have been formed so far, and evaluation of the potential schedule length at each node will determine whether or not the search from that node can continue.

In a summary, applying the branch-and-bound method to a given problem requires consideration of two issues: (1) the branching procedure and its search strategy, and (2) the bounding procedure and its eliminating criteria [Błazewicz94].

It is known that the computational complexity of a branch-and-bound algorithm is exponential with respect to problem size. The time required to solve a problem is unpredictable, and it is largely affected by the searching strategy [French82]: a frontier

search generally finds an optimal schedule faster than a depth-first search, but requires a significantly more storage. Furthermore, it is important that the evaluation of lower bounds is accurate in order to effectively eliminate the infeasible branches and thus reduce the computation time. Computation time may also be reduced by employing other methods such as priming the search with a good trial schedule or accepting a sub-optimal solution.

For RP job scheduling, the obstacle of using the branch-and-bound method is that it is difficult to accurately evaluate the lower bound of the objective function, especially at the earlier stage of the searching process. Therefore, lower bound evaluation is impractical for reducing the search space and the computation time. In its place, this thesis therefore aims to develop new strategies to effectively reduce the search space for the branch-and-bound method so that it can be implemented to solve the RP job-scheduling problem. The development of these strategies is based on the characteristics of the RP job queue and scheduling constraints.

2.4 OBSERVATION FOR THIS THESIS

With regard to this thesis, the following observations are made concerning past work:

1. Current remote RP systems do not address the job scheduling issue;
2. To improve the utilization of current remote RP systems, appropriate job scheduling methods are needed to generate efficient RP job schedules with respect to minimizing the machine idle time;
3. The branch-and-bound method can serve as the basis for a search for an efficient RP job schedule, provided a strategy can be found to replace the conventional lower bound evaluation, which is impractical in the case of RP job schedules. To be effective, this new strategy must consider the characteristics of RP job queues and schedules.

Chapter 3

RAPID PROTOTYPING JOB SCHEDULING

The proposed solution for finding a RP job schedule with minimum machine idle time is based on the branch-and-bound method. This solution requires developing a strategy to effectively reduce the search space and the computation time associated with the branch-and-bound method. This chapter describes the development of such a strategy. It begins with the modeling of the RP job scheduling problem. It then points out several important characteristics of RP job queues and schedules. These characteristics lead to the development of an effective search strategy that can be used in the branch-and-bound method to reduce the computation time.

3.1 MODELING THE RP JOB SCHEDULING PROBLEM

Most rapid prototyping systems today fabricate parts in two steps: job setup and part building. Job setup is a manual process that requires an operator to configure the machine and unload any previously finished parts, and it is usually completed within an hour. Part building is a fully automated process that does not require human intervention, but it may take days to complete.

Because of the manual setup process, the RP job schedules are affected by the operator's schedule. If the operator is not available to start a new job when the current job is completed, the machine has to wait in an idle state and hence idle time is generated in the job schedule. The following sections create a basic model for describing the RP job scheduling problem. First, Section 3.1.1 describes the assumptions. Next, Sections 3.1.2 and 3.1.3 describe the notations for the RP job schedule and the operator's schedule. Section 3.1.4 describes the calculation of job schedule. Finally, Section 3.1.5 discusses the scheduling criterion.

3.1.1 MODEL ASSUMPTIONS

Based on the general operating procedures of RP systems as described earlier, the RP job scheduling problem is assumed to be constrained as follows:

1. The system queuing capacity is effectively infinite, and the job queue consists of a sequence of jobs awaiting processing.
2. The operator's availability schedule is known for any period in question.
3. An RP job event is created when the job data is sent to the job queuing system. No two job events are created at the same time; i.e., for any given instant, only one job can enter the queuing system.
4. When a new job event is created, all the pre-existing jobs in the queue are subjected to rescheduling.
5. The processing time for each job is known when the job event is created, and this time is sequence independent.
6. The RP jobs may not be preempted.

3.1.2 THE RAPID PROTOTYPING JOB QUEUE AND SCHEDULE

The following notations are used in this thesis to represent an RP job queue:

1. $\{ J_1, J_2, \dots, J_N \}$ represents an unordered set of N jobs with no sequencing information implied.
2. (J_1, J_2, \dots, J_N) represents an ordered set or sequence of N jobs to be executed in the order listed.
3. For job J_i , the job processing time is T_i ; the job arrival time, ta_i , is the time that J_i enters the queuing system; the job start time, ts_i , is the time that the RP machine starts processing J_i ; and the job finish time, te_i , is the time that the RP machine finishes the part building process for J_i . The start time and finish time are subject to change whenever the job schedule is updated; in particular, $te_i = ts_i + T_i$.
4. $(JS_1, JS_2, \dots, JS_N)$ represents the job schedule, where $JS_i = [ts_i, te_i]$ for $i \in [1, N]$.

3.1.3 RAPID PROTOTYPING OPERATOR SCHEDULE

The operator's schedule appears as an ordered set of time intervals. Each interval indicates the beginning and end of a period that an operator is available. The following notations are used in this thesis to describe the operator's schedule:

1. $(OS_1, OS_2, \dots, OS_K)$ represents the operator's schedule. It is an ordered sequence of K time intervals, each of which indicates the period that the operator is available. This sequence is referred to as the operator schedule sequence.
2. $OS_i = [tos_i, toe_i]$ for $i \in [1, K]$; tos_i and toe_i are the start and end time of the interval OS_i , respectively.
3. The interval between OS_i and OS_{i+1} is the period that the operator is unavailable, and it is referred as the gap, OG_i , in the operator's schedule. $OG_i = [toe_i, tos_{i+1}]$ for $i \in [1, K-1]$.
4. Given that the operator's schedule is known for any period, we assume K is sufficiently large such that, for any time t considered during the scheduling process, the condition $tos_1 \leq t \leq toe_K$ holds.

3.1.4 CALCULATING JOB SCHEDULE AND TOTAL COMPLETION TIME

Given a sequence of N jobs (J_1, J_2, \dots, J_N) that is available for scheduling at time t subject to an operator schedule $(OS_1, OS_2, \dots, OS_K)$, the resulting job schedule can be generated as follows:

1. Let t_s be the earliest machine available time. If $t < t_s$, then set $t = t_s$.
2. For $i = 1$ to N ,
 - a. If t is within the operator's available time, i.e., $tos_j \leq t \leq toe_j$ for $j \in [1, K]$, then set $ts_i = t$ and $te_i = ts_i + T_i$.
 - b. If t is in a gap of the operator's schedule, i.e., $toe_j < t < tos_{j+1}$ for $j \in [1, K-1]$, then set $t = tos_{j+1}$, $ts_i = t$, and $te_i = ts_i + T_i$.

- c. Update $t = te_i$.
3. The total completion time for the job schedule is then calculated as the difference between the start time of J_1 and the finish time of J_N ; i.e., $C_{\max} = te_N - ts_1$.

3.1.5 THE SCHEDULING CRITERIA

The object of rapid prototyping job scheduling is to reduce machine idle time and hence increase system productivity. As stated in Chapter 2, machine idle time directly impacts the total completion time for the entire set of jobs in the queue. Therefore, the total completion time, C_{\max} , for the entire job set is selected as the criterion for determining the optimal rapid prototyping job scheduling: the job sequence that generates the shortest schedule length (i.e., the total completion time) will be used to determine the optimal job queue.

3.2 SCHEDULING ALGORITHM

The proposed scheduling algorithm is based on the branch-and-bound method to generate all the feasible job sequences, evaluate the corresponding schedules, and find a schedule with the shortest total completion time. The branch-and-bound method is an enumerative method that ensures an optimal result. However, it is computationally intensive, and an efficient strategy must be provided to reduce the search space and the associated computation time.

In this thesis, the search space reduction strategy is based on certain characteristics of contiguous sequences found in RP job schedules (Section 3.2.1). In particular, it is based on that a schedule is non-optimal if any of its sub-schedules is not optimal for the set of jobs in that sub-schedule, because an improvement of the sub-schedule will create a better schedule for the whole set of jobs than the original one. Hence, the nodes in the branch-and-bound search tree that correspond to such non-optimal schedules can be disregarded for further consideration. The following sections discuss this strategy in more detail: Section 3.2.1 explores the characteristics of the RP job schedules and provides a method for identifying non-optimal sub-schedules that can be eliminated;

while Section 3.2.2 applies these findings to help the branch-and-bound method execute more efficiently.

3.2.1 CHARACTERISTICS OF RP JOB QUEUES AND SCHEDULES

As described in previous chapters, the machine idle time in the RP job schedule is caused by the gaps in the operator's schedule. Within a gap, a RP job cannot be started, but its build may continue if the job starts prior to the gap. This imposes certain characteristics upon RP job schedules and leads to the findings of contiguous sequence described in Section 3.2.1.1. Based on these findings, a method of identifying a non-optimal sub-schedule is then provided in Sections 3.2.1.2 through 3.2.1.4 by seeking an improvement for the sub-schedule that corresponds to a contiguous sequence.

3.2.1.1 Contiguous Sequences in a RP Job Schedule

For a given RP job schedule, a *contiguous sequence* is defined as a sequence of jobs for which the corresponding schedule does not contain machine idle time. Figure 3.1 illustrates the formation of two contiguous sequences. For the given operator schedule and job sequence, the job schedule is broken into several pieces separated by machine idle time. Each of these pieces contains a subset of jobs that are processed contiguously in sequence; hence the term *contiguous sequence*. A contiguous sequence has the following properties:

1. Each contiguous sequence is associated with the start time of its first job. For the example in Figure 3.1, the contiguous sequences (J_1, J_2, J_3) and (J_4, J_5, J_6, J_7) are associated with the start times t_1 and t_2 , respectively. If the sequence (J_4, J_5, J_6, J_7) is started at time other than t_2 (e.g., t_3), then job J_7 will be delayed until after Gap II, and the sequence (J_4, J_5, J_6, J_7) will no longer be a contiguous sequence. Hence, moving a contiguous sequence to a time other than its original start time will not guarantee the validity of that contiguous sequence.

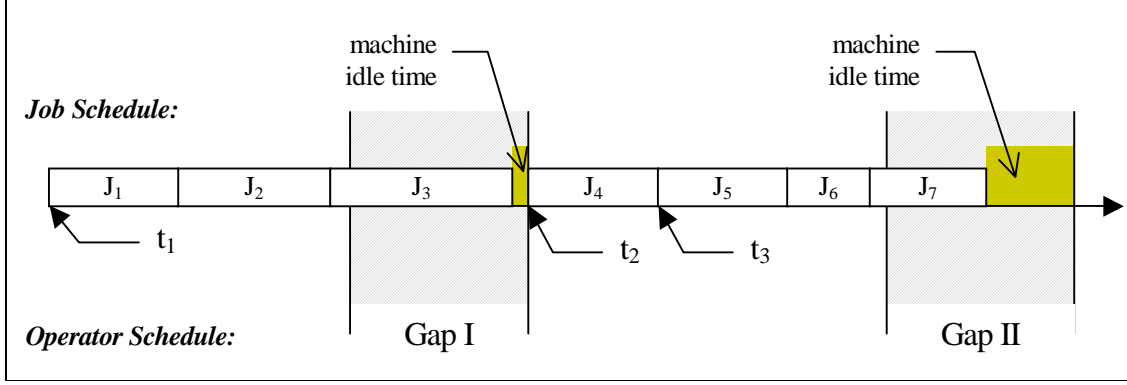


Figure 3.1 An example of two contiguous sequences: (J_1, J_2, J_3) and (J_4, J_5, J_6, J_7) .

2. The definition of a contiguous sequence implies that the sub-sequences of a contiguous sequence are also contiguous sequences. Hence, for the contiguous sequence (J_4, J_5, J_6, J_7) in Figure 3.1, the sub-sequences (J_4, J_5, J_6) and (J_5, J_6, J_7) are also contiguous sequence. However, while the sequence (J_4, J_5, J_6) starts at the same time as (J_4, J_5, J_6, J_7) , the sequence (J_5, J_6, J_7) starts at a different time t_3 .
3. A contiguous sequence represents an optimal schedule for the jobs it contains during the period it has been allocated, because there is no machine idle time within that period.
4. Because a contiguous sequence is optimal, it is not necessary to reshuffle its jobs. For instance, in Figure 3.2, the job schedules I and II illustrate a set of contiguous sequences that have been needlessly reshuffled. In the original job schedule, the two contiguous sequences, (J_1, J_2, J_3) and (J_4, J_5, J_6, J_7) , are formed. Schedule I is the result of exchanging the positions of jobs J_1 and J_2 in the first contiguous sequence, which does not reduce the machine idle time relative to the original schedule. Schedule II is the result of exchanging the position of jobs J_2 and J_3 in the first contiguous sequence. This change, however, actually increases the machine idle time by forcing a shortening of the first contiguous sequence and delaying the end of it to spill over and impact the second contiguous sequence. Likewise, similar situations will occur if the jobs within the second contiguous sequence are reshuffled. Hence, from the RP job scheduling point of view, any job reshuffling within a contiguous sequence wastes computational time and should be avoided.

These observations imply that a scheduling method which is based on the branch-and-bound method, should therefore attempt to (1) eliminate any branches that cause job reshuffling within a contiguous sequence; and (2) extend the lengths of the contiguous sequences. Fortunately, these two objectives are related. As a contiguous sequence is extended, the number of branches that cause job reshuffling—and that hence can be eliminated from further consideration—increases. By eliminating these branches, and those that contain the original sub-schedule (which corresponds to the original contiguous sequence that is extended, and hence does not add any interesting alternatives), the search space for the branch-and-bound method is significantly reduced. This is discussed further in Section 3.2.2.

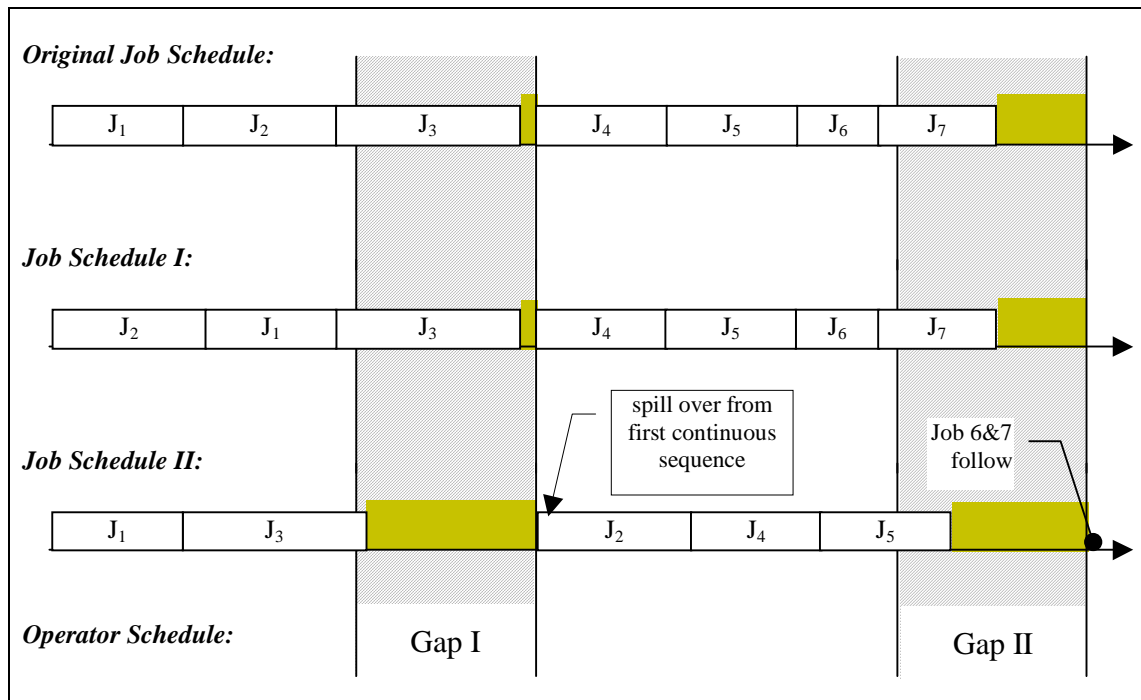


Figure 3.2 Reshuffling the jobs within the contiguous sequence (J_1 , J_2 , J_3) result in either no improvement (Schedule I) or worse performance (Schedule II).

The following three sections (3.2.1.2 through 3.1.1.4) present a method for identifying the non-optimal sub-schedule by investigating the opportunity to expand any given contiguous sequence within a partially formed RP job schedule. First, Section 3.2.1.2 describes a method for expanding contiguous sequences that span only one gap. Next, Section 3.2.1.3 discusses situations where a contiguous sequence spans

multiple gaps. Finally, Section 3.2.1.4 discusses how to select candidate jobs that will be used to expand a given contiguous sequence.

3.2.1.2 Expanding Contiguous Sequences

A contiguous sequence can be expanded by inserting an appropriate job into an appropriate position in that sequence. The example in Figure 3.3 shows that by inserting the job J_4 into the third position of the original contiguous sequence (J_1, J_2, J_3) , a longer contiguous sequence (J_1, J_2, J_4, J_3) is formed. Because of the improvement, the original sub-schedule for the job set $\{J_1, J_2, J_3, J_4\}$ is proved to be non-optimal. This further implies that the original schedule is not optimal. This idea of using the expansion of contiguous sequences to identify non-optimal sub-schedules will be applied to the branch-and-bound method in Section 3.2.2 to reduce the search space. The following discusses how to expand a given contiguous sequence.

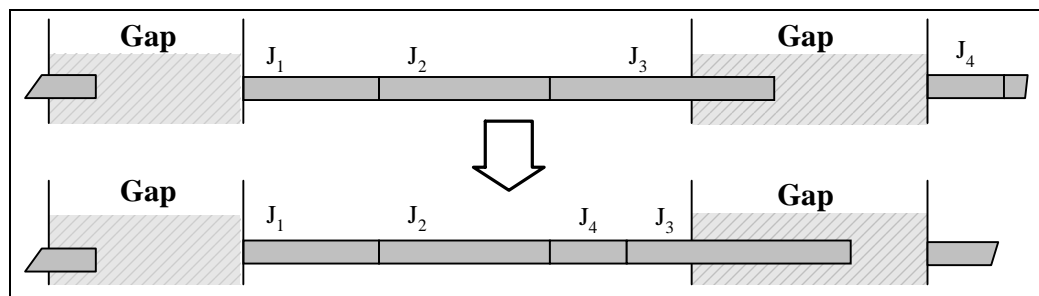


Figure 3.3 An example of expanding the length of the contiguous sequence.

To illustrate a method for expanding the length of a contiguous sequence, consider a contiguous sequence $S = (J_1, J_2, \dots, J_k)$ as shown in Figure 3.4. Suppose job J_n is a candidate for expanding the length of this sequence. It is clear that J_n must initially appear after S in the schedule; otherwise, the manipulation of J_n may affect the start time and, hence, the validity of the sequence S .

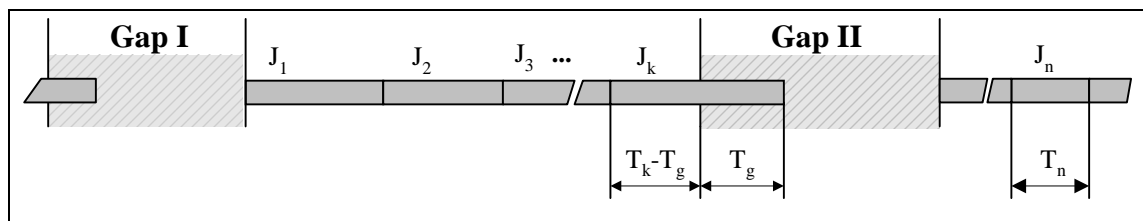


Figure 3.4 For a contiguous sequence (J_1, J_2, \dots, J_k) , the candidate J_n for expanding the length of the sequence should appear after this sequence in the schedule.

In Figure 3.4, T_k is the processing time of job J_k , T_g is the portion of Gap II that is used by J_k , and T_n is the processing time of job J_n . Given this situation, the following discussion focuses on the three cases, $T_n \leq T_k - T_g$, $T_k - T_g < T_n \leq T_k$, and $T_k < T_n$:

1. **When $T_n \leq T_k - T_g$** , we can simply insert J_n into the k th position in S as shown in Figure 3.5. Because $T_n \leq T_k - T_g$, job J_n will finish before Gap II starts and hence allows job J_k to be processed immediately. This results in the longer contiguous sequence $S' = (J_1, J_2, \dots, J_{k-1}, J_n, J_k)$.

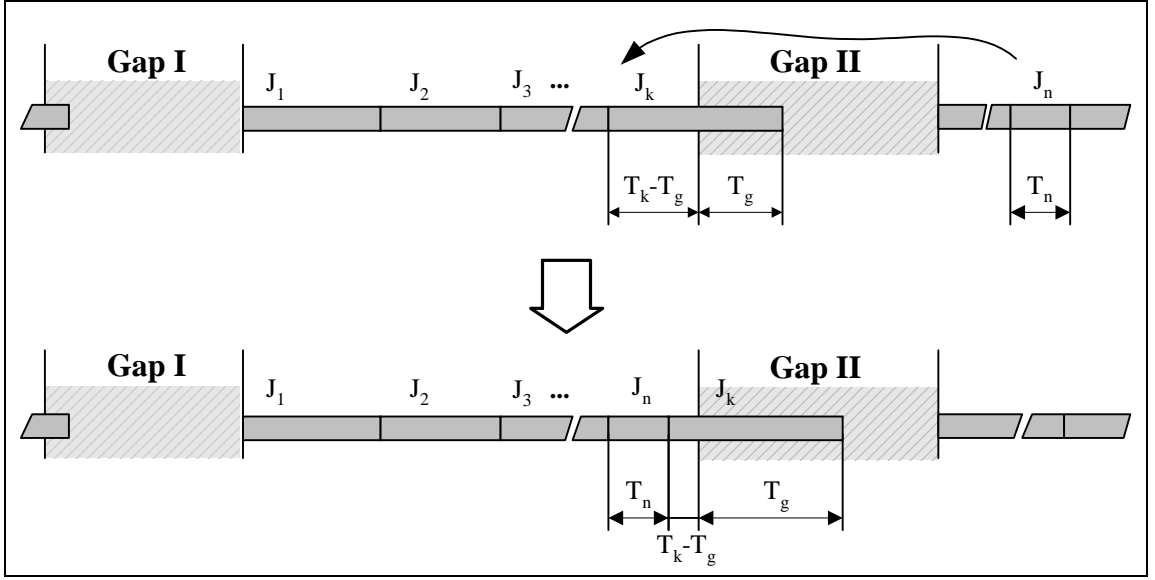


Figure 3.5 Expanding the contiguous sequence with job J_n when $T_n \leq T_k - T_g$.

2. **When $T_k - T_g < T_n \leq T_k$** , we cannot simply insert J_n in the front of J_k , because job J_k would then be forced to start after Gap II: Since $T_n \leq T_k$, the machine idle time would then increase and result in a shorter contiguous sequence $(J_1, J_2, \dots, J_{k-1}, J_n)$.

The solution is to remove the smallest job, J_i , if any, preceding J_k in S , such that $T_i < T_n$ (to increase the sequence) and $T_k - T'_g = T_k - T_g + T_i \geq T_n$ (such that J_n does not cause J_k to shift into Gap II). Hence, J_i should be selected such that $T_n > T_i \geq T_n - T_k + T_g$. This selection can be achieved as follows:

- i. Find the shortest job J_i from the original sequence $(J_1, J_2, \dots, J_{k-1})$;

- ii. If $T_n > T_i \geq T_n - T_k + T_g$, then remove J_i from the original sequence and insert job J_n in front of J_k , and terminate. This results in the longer contiguous sequence $S' = (J_1, J_2, \dots, J_{i-1}, J_{i+1}, \dots, J_{k-1}, J_n, J_k)$.
 - iii. Otherwise, find the next shortest job and repeat step ii until $T_n \leq T_i$ or all jobs in S have been checked. If no suitable job J_i is found, then job J_n is not a suitable candidate for expanding S .
3. **When $T_n > T_k$** , the contiguous sequence S can be extended by removing the shortest job, J_i , from S , such that $T_n > T_i > T_g$. This will shorten the sequence such that its end is moved to before Gap II, and such that the job J_n can be appended to its end to increase its overall length (Figure 3.6). This can be achieved as follows:
- i. Find the shortest job J_i from the original sequence $(J_1, J_2, \dots, J_{k-1})$;
 - ii. If $T_n > T_i \geq T_g$, then remove J_i from the original sequence and append the job J_n to the end of the sequence, and terminate. This results in the longer contiguous sequence $S' = (J_1, J_2, \dots, J_{i-1}, J_{i+1}, \dots, J_k, J_n)$.
 - iii. Otherwise, find the next shortest job and repeat step ii until job J_k is selected. Then job J_k is removed from the original sequence and job J_n is appended to the end of the sequence, and terminate. This results in the longer contiguous sequence $S' = (J_1, J_2, \dots, J_{k-1}, J_n)$.

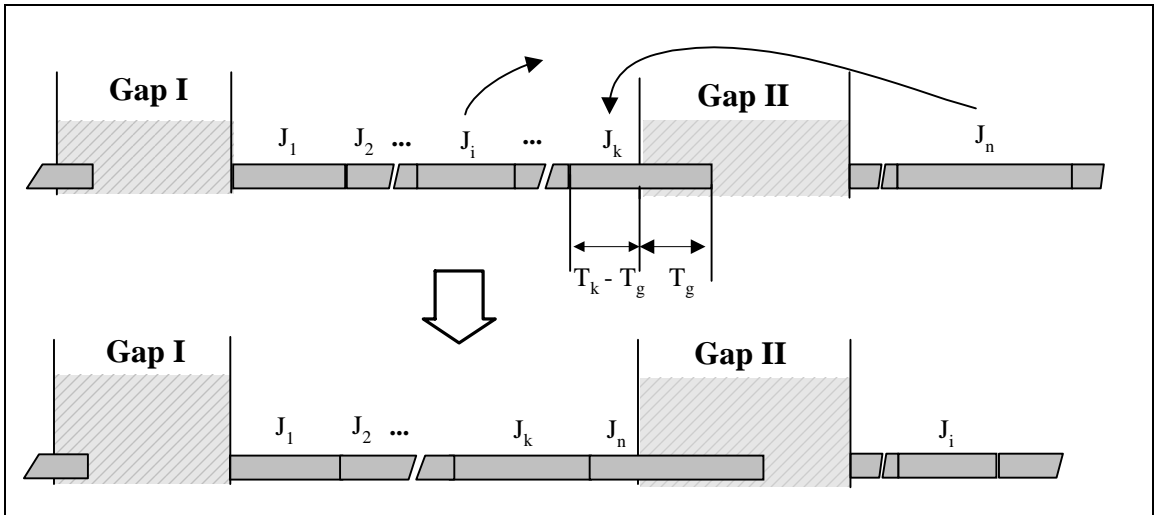


Figure 3.6 Expanding the contiguous sequence with job J_n when $T_n > T_k$.

3.2.1.3 Multi-Gap Contiguous Sequences

When a contiguous sequence spans multiple gaps as shown in Figure 3.7, the situation becomes more complicated. In Figure 3.7, any manipulation of jobs that appear before Gap II requires the re-evaluation of the influence of both Gap II and Gap III. One solution to this problem is to only consider for re-arrangement those jobs in the sub-sequence that are located between the last two gaps, while leaving all other jobs in the contiguous sequence intact. This reduces the problem of expanding a contiguous sequence between two non-adjacent gaps to a problem of expanding the *sub-sequence* between the last two gaps as illustrated in Figure 3.7, which hence permits us to apply the methods discussed earlier.

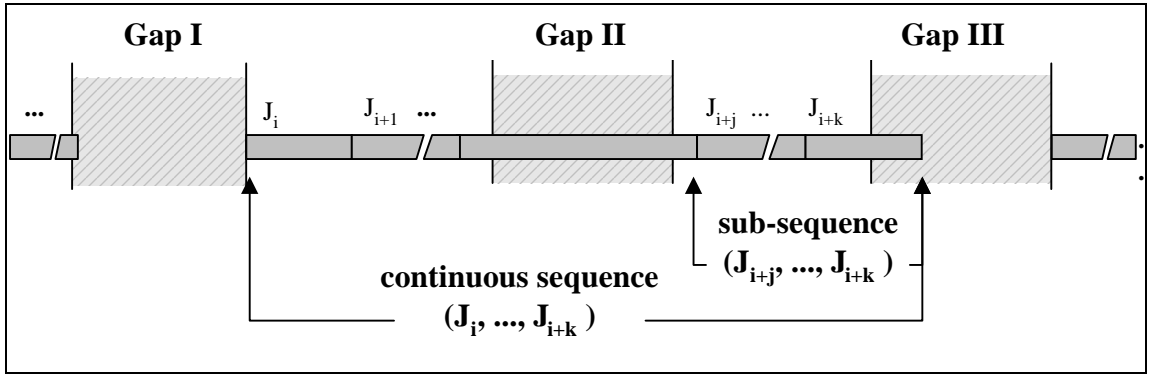


Figure 3.7 For a contiguous sequence $(J_i, J_{i+1}, \dots, J_{i+k})$ between non-adjacent gaps, its sub-sequence $(J_{i+j}, \dots, J_{i+k})$ between the last two gaps is considered for expanding.

This solution, by itself, clearly does not guarantee an optimal schedule for the whole set of jobs. It is not comprehensive and it does not consider all available possibilities for expanding a multi-gap contiguous sequence. For instance, in Figure 3.7, jobs J_i through J_{i+j-1} are not considered for re-arrangement. A brute-force method would be able to consider such cases, but at a significant added computational cost each time the branch-and-bound method generates a branch. The effect of adding this completeness and its associated overhead on the overall computational time has not been studied in this thesis.

Instead, an optimal schedule is found by using the above solution to identify the nodes in the branch-and-bound search tree that correspond to non-optimal schedules, removing these nodes from the search tree, and then searching for the optimal schedule among the nodes that are left. The branch-and-bound method is in itself a comprehensive

enumerative method that will thus ensure that an optimal solution is found. The purpose of quickly identifying contiguous sequences and then expanding them whenever it requires minimal effort, as shown above and in Section 3.2.1.4, is to reduce the search space for the computationally expensive branch-and-bound procedure: When the branch-and-bound procedure generates a node, expansions will be attempted on the contiguous sequences within the associated job set. If any of these sequences can be expanded, then the sub-schedule is not optimal and its corresponding node can be eliminated from further consideration by the branch-and-bound procedure. This processes is discussed in more detail in Section 3.2.2.

3.2.1.4 Selecting an Insertion Candidate

The discussion thus far has been concerned with expanding a contiguous sequence by inserting a given candidate job J_n into this sequence. The following will discuss how to select such a candidate job. To illustrate a suitable method for selecting a candidate job, consider the schedule shown in Figure 3.8. The job schedule is divided into a series of contiguous sequences $(S_1, \dots, S_{i-1}, S_i, S_{i+1}, \dots)$. Suppose the contiguous sequence S_i is considered for expansion, and the contiguous sequence $S_{i+1}=(J_j, J_{j+1}, \dots, J_{j+k-1}, J_{j+k})$ succeeds S_i . The candidate jobs for expanding S_i should be selected from: either (a) the sequence S_{i+1} , provided S_{i+1} does not overlap any gaps; or (b) the sub-sequence $(J_j, J_{j+1}, \dots, J_{j+k-1})$ of S_{i+1} , if S_{i+1} overlaps one or more gaps and J_{j+k} is the first job in S_{i+1} that overlaps a gap.

This selection method is justified for the following two reasons. First, selecting the candidate job for expanding S_i from S_{i+1} minimizes the effort on subsequent contiguous sequences. For instance, if a job from the sequence S_{i+2} is used for expanding S_i , then the processing of jobs in S_{i+1} might be delayed. Such a delay might further impact other jobs in the succeeding sequences to the extend that it is possible that the resulting delay is not compensated by the gain in the expansion of S_i . In that case, the expansion of S_i actually leads to an inferior sub-schedule for the set of jobs in S_i, S_{i+1} , and any subsequent sequences that are affected. To avoid this, all affected sequences would thus have to be re-evaluated, which would complicate the selection procedure. On the other hand, if only jobs in S_{i+1} are considered, then the resulting schedule will either finish the jobs in S_i and

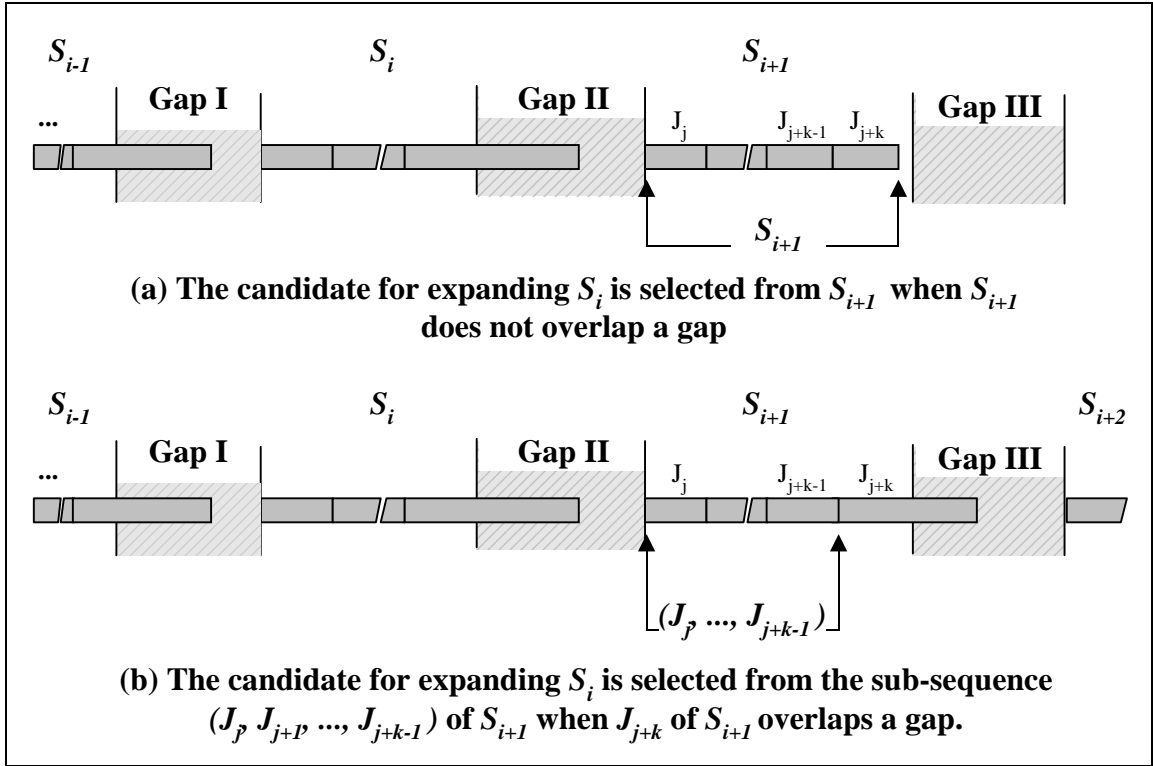


Figure 3.8 To expand the contiguous sequence S_i , the candidate jobs should be selected from (a) the contiguous sequence S_{i+1} or (b) its sub-sequence (J_j, \dots, J_{j+k-1}) .

S_{i+1} within a shorter period, or, in the worst case, show no improvement; and hence jobs in other contiguous sequences will not need to be re-evaluated because of delay.

Second, selecting a job later than J_{j+k-1} , where J_{j+k} is the first job in S_{i+1} that overlaps a gap, may very well cause a delay in subsequent contiguous sequences. Figure 3.9a shows such an example. In this example, J_6 is the job in S_{i+1} that overlaps with Gap III. If J_6 is used to expand S_i , then jobs J_2 , J_3 , and J_5 are delayed, and the sequence S_{i+2} is impacted by J_5 as shown in the figure. Although the sequence S_i is expanded successfully, the net result is a less efficient schedule. On the other hand, if only the jobs in (J_3, J_4, J_5) were to be considered, then none of jobs in S_{i+1} would be delayed enough to affect the sequence S_{i+2} . Rather, instead S_i would be expanded to yield a definite improvement over the original sub-schedule that includes both S_i and S_{i+1} (Figure 3.9b). No matter which job from (J_3, J_4, J_5) is selected, J_6 will never be delayed, and nor will the subsequent jobs. Hence, by generalizing this method to the situation where S_{i+1} overlaps with more than one gap, the candidate job for expanding S_i should be selected from the

sub-sequence $(J_j, J_{j+1}, \dots, J_{j+k-1})$ of S_{i+1} , where J_j is the first job of S_{i+1} and J_{j+k} is the first job in S_{i+1} that overlaps a gap.

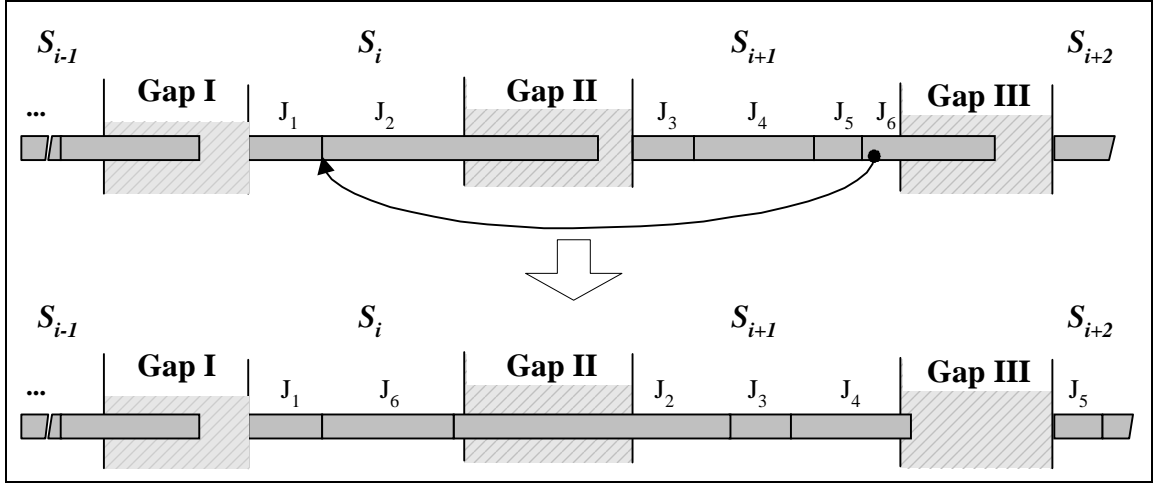


Figure 3.9a An example shows that using the job in S_{i+1} that overlaps with a gap to expand S_i might delay subsequent contiguous sequences.

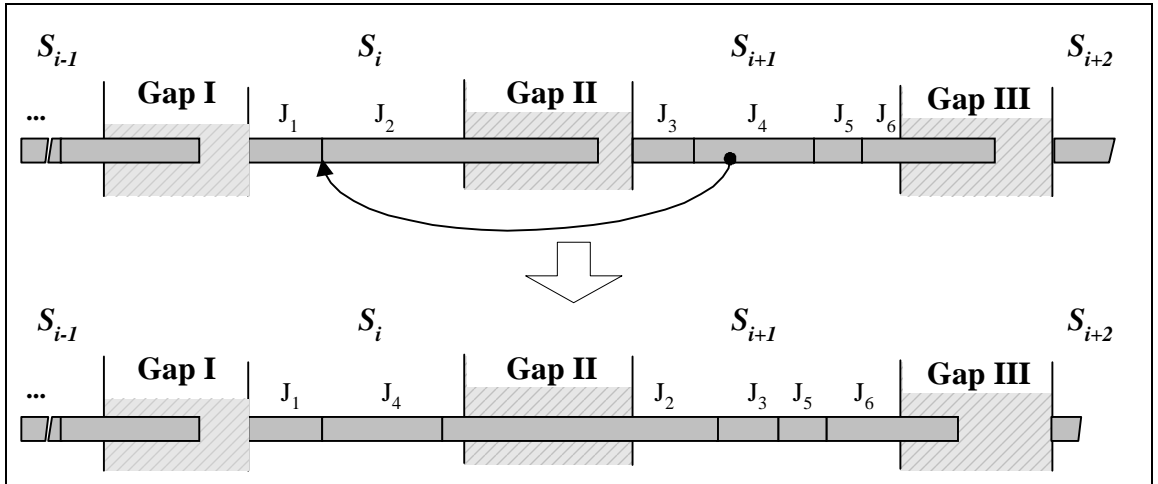


Figure 3.9b Selecting a candidate job from the sub-sequence $(J_j, J_{j+1}, \dots, J_{j+k-1})$ of S_{i+1} guarantees that none of J_{j+k} and the subsequent jobs will be delayed because of the expansion of S_i .

Once the candidate job set has been determined (e.g., the job set $\{J_3, J_4, J_5\}$ in Figure 3.9b) for a given contiguous sequence, then the jobs from this set should be considered in the decreasing order of job-processing-time for expanding the contiguous sequence. This is because using a larger job to expand a contiguous sequence increases the probability of forming a longer contiguous sequence. This expansion operation is then repeated until all the candidate jobs have been checked.

When the expansion operation for a given contiguous sequence ends with a successful expansion, a longer contiguous sequence is formed, the original sub-schedule is identified as a non-optimal sub-schedule, and no further expansion operations will be attempted on subsequent contiguous sequences. On the other hand, if the given contiguous sequence cannot be expanded, then the next contiguous sequence will be investigated for its expandability. The resulted longer contiguous sequence and the non-optimal sub-schedule will be used by the branch-and-bound method to eliminate unpromising branches. The following will discuss this in more detail.

3.2.2 BRANCH-AND-BOUND METHOD

The branch-and-bound method solves a given problem through the recursive decomposition of a problem into sub-problems. It consists of two procedures: the branching procedure and the bounding procedure. The branching procedure generates a set of search directions, and the bounding procedure evaluates the feasibility of each direction. This thesis uses a depth-first search to reduce memory usage. The following sections discuss how to apply the contiguous sequences identified in Section 3.2.1 to the branching and bounding procedures, separately, to help identify and avoid inferior search directions, and thereby reduce the computational time.

3.2.2.1 Branching Procedure and Problem Decomposition

The branching procedure can be conveniently described using a branching tree. The node at level 0 is the root of the branching tree, and it represents the original problem, in which N jobs are to be scheduled. From the root, the branching tree branches into N nodes in level 1, and each of these N nodes represents a selection for the first job in the job schedule. Then every node in level 1 branches to $N-1$ nodes in level 2, where every node corresponds to the selection of the second job in the job schedule. The branching procedure continues until there are no more nodes.

Hence, at each level n , there are $\prod_{i=1}^n (N+1-i)$ nodes representing $\prod_{i=1}^n (N+1-i)$ search directions. The total number of nodes in the branching tree is therefore

$\sum_{n=1}^N \left(\prod_{i=1}^n (N+1-i) \right)$, and the number of all possible solutions equals $\prod_{i=1}^N (N+1-i) = N!$.

Searching all these nodes quickly becomes time consuming as the problem size increases. It is therefore important to use appropriate techniques to narrow down the search. This is generally achieved with a well-selected problem-decomposition method in the branching procedure, and with effective bounding criteria in the bounding procedure.

Either procedure can eliminate the infeasible branches from the search tree. However, the branching procedure prunes an infeasible branch before the job schedule at the node is evaluated, while the bounding procedure usually deletes this infeasible branch after the job schedule is evaluated (Section 3.2.2.2). It is therefore advantageous to eliminate infeasible branches at the branching stage. The following will discuss how this may be achieved while building on the knowledge of contiguous sequences developed in Section 3.2.1.

It would be helpful to use a simple example to illustrate the problem decomposition process with contiguous sequences. Figure 3.10a shows the branching tree for job set $\{J_1, J_2, J_3, J_4, J_5, J_6\}$. Each node in the tree corresponds to the selection of a job (e.g., node A corresponds to the selection of J_1 as the first job in the schedule, and node C corresponds to the subsequent selection of J_4 as the second job in the schedule). The branch from the root to a node represents the intermediate job sequence formed at that node (e.g., the branch from the root to node D represents the partial sequence (J_1, J_2, J_3, J_4) formed at node D). To describe a branch, the notation $\langle J_i \rightarrow \dots \rightarrow J_k \rightarrow J_l \rightarrow \dots \rangle$ is used, where (J_i, \dots, J_k, J_l) corresponds to the partially formed sequence at the end of that branch (e.g., $\langle 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow \dots \rangle$ describes the branch from the root to node D). The bold edges in Figure 3.10a indicate the contiguous sequence (J_2, J_3, J_4) that is formed at node D during the branching procedure.

Section 3.2.1.1 showed that one should avoid any branches that lead to job reshuffling within a contiguous sequence. In Figure 3.10a, these branches are represented by dashed edges; and the branches that are not affected by the contiguous sequence (J_2, J_3, J_4) are

omitted for clarity (e.g., the branch $\langle 2 \rightarrow 1 \rightarrow \dots \rangle$, which is located off node B, is not affected by the contiguous sequence (J_2, J_3, J_4) and is hence not shown in the figure).

The branching procedure must check the branch to be generated against the related contiguous sequences to determine whether or not this branch should be created. If a branch leads to job reshuffling within a contiguous sequence, then this branch should be avoided and its end node should be deleted from the tree (e.g., the branch $\langle 1 \rightarrow 3 \rightarrow 2 \dots \rangle$ causes job reshuffling within the contiguous sequence $(2,3)$; hence its end node, node E, should be removed from the tree). To efficiently implement such a branching procedure, it is necessary to note the following facts:

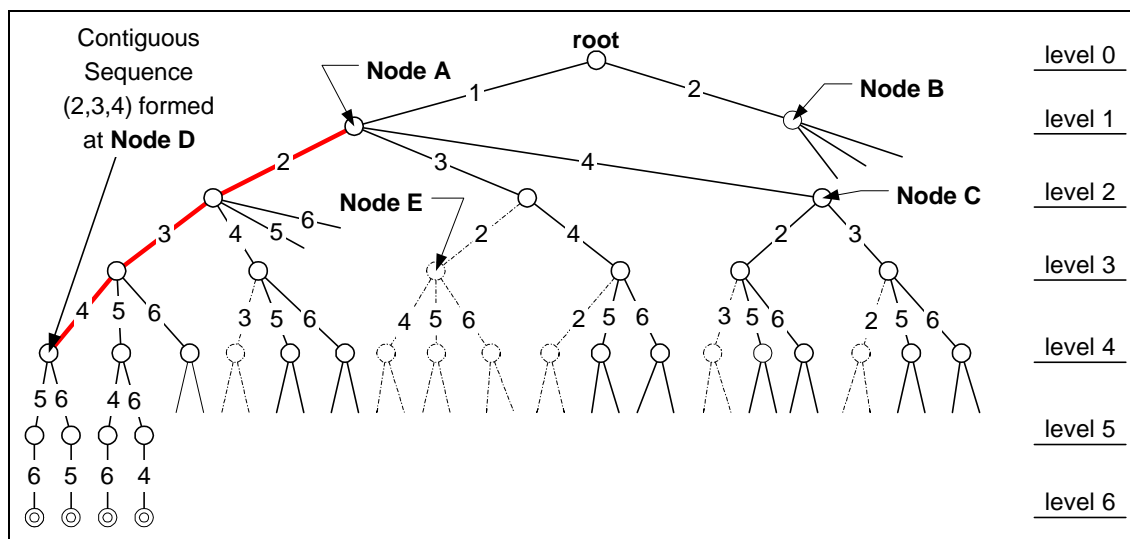


Figure 3.10a A branching tree with a contiguous sequence (J_2, J_3, J_4) .

1. Because of the depth-first search, contiguous sequences are formed as the branching procedure proceeds from the root down to the bottom level.
2. A contiguous sequence is associated with two levels: a top level where the sequence starts, and a bottom level where the sequence ends. For the contiguous sequence (J_2, J_3, J_4) in Figure 3.10a, its top and bottom levels are levels 2 and 4, respectively.
3. The parent node of a contiguous sequence is the node from which the selection of the first job in that sequence is made. For the contiguous sequence (J_2, J_3, J_4) in Figure 3.10a, its parent node is node A, shown in level 1.

4. The sub-sequence of a contiguous sequence is itself a contiguous sequence. For the contiguous sequence (J_2, J_3, J_4) in Figure 3.10a, its sub-sequence (J_2, J_3) is a contiguous sequence with the same parent node. Hence, the branch $\langle 1 \rightarrow 3 \rightarrow 2 \rightarrow \dots \rangle$ and its nodes (including node E) should be deleted from the tree because they lead to job reshuffling within the contiguous sequence (J_2, J_3) .
5. A contiguous sequence is only valid for the branches that spring out from the parent node of this sequence. These branches and their nodes are here referred to as the valid branches and nodes for this contiguous sequence. For instance, in Figure 3.10b, the contiguous sequence (J_2, J_3, J_4) is valid only for the branches growing out from node A, as shown in the shaded area. When the search goes back to one of the other nodes at level 1, such as node B, then this sequence becomes invalid. An invalid contiguous sequence should be discarded from further consideration.

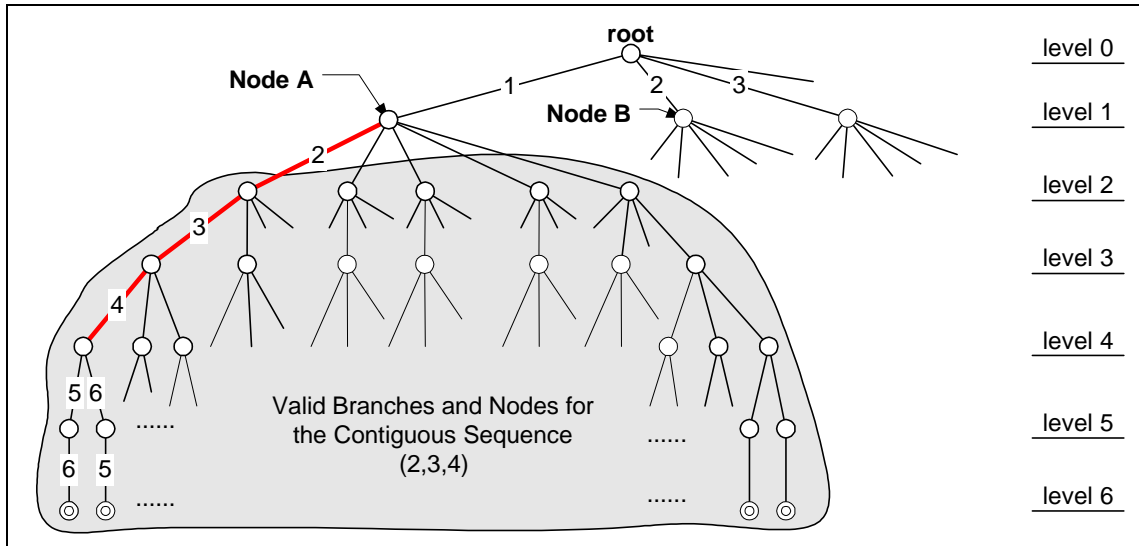


Figure 3.10b The contiguous sequence $(2, 3, 4)$ is only valid for the nodes in the shaded region, and it should be discarded from consideration when the search proceeds to the nodes out of this region.

6. A contiguous sequence is active for its valid nodes that lie below the top level, but not below the bottom level, of this contiguous sequence. Beyond this region, the contiguous sequence is inactive. For instance, the contiguous sequence (J_2, J_3, J_4) is active for its valid nodes in levels 3 and level 4, as shown in Figure 3.10c, but inactive for other nodes.

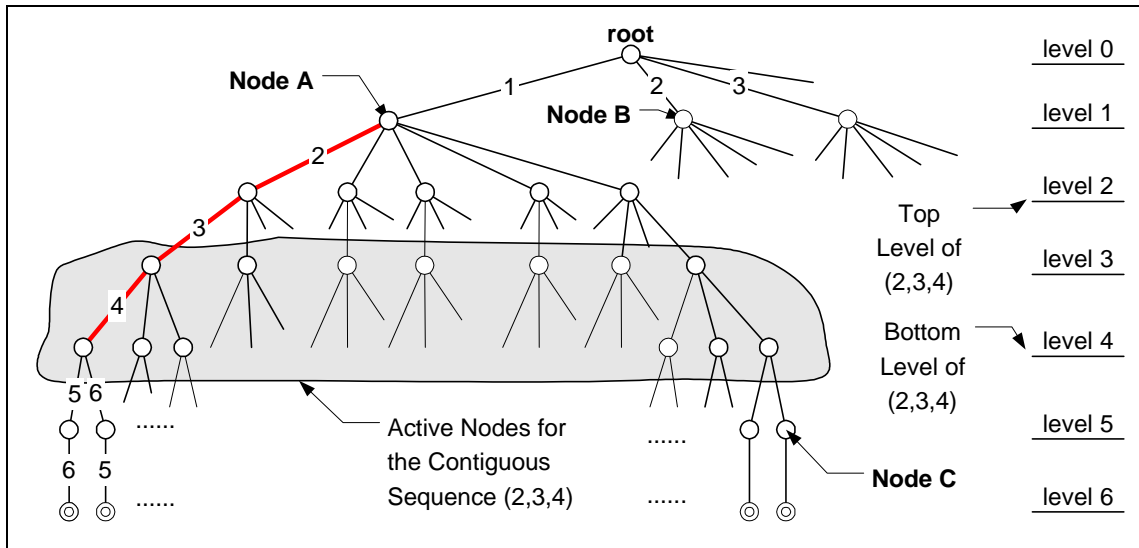


Figure 3.10c The contiguous sequence (2, 3, 4) is active for its valid nodes that lie in level 3 and 4, but inactive for other valid nodes.

7. The branching procedure only considers the active contiguous sequences at a node when examining the potential for job reshuffling at that node. For instance, in Figure 3.10c, the contiguous sequence (2, 3, 4) will be considered only when the branching procedure attempts to generate the nodes in the shaded area. For the nodes outside the shaded area, this contiguous sequence is inactive and does not need to be considered for the following two reasons: First, when the branching procedure reaches a valid node at its top level (i.e., level 2), at most one job from this sequence (e.g., job 3) is selected. With the partial sequence formed at this point, (1, 3), there is not enough information to determine whether there will be a job reshuffling within the contiguous sequence (2, 3, 4). Hence, the consideration of this contiguous sequence should be postponed until the branching procedure reaches its valid nodes at the next level. Second, when the branching procedure reaches a valid node below the bottom level of this contiguous sequence (e.g., node C in Figure 3.10c), it means that the current branch will never cause job reshuffling within this sequence; otherwise this branch would have been eliminated before it reached this node. Hence, this contiguous sequence does not need to be considered when the branching procedure reaches the nodes below its bottom level.

Once the entire set of current jobs has been organized into an optimal sequence, it is important for computational efficiency to treat this sequence as contiguous each time a new job arrives. This is because this sequence is optimal for these pre-existing jobs. Subsequent scheduling should therefore avoid repeating prior computations, such as considering the reshuffling of these pre-existing jobs. This can be achieved by treating a pre-existing optimal sequence as contiguous during subsequent scheduling, even though there might be actual gaps between these jobs. By viewing the pre-existing schedule, (J_1, J_2, \dots, J_K) , as a contiguous sequence, the branching procedure can thus remove $\sum_{i=2}^K (i-1)(K-i)!$ inferior sequences from the search tree for the set of $(K+1)$ jobs:

These eliminated sequences are all in the form of $(J_1', \dots, J_i', J_{new}, J_{i+1}', \dots, J_K')$, where J_{new} is the new job, (J_1', \dots, J_i') is the permutation of the job set $\{J_1, J_2, \dots, J_i\}$ except the original sequence (J_1, J_2, \dots, J_i) , and (J_{i+1}', \dots, J_K') is the permutation of the remaining $(K-i)$ jobs left.

In a summary, the branching procedure eliminates the inferior nodes by comparing the sequences represented by the nodes to be generated against the contiguous sequences that are active at these nodes. The nodes that lead to job reshuffling within a contiguous sequence are pruned from the search tree. The remaining nodes form the new branches that will then be processed by the bounding procedure.

3.2.2.2 Bounding Procedure and Elimination Criteria

The bounding procedure is also critical for reducing the number of nodes that are to be evaluated. It is performed after a node is successfully generated in the branching procedure, and it requires the evaluation of elimination criteria for that node. The nodes that pass this bounding procedure evaluation will be subjected to further branching procedure iterations, while those that fail will be eliminated from the search tree.

The most frequently used elimination criterion for a given node is its lower bound of the objective function. In the case of RP job scheduling, this translates into the lowest total completion time that may be achieved when the branching procedure proceeds from that node. If this lower bound is greater than the lowest total completion time obtained

from previous searches, then this node will be eliminated and no further branching will be performed for this node.

It is clear that the accuracy of lower bound evaluation is important to the bounding procedure. A precise evaluation can effectively reduce the size of problem. However, for RP job scheduling, it is computationally impractical to achieve an accurate lower bound evaluation of the total completion time. Instead, the bounding procedure therefore evaluates the total completion time only when the sequence for the full set of jobs are formed (i.e., at the bottom of the search tree). For the intermediate nodes in the search tree, the bounding procedure uses an alternate approach to determine their feasibilities. This approach is based on the study of expanding contiguous sequences that was presented in Section 3.2.1.

In particular, it relies on the property that, for an optimal schedule, any subset of this schedule is also optimal for the jobs within that subset. If this were not true, then replacing the sub-schedule with the optimal would create a better schedule than the original optimal schedule. In another word, given a sequence of jobs and its corresponding schedule, if there exists a sub-sequence whose schedule is not optimal for the jobs within that subset, then the complete schedule is not optimal for the total job set.

The bounding procedure uses this property to establish the elimination criterion. During the bounding procedure, the schedule for the partially formed sequence at the current node is calculated. If, within this schedule, a sub-schedule is found to be non-optimal, then any final schedules derived from this node for the complete set of jobs cannot be optimal; and the node can therefore be eliminated from the search tree.

To evaluate this criterion, the bounding procedure expands contiguous sequences to find a non-optimal sub-schedule. Figure 3.11 illustrates this approach: Within the original schedule formed at a given node, the sub-schedule for the two contiguous sequences S_i and S_{i+1} is found to be non-optimal because expanding S_i using the method described in Section 3.2.1 improves the schedule for the jobs in S_i and S_{i+1} . This expansion operation shows that the given node failed the elimination criterion, and it generates a longer contiguous sequence that can be used to eliminate other inferior nodes during the branching procedure.

The bounding process can therefore be implemented as follows:

1. Generate the job schedule for the job sequence formed thus far at the current node.
2. Identify and record the contiguous sequences formed in the schedule created in step 1.
3. If the current node is at the bottom of the search tree, then evaluate the total completion time. If it is larger than the previous value, then eliminate this node and return to the branching procedure. Otherwise, go to step 4.
4. From the beginning of the job sequence, expand each contiguous sequence sequentially using the expansion method described in Sections 3.2.1.2 through 3.2.1.4.
5. If a contiguous sequence is successfully expanded, then record the new contiguous sequence, delete the current node, and return to the branching procedure.
6. If no contiguous sequence can be expanded, then the current node passes the elimination criterion and the branching procedure will proceed from this node.

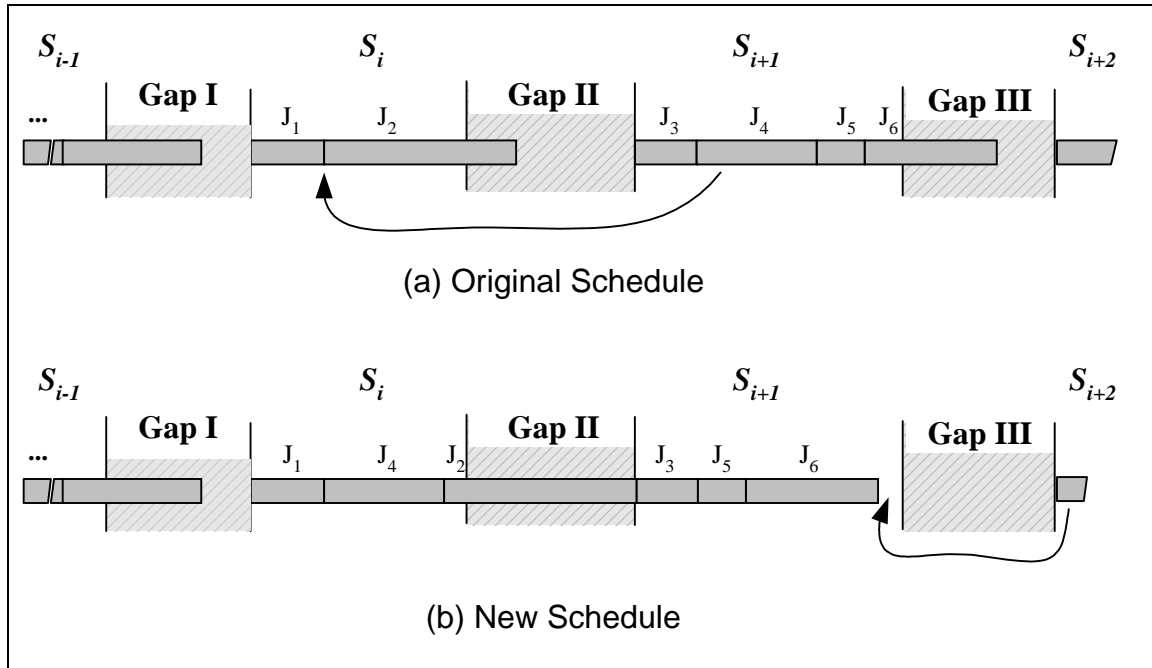


Figure 3.11 Within the original schedule of the partially formed sequence, the sub-schedule for the jobs in S_i and S_{i+1} is found to be non-optimal because an expansion operation is performed successfully on S_i as shown in the new schedule.

In a summary, the search for the optimal schedule starts from the root of the search tree and iteratively performs the branching and bounding procedures. The branching procedure generates a new branch from the current node and evaluates this branch against the active contiguous sequences. If the branch leads to job reshuffling within a contiguous sequence, then it will be pruned from the search tree and the branching procedure continues to create another branch until a branch survives this evaluation. Then for each new branch, the bounding procedure evaluates the elimination criterion for its node using the method of expanding contiguous sequences: The bounding procedure first generates the schedule for the partially formed sequence at this node. It then identifies the contiguous sequences in this schedule and performs the expansion operation. If there is a contiguous sequence that is successfully expanded, then the current node can be eliminated and the search returns to the branching procedure with the expanded contiguous sequence. If no contiguous sequences can be expanded, then the branching procedure proceeds from the current node. The next section shows the flow charts that describe this branch-and-bound method.

3.2.3 FLOW CHART OF THE RP JOB SCHEDULING METHOD

Figure 3.12-14 show the flow charts for the RP job scheduling method. Figure 3.12 describes the basic procedure of the branch-and-bound method, while Figure 3.13 and 3.14 describe the branching and bounding subroutines, respectively.

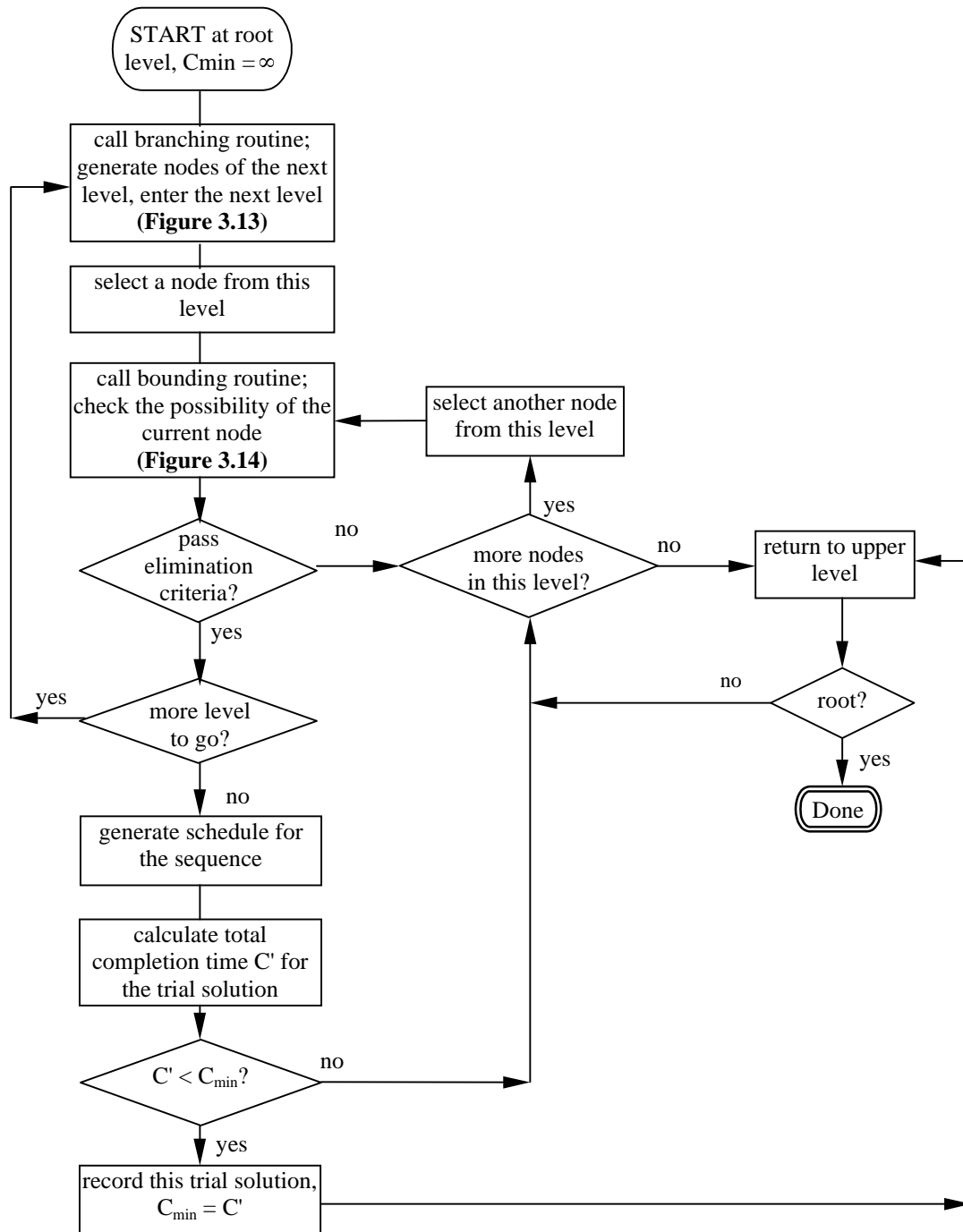


Figure 3.12 Flow chart for the RP job scheduling method.

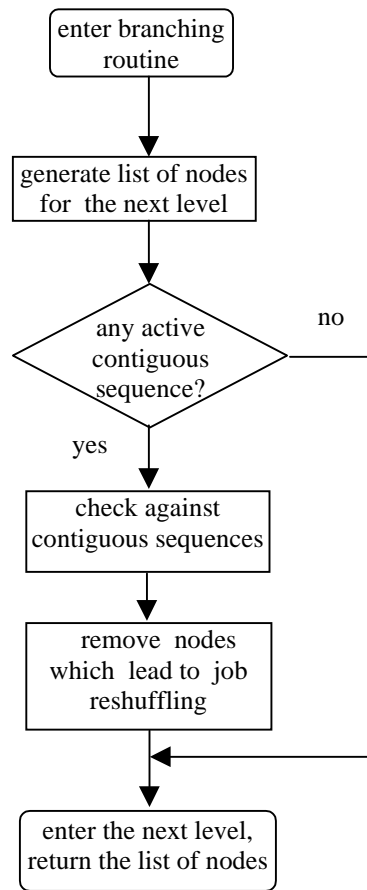


Figure 3.13 Flow chart for the branching subroutine.

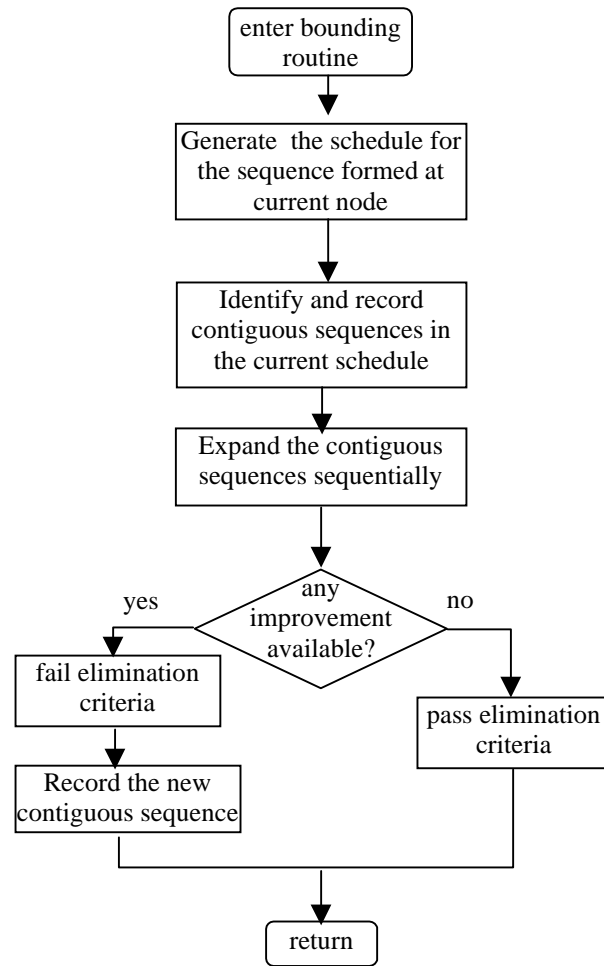


Figure 3.14 Flow chart for the bounding subroutine.

Chapter 4

FDM TEST-BED AND SCHEDULING RESULT

This chapter tests the proposed RP job scheduling method for the FDM 1600 rapid prototyping system. A simple FDM job queuing system is constructed using two scheduling methods: the FIFO-based scheduling method, and the proposed RP job scheduling method. The former is used to create the benchmark schedules against which the results of the latter are compared. This chapter first describes the system structure and components of the queuing system, the sample job sequences used for the test, and the creation of the benchmark schedules. It then compares the results from the RP job scheduling method with the benchmarks. Finally, it shows that the RP job-queue based search strategy effectively reduced the computation time for the branch-and-bound method.

4.1 FDM JOB QUEUING SYSTEM

To test the proposed RP job scheduling method, a FDM job queuing system is constructed for the FDM 1600 rapid prototyping system using two scheduling methods: the FIFO based scheduling method and the proposed RP job scheduling method. This system uses the client-server structure, and it consists of three components as shown in Figure 4.1.

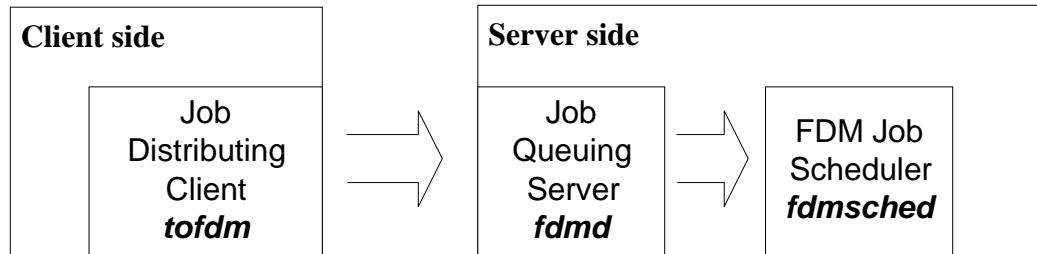


Figure 4.1 The FDM job queuing system consists of three components: job distributing client, job queuing server, and the FDM job scheduler.

The basic functions of this client-server program include sending job data files from the client side to the queuing server, and activating the scheduler to perform job

scheduling using the appropriate method. The three components are written in the C and C++ programming languages, and their functions are described below:

1. **tofdm** is the client side program that sends job requests and data files to the queuing server. It is written in the C programming language.
2. **fdmd** is the queuing server program that communicates with the client program. It accepts job requests and activates the job scheduling program. It is written in the C programming language.
3. **fdmsched** is the job scheduling program, and it is written in the C++ programming language.

The programs **tofdm** and **fdmd** are a client-server package that uses 4.3BSD socket programming over a connection-oriented TCP/IP protocol [Stevens98]. The program **fdmd** is a concurrent server that spawns a child **fdmd** process whenever the **tofdm** sends it a job request. The child **fdmd** process takes over the communication with the **tofdm** client, receives job data, and activates the job scheduler **fdmsched**, while the parent **fdmd** waits for other incoming job requests from the client. Figure 4.2 shows the data flow within the queuing system: The program **tofdm** sends job data files to the program **fdmd**, which in turn passes the jobs to the program **fdmsched** for scheduling.

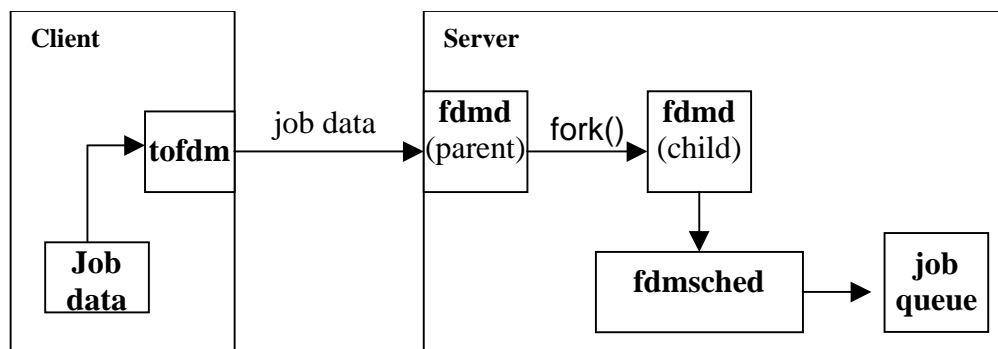


Figure 4.2 Data flow within the FDM job scheduling system.

To compare the scheduling results, the scheduler program **fdmsched** was implemented using both the FIFO algorithm and the proposed branch-and-bound based algorithm. The FIFO algorithm was used to create the benchmark schedules, and the proposed RP scheduling method was used to create the optimized schedules. These

programs were compiled and run on a SGI Octane workstation (195 MHz R10000 CPU, 640 MB RAM) under the IRIX 6.5 operating system.

4.2 TEST SETUP

The two scheduling methods were compared using two sequences of thirty jobs that had been extracted from the usage logs for the FDM 1600 rapid prototyping system in the Department of Mechanical Engineering at Virginia Tech (Appendix A). These two sequences of jobs are representative samples of the actual jobs, and their distributions of job processing times are shown in Figures 4.3 and 4.4. The average job processing times are 13.5 and 11.5 hours for Job Sequence I and II, respectively. For simplicity, all the job setup times were assumed to be 30 minutes.

The tests were performed under 22 different situations as marked in Table 4.1. First, two operator schedules were used to represent the real life working schedules: one is from 8AM to 5PM during the weekdays, and the other is from 9AM to 4PM during the weekdays with one hour break from 12PM to 1PM. Neither schedule has working hours during the weekends. Second, for both sequences, jobs were sent to the scheduling system at three different rates: one job per 10 hours, 12 hours, 16 hours, and 20 hours. These rates were selected based on the value of the average job processing times, and they are less than, approximate to, and larger than the average job processing times. Finally, the tests were performed under two different job-request-start times: 10AM Monday, and 10AM Friday. Most of the tests were performed as the job requests started early in a week, i.e., 10AM Monday. A few more cases were generated in which the job requests started close to the end of a week, i.e. 10AM Friday. The purpose of this change is to examine the effect of the weekends.

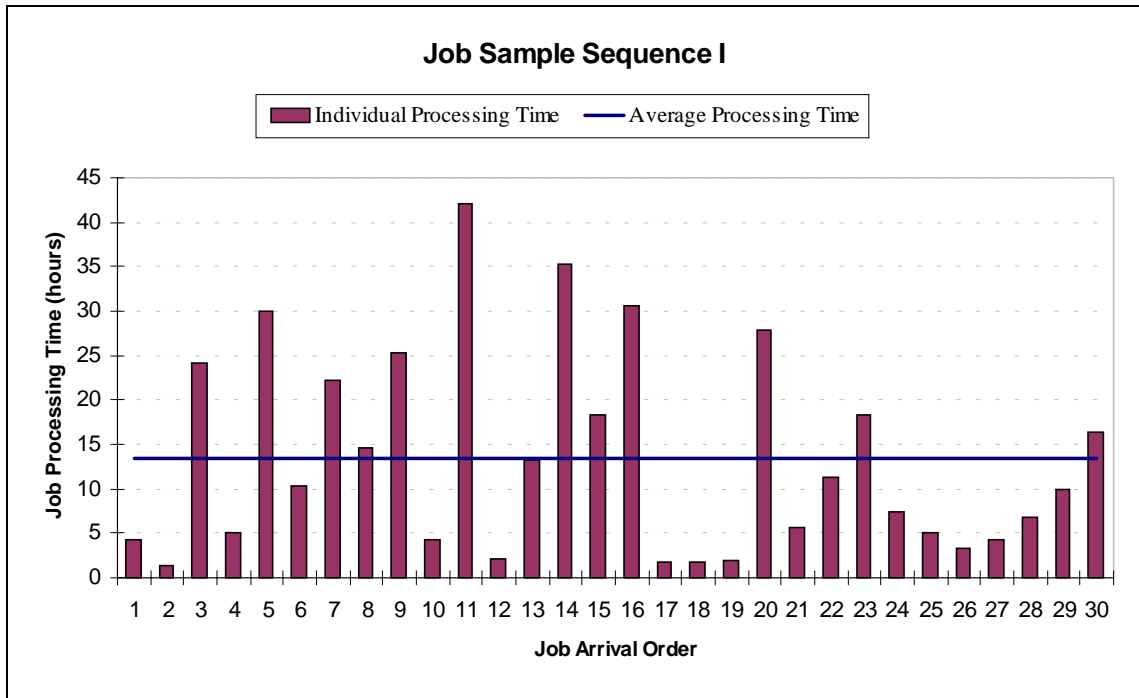


Figure 4.3 Job processing times for job sample sequence I

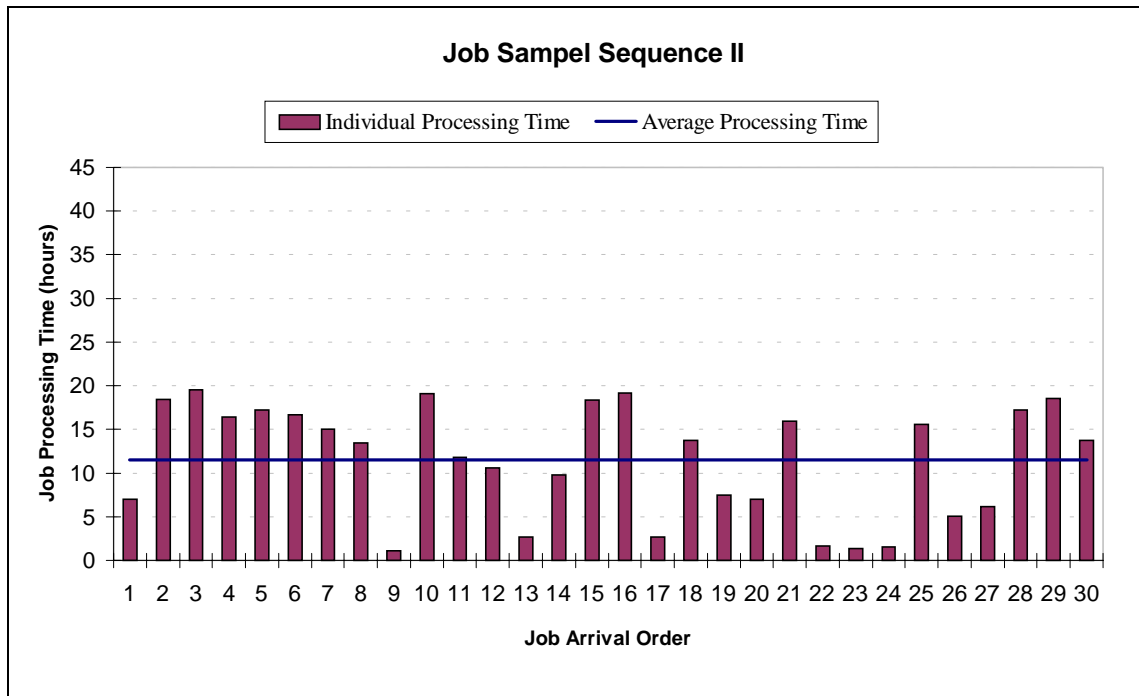


Figure 4.4 Job processing times for job sample sequence II

Table 4.1 The tests were performed under 22 situations.

				Job Sample Sequence I				Job Sample Sequence II			
Arriving Rate (hours)				10	12	16	20	10	12	16	20
Operator Schedule	8AM - 5PM	Job Requests Started at	10AM Monday	X	X	X	X	X	X	X	X
			10AM Friday	-	X	X	X	-	X	X	X
	9AM-12PM / 1PM-4PM		10AM Monday	X	X	X	X	X	X	X	X
			10AM Friday	-	-	-	-	-	-	-	-

4.3 TEST RESULTS

For each situation in Table 4.1, two job schedules were generated: one for the FIFO job schedule to serve as the benchmark, and the other to demonstrate the proposed RP job scheduling method. These two schedules were compared for the total completion time, the size of queue, and the machine idle time.

Figures 4.5-24 show the test results for each situation (Appendix B lists the values for these graphs). In Figures 4.5 through 4.10, the total completion times for the jobs arrived are compared at different job request rates using different operator's schedules. The queue sizes are compared in Figure 4.11 through 4.16, and the machine idle times are compared in Figure 4.17 through 4.22. In addition, the numbers of weekends covered in each schedule are shown in Figures 4.23 and 4.24.

Finally, the computation times consumed by the scheduling processes were recorded and compared. These include (a) the time consumed by the proposed RP job scheduling method using the RP job-queue-based search-space-reduction strategy, and (b) the time consumed by a branch-and-bound implementation using only the lower bound evaluation to reduce the search space. The computation times are shown in Table 4.2.

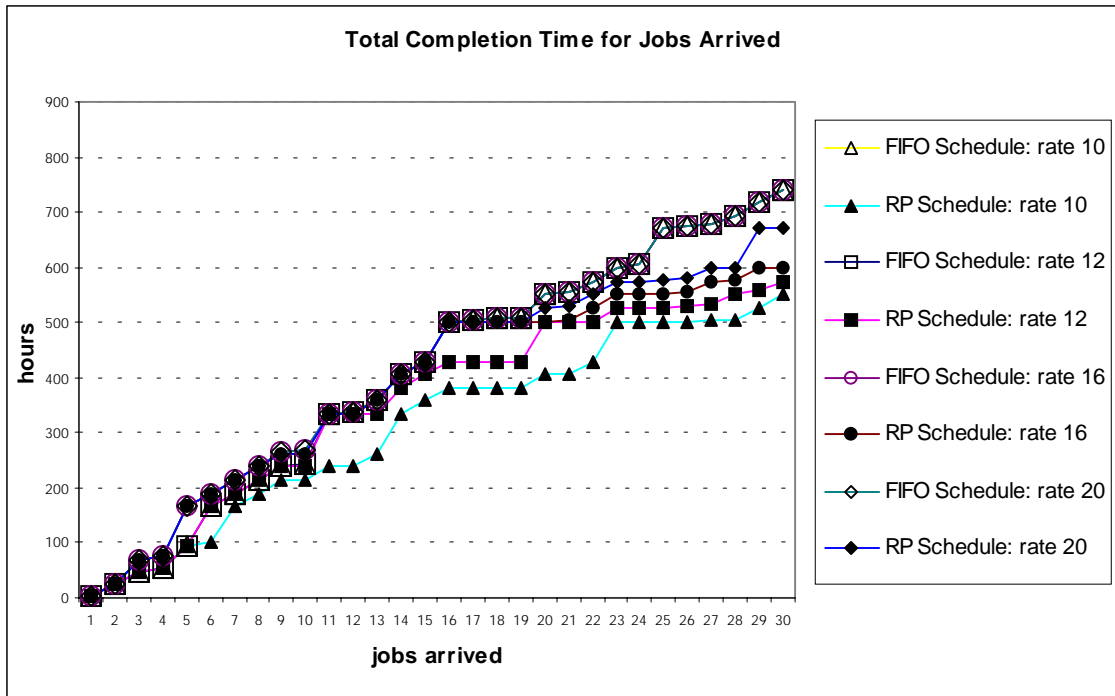


Figure 4.5 Comparison of total completion time between the FIFO Schedules and the RP Schedules for Job Sequence I issued at 10AM on Monday. The operator schedule is from 8AM to 5PM, Monday through Friday.

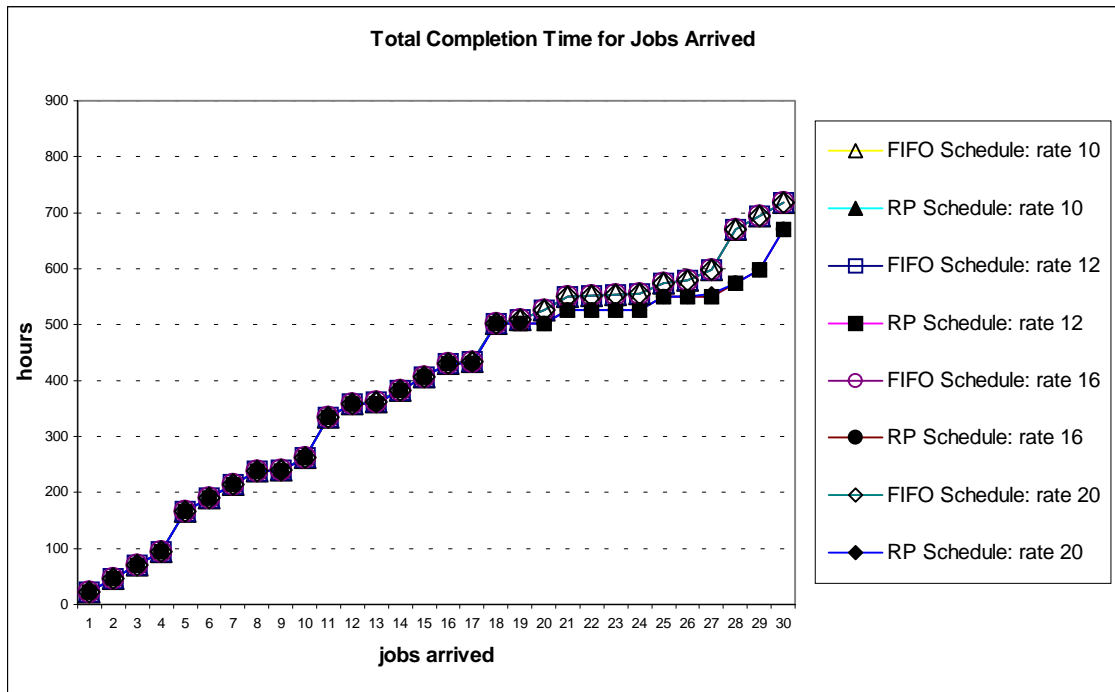


Figure 4.6 Comparison of total completion time between the FIFO Schedules and the RP Schedules for Job Sequence II issued at 10AM on Monday. The operator schedule is from 8AM to 5PM, Monday through Friday.

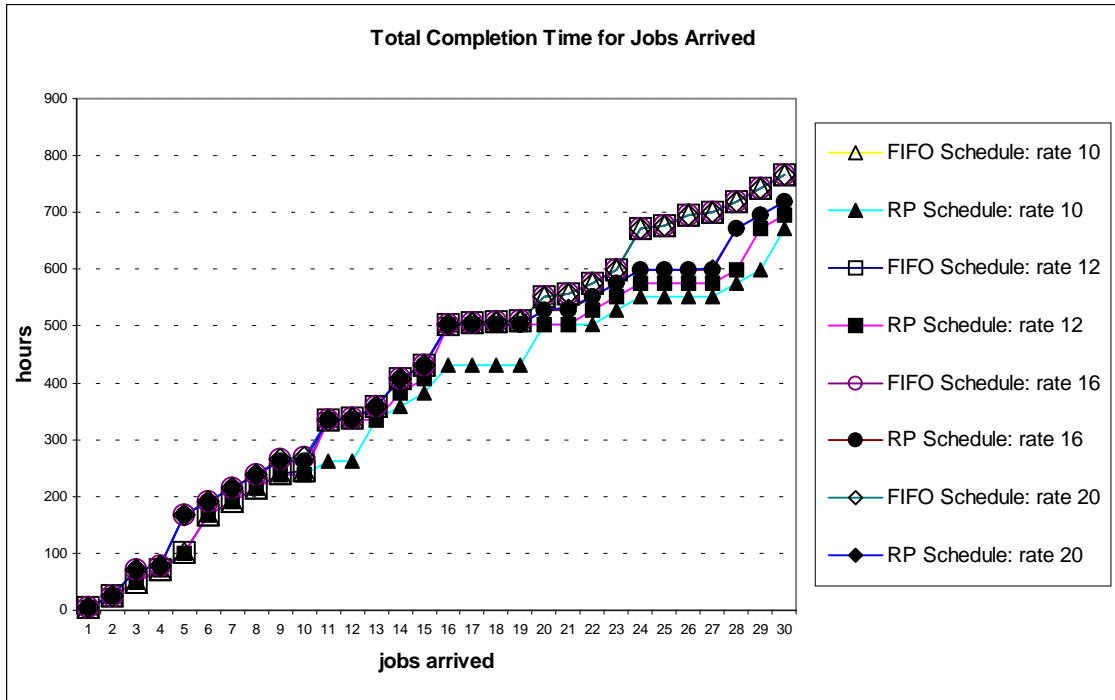


Figure 4.7 Comparison of total completion time between the FIFO Schedules and the RP Schedules for Job Sequence I issued at 10AM on Monday. The operator schedule is from 9AM to 12PM and 1PM to 4PM, Monday through Friday.

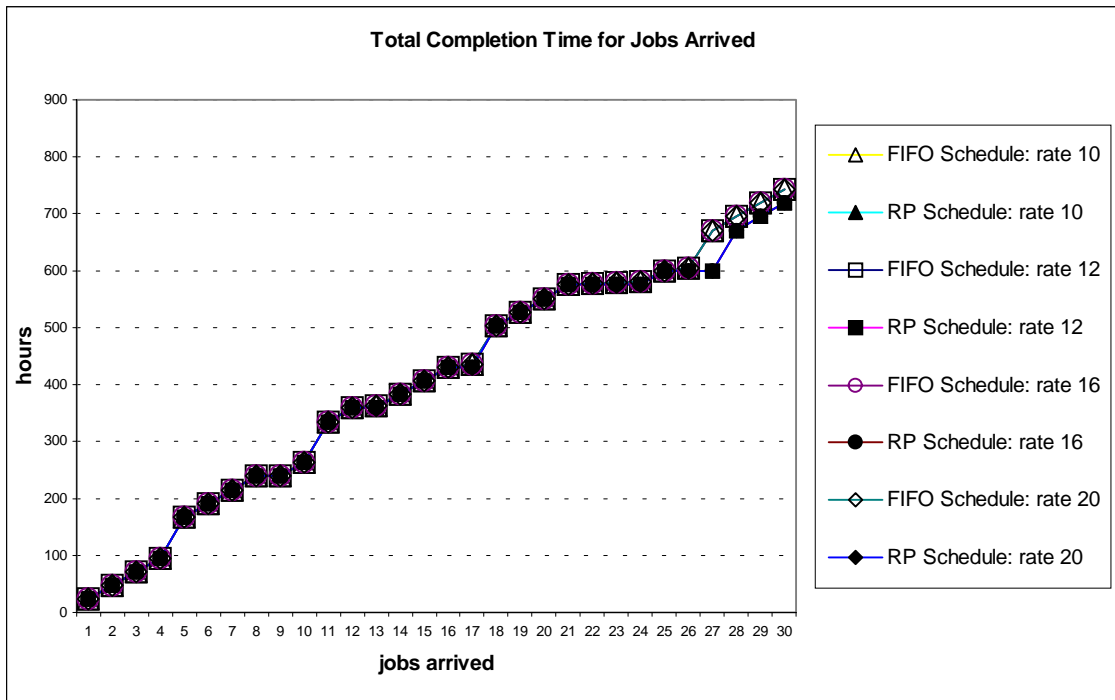


Figure 4.8 Comparison of total completion time between the FIFO Schedules and the RP Schedules for Job Sequence II issued at 10AM on Monday. The operator schedule is from 9AM to 12PM and 1PM to 4PM, Monday through Friday.

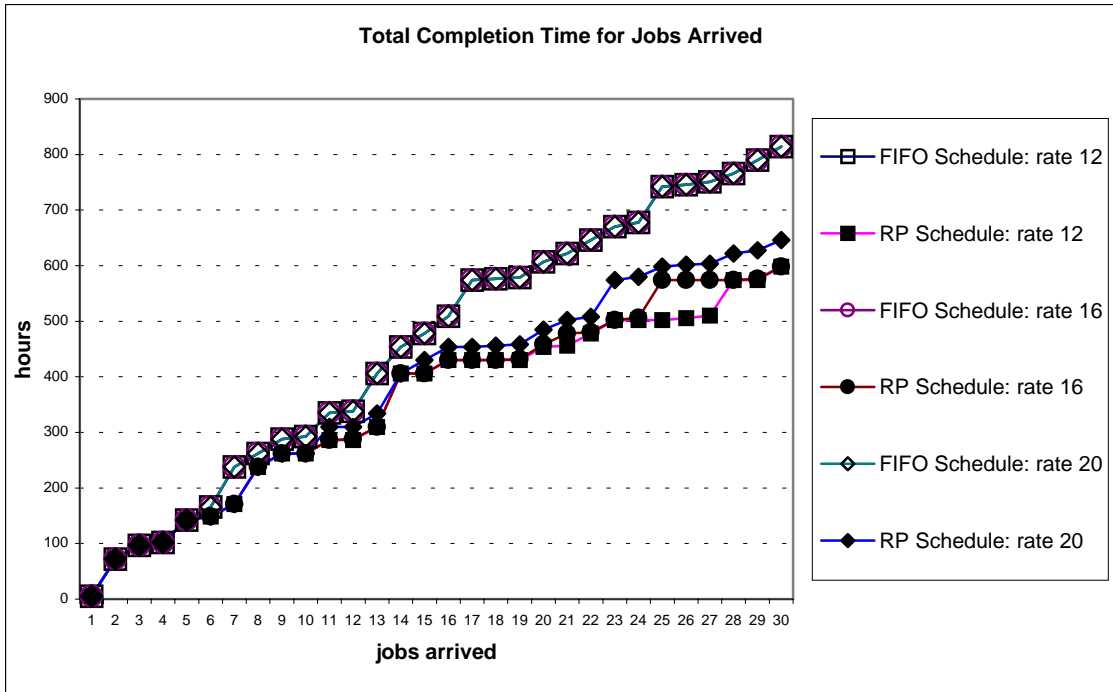


Figure 4.9 Comparison of total completion time between the FIFO Schedules and the RP Schedules for Job Sequence I issued at 10AM on Friday. The operator schedule is from 8AM to 5PM, Monday through Friday.

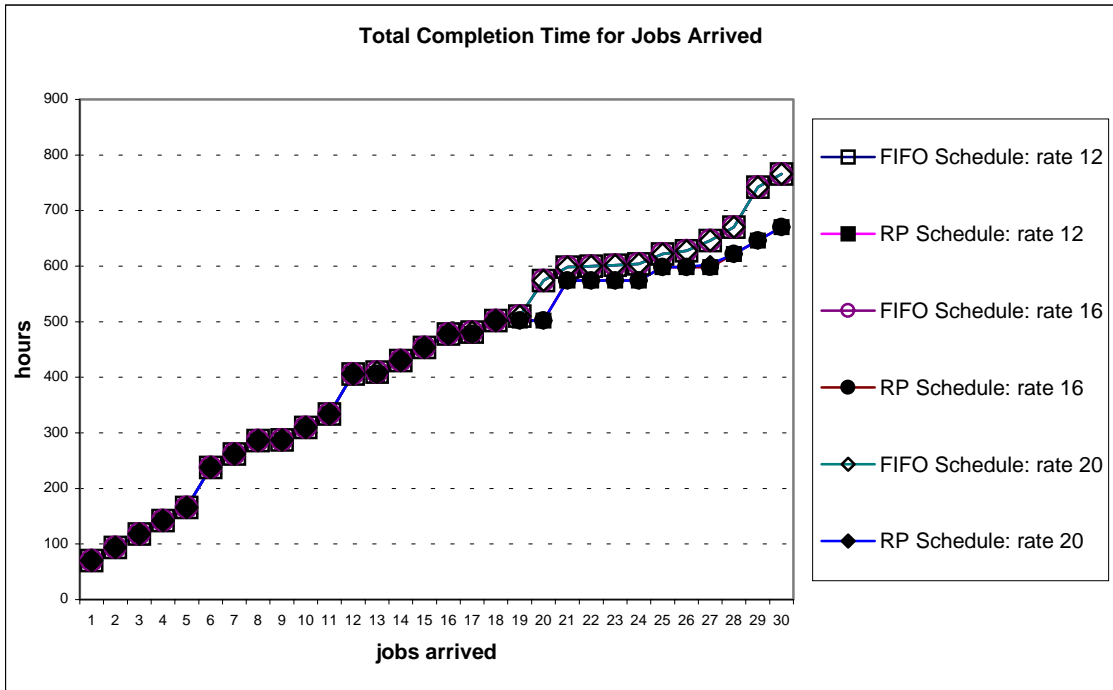


Figure 4.10 Comparison of total completion time between the FIFO Schedules and the RP Schedules for Job Sequence II issued at 10AM on Friday. The operator schedule is from 8AM to 5PM, Monday through Friday.

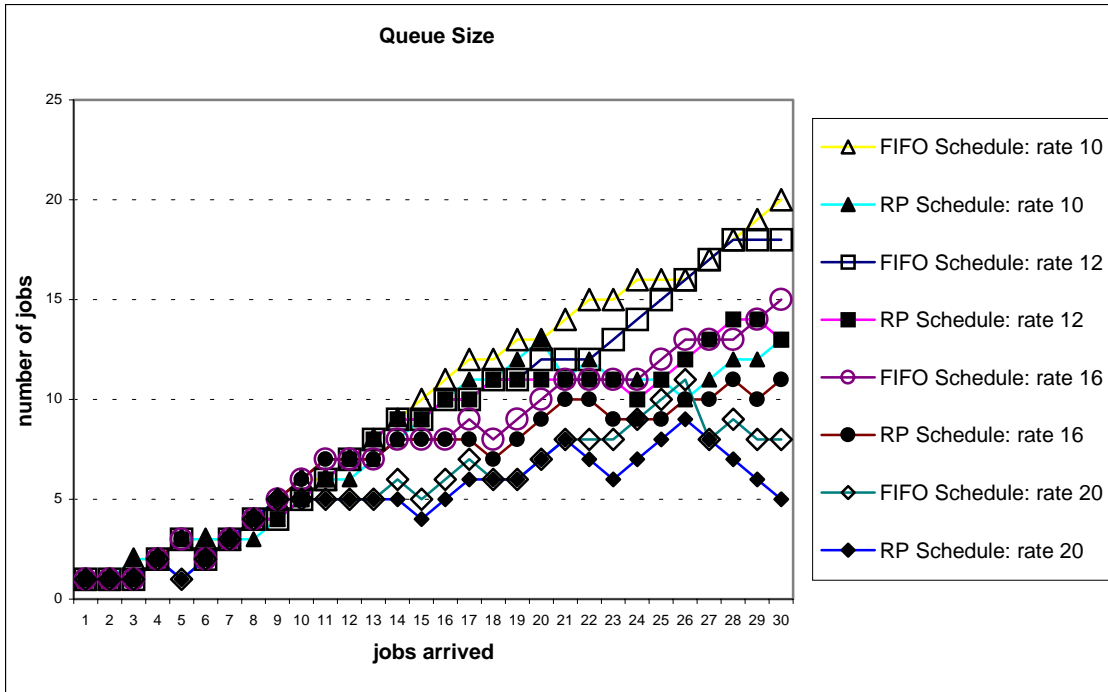


Figure 4.11 Comparison of the queue size between the FIFO Schedules and the RP Schedules for Job Sequence I issued at 10AM on Monday. The operator schedule is from 8AM to 5PM, Monday through Friday.

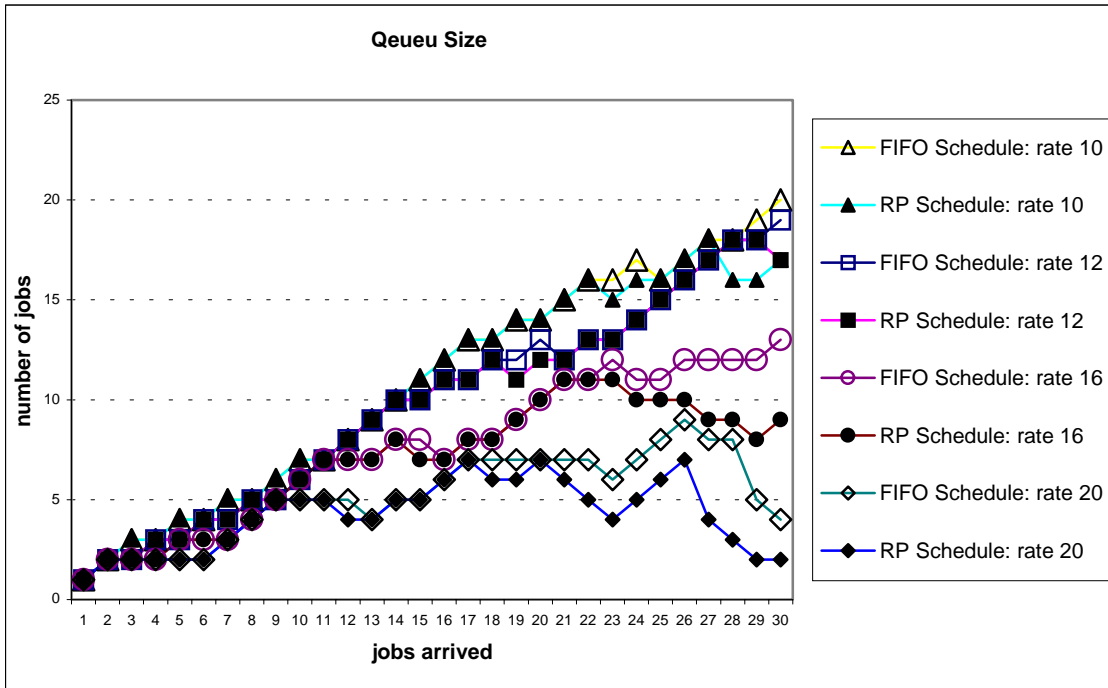


Figure 4.12 Comparison of the queue size between the FIFO Schedules and the RP Schedules for Job Sequence II issued at 10AM on Monday. The operator schedule is from 8AM to 5PM, Monday through Friday.

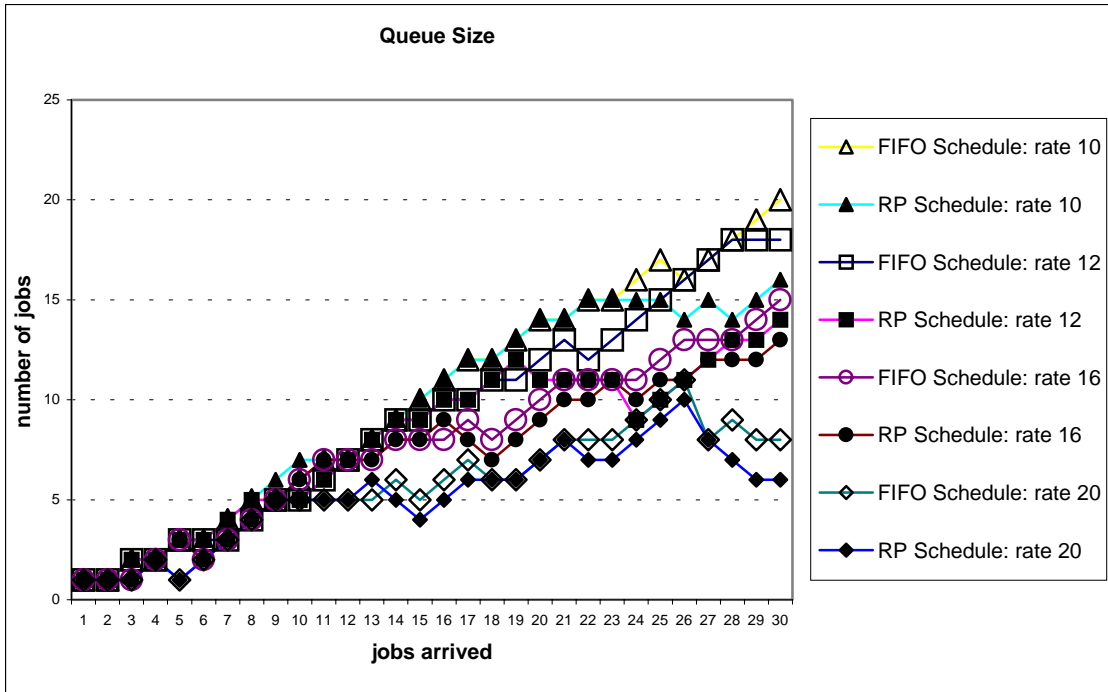


Figure 4.13 Comparison of the queue size between the FIFO Schedules and the RP Schedules for Job Sequence I issued at 10AM on Monday. The operator schedule is from 9AM to 12PM and 1PM to 4PM, Monday through Friday.

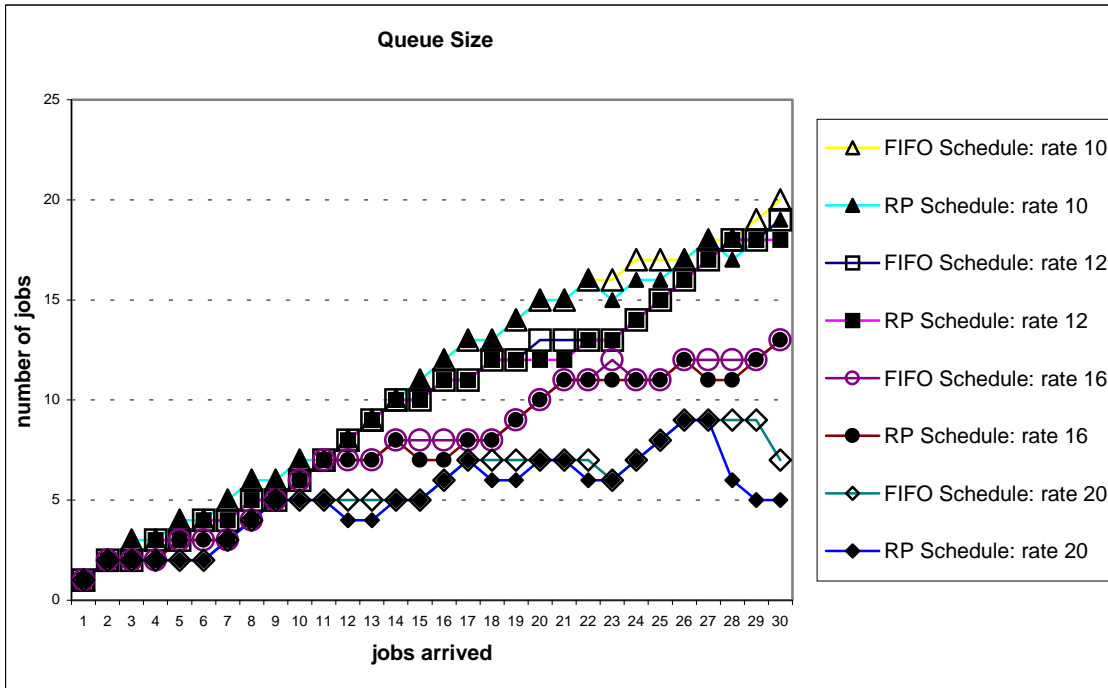


Figure 4.14 Comparison of the queue size between the FIFO Schedules and the RP Schedules for Job Sequence II issued at 10AM on Monday. The operator schedule is from 9AM to 12PM and 1PM to 4PM, Monday through Friday.

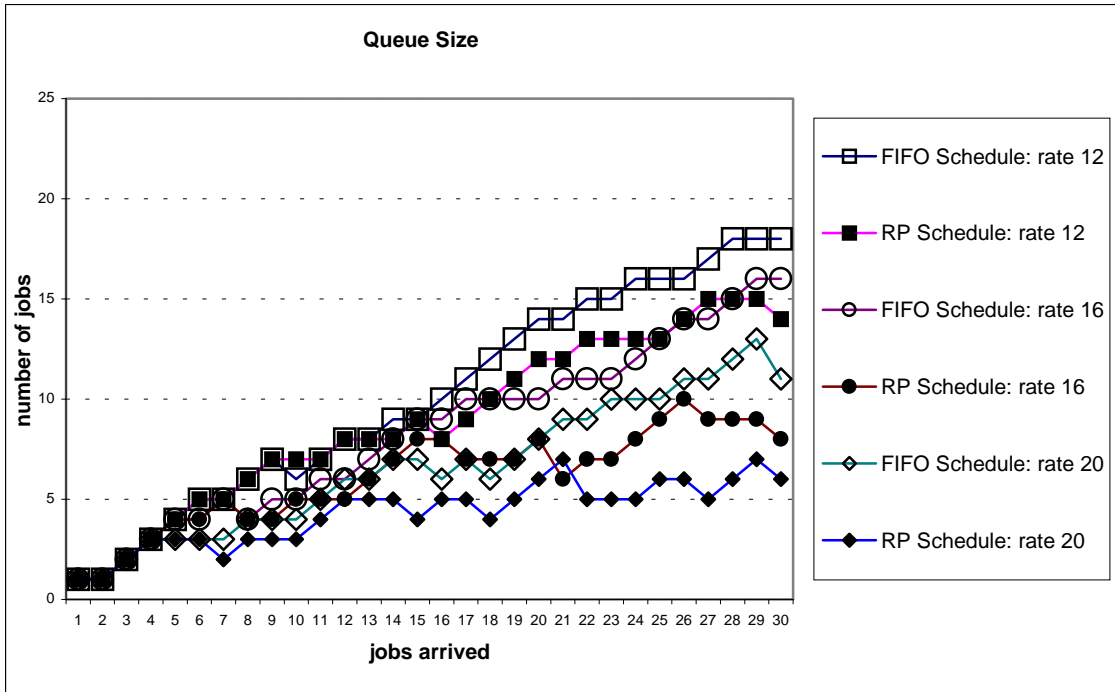


Figure 4.15 Comparison of the queue size between the FIFO Schedules and the RP Schedules for Job Sequence I issued at 10AM on Friday. The operator schedule is from 8AM to 5PM, Monday through Friday.

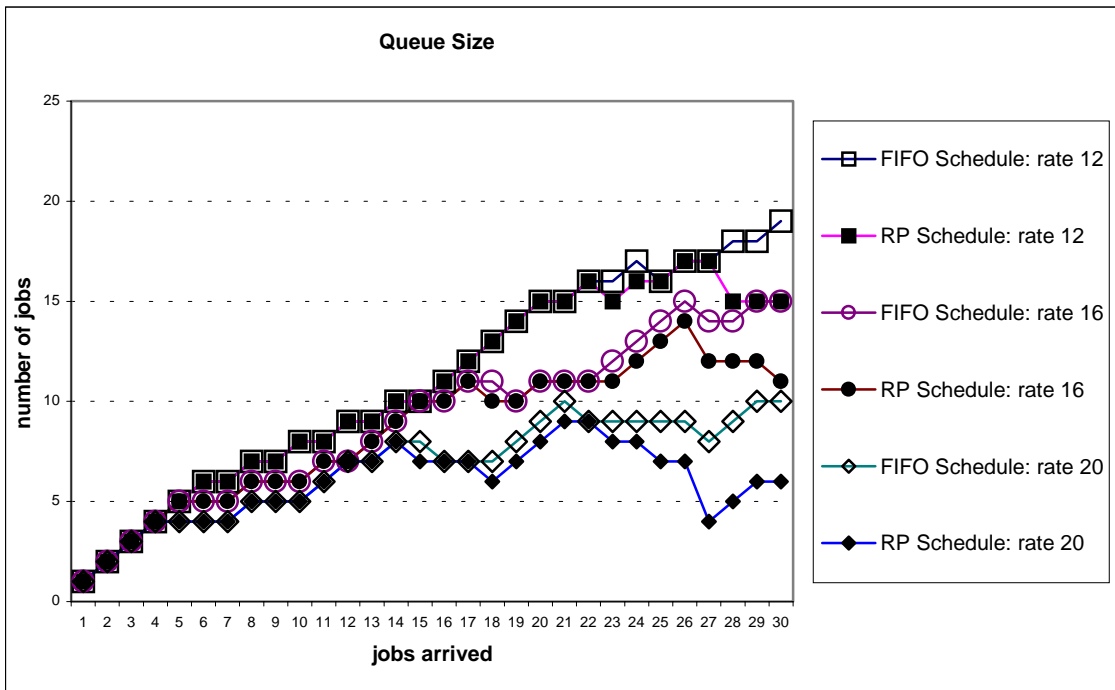


Figure 4.16 Comparison of the queue size between the FIFO Schedules and the RP Schedules for Job Sequence II issued at 10AM on Friday. The operator schedule is from 8AM to 5PM, Monday through Friday.

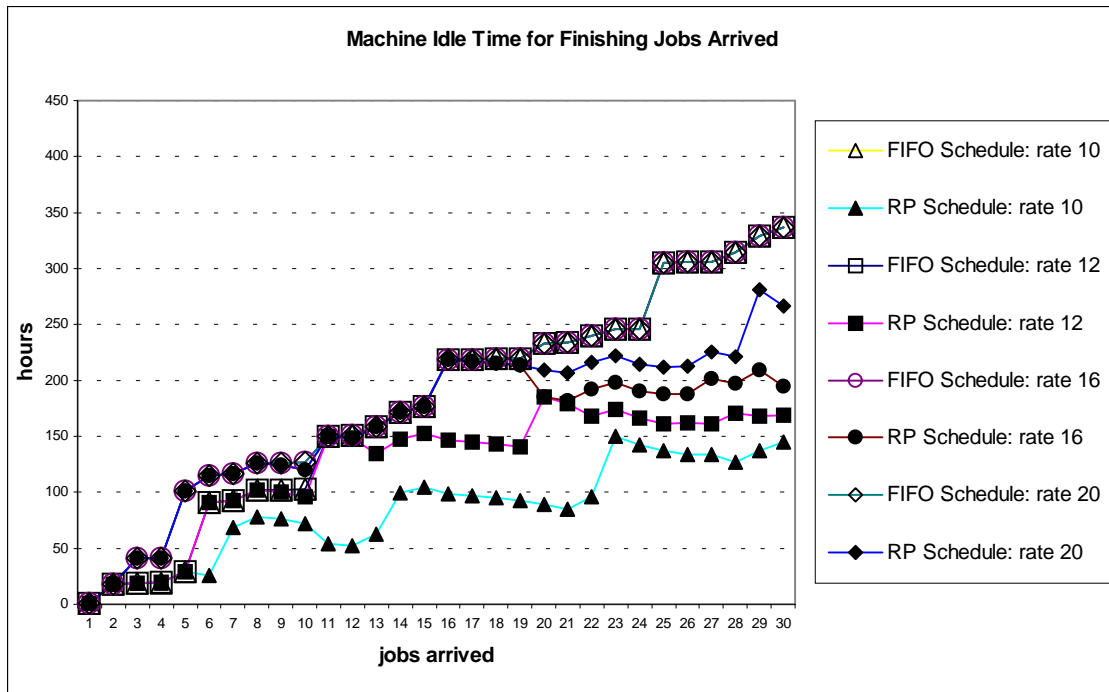


Figure 4.17 Comparison of the machine idle time between the FIFO Schedules and the RP Schedules for Job Sequence I issued at 10AM on Monday. The operator schedule is from 8AM to 5PM, Monday through Friday.

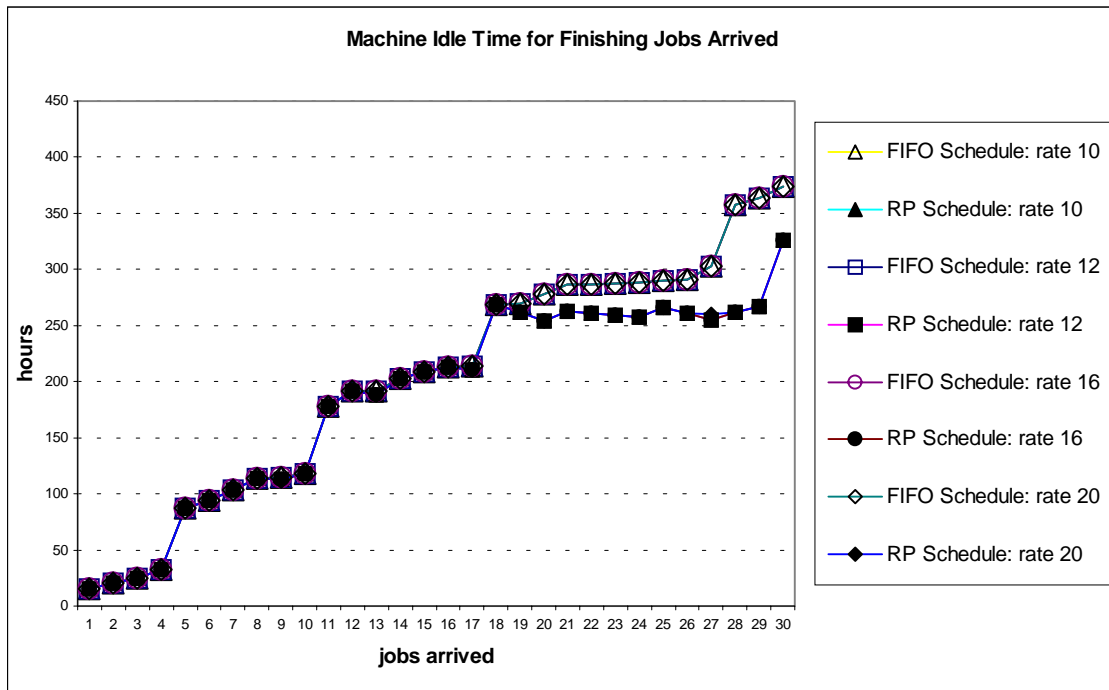


Figure 4.18 Comparison of the machine idle time between the FIFO Schedules and the RP Schedules for Job Sequence II issued at 10AM on Monday. The operator schedule is from 8AM to 5PM, Monday through Friday.

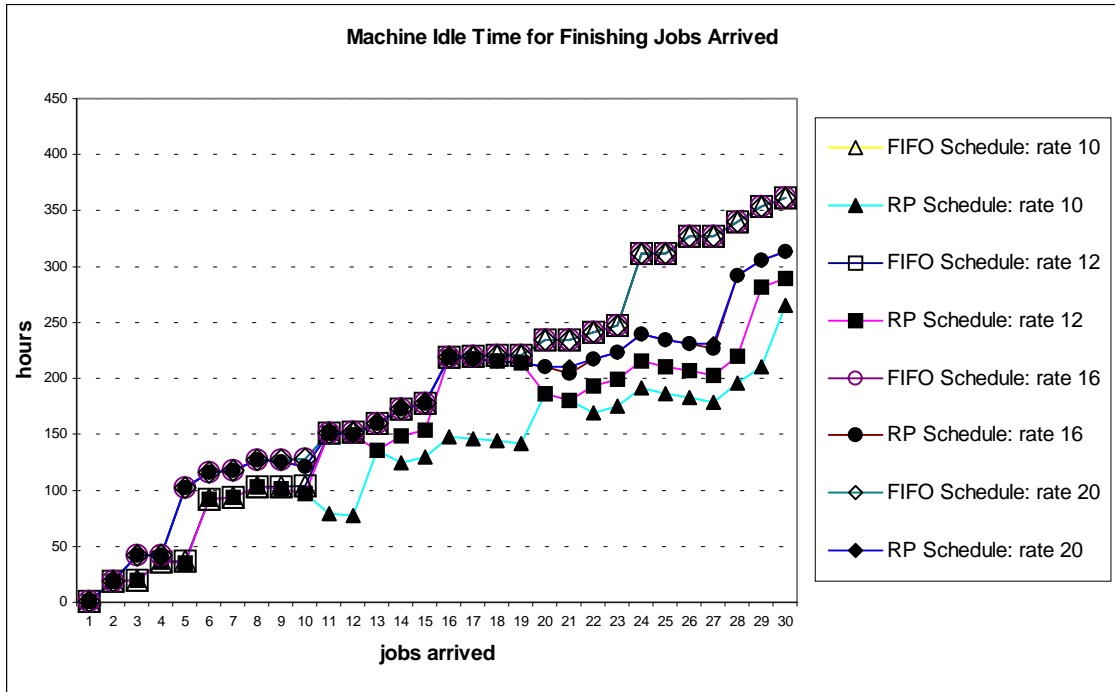


Figure 4.19 Comparison of the machine idle time between the FIFO Schedules and the RP Schedules for Job Sequence I issued at 10AM on Monday. The operator schedule is from 9AM to 12PM and 1PM to 4PM, Monday through Friday.

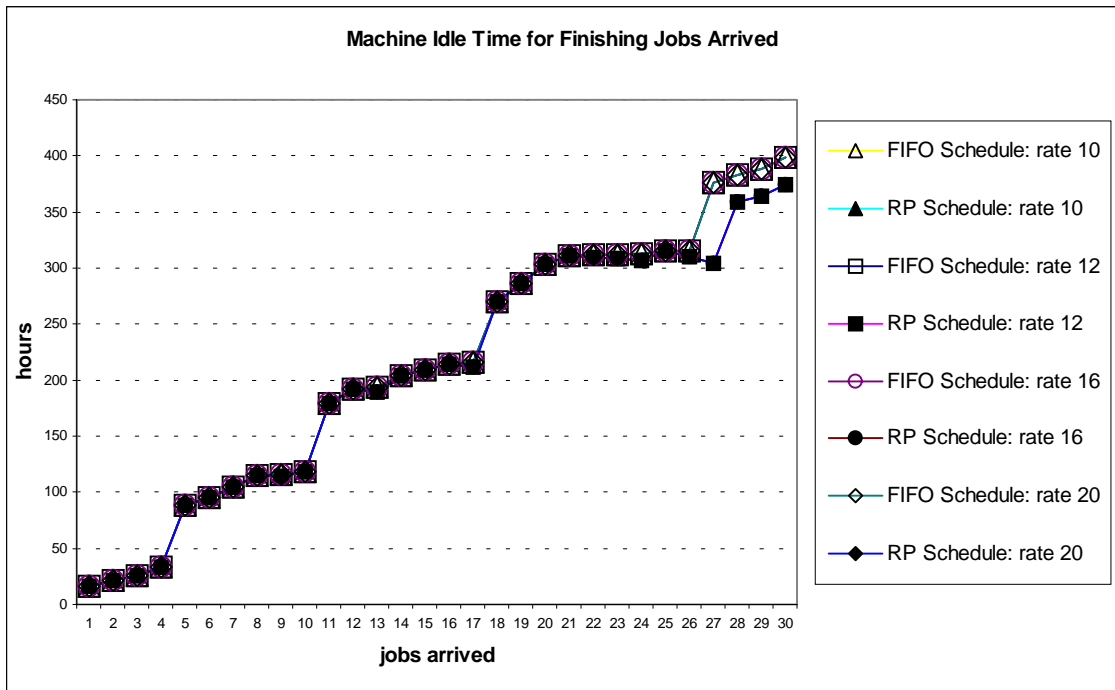


Figure 4.20 Comparison of the machine idle time between the FIFO Schedules and the RP Schedules for Job Sequence II issued at 10AM on Monday. The operator schedule is from 9AM to 12PM and 1PM to 4PM, Monday through Friday.

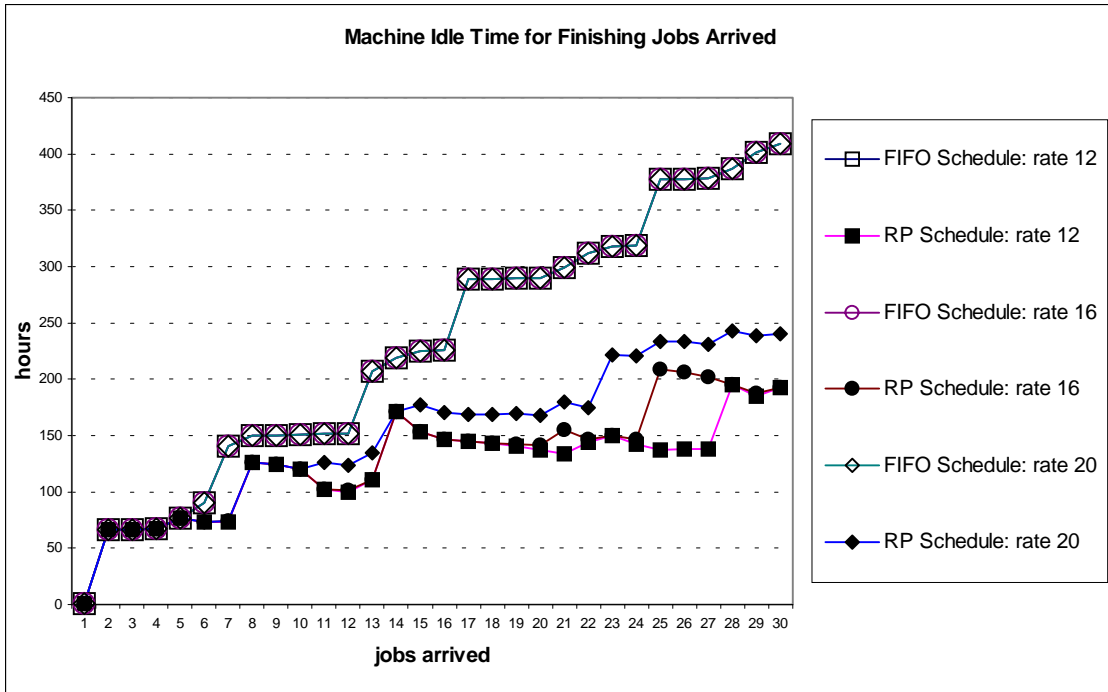


Figure 4.21 Comparison of the machine idle time between the FIFO Schedules and the RP Schedules for Job Sequence I issued at 10AM on Friday. The operator schedule is from 8AM to 5PM, Monday through Friday.

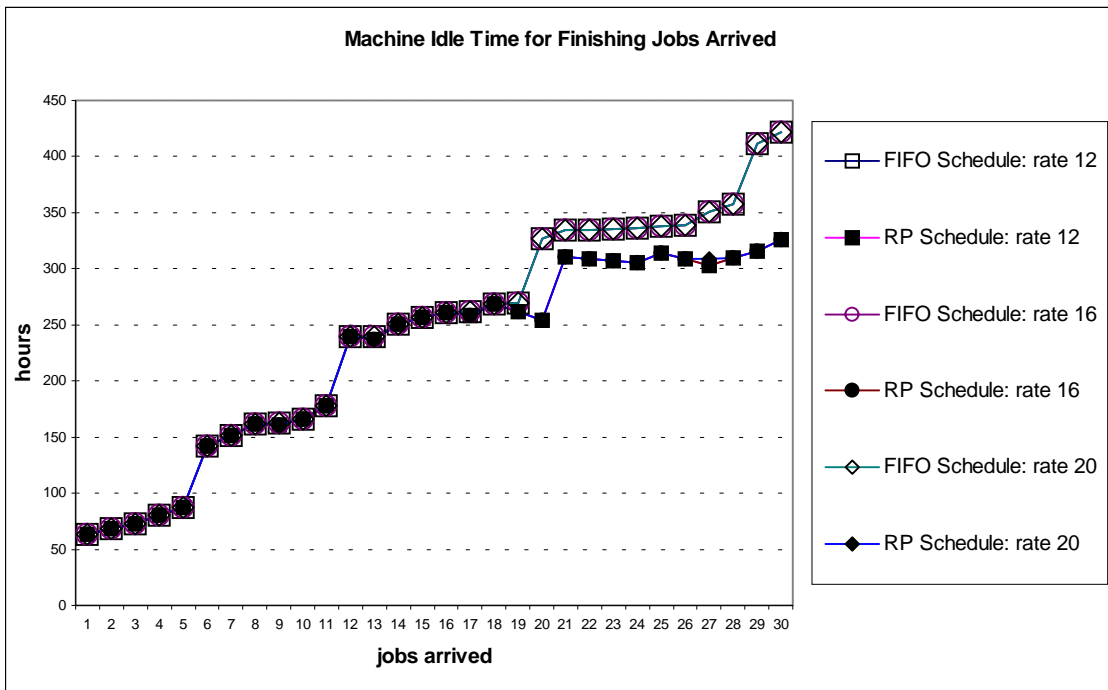


Figure 4.22 Comparison of the machine idle time between the FIFO Schedules and the RP Schedules for Job Sequence II issued at 10AM on Friday. The operator schedule is from 8AM to 5PM, Monday through Friday.



Figure 4.23 The number of weekends in the job schedules for Job Sequence I.



Figure 4.24 The number of weekends in the job schedules for Job Sequence II.

Table 4.2 shows the computation times for the scheduling processes. It records both the time consumed by the proposed RP scheduling method (which is a branch-and-bound method that uses the RP job-queue-based search-space-reduction strategy), and the time consumed by a branch-and-bound method using only the lower bound evaluation to reduce search space.

Table 4.2 Computation times recorded for the scheduling processes.

Job Queue Size	Time used for the scheduling processes			
	RP job-queue-based strategy		Lower bound evaluation	
	<i>min</i>	<i>max</i>	<i>min</i>	<i>max</i>
1-10	< 1 second	10 seconds	< 1 second	1 minute
11	< 1second	10 seconds	1 minute	10 minutes
12	8 seconds	1 minute	40 minutes	1 hour
13-19	1 minute	25 minutes	> 1 hour	>> 1 hour

Table 4.3 Improvements of the RP job schedules over the FIFO schedules.

	Average values for all cases shown in Table 4.1					
	<i>Total completion time for all 30 jobs (hours)</i>		<i>Total Machine idle time for finishing all 30 jobs (hours)</i>		<i>Queue size after all 30 jobs are submitted</i>	
	Job Sequence I	Job Sequence II	Job Sequence I	Job Sequence II	Job Sequence I	Job Sequence II
FIFO Schedules	770.7	740.2	365.7	395.2	15.2	14.5
RP Schedules	640.2	687.8	235.2	342.8	10.8	11.1
Improvement	16.9%	7.1%	35.7%	13.3%	29%	23.4%

4.4 OBSERVATIONS

Figures 4.5-22 show the consistent improvement of the RP job schedules over the FIFO schedules. Figures 4.5 to 4.10 show that the total completion times for Job Sequence I and II in the RP schedules are always less than that of the FIFO schedules. The numbers of jobs in the waiting queues and the machine idle time were reduced significantly. Table 4.3 summarizes the overall improvements.

It is observed that as the job request rate increased (i.e., going from one job every 20 hours to one job every 10 hours), the total completion time for Job Sequence I and the corresponding machine idle time decreased. This is because the increased job request rate generally increased the job queue size and hence the opportunities to reduce the total completion time through job reshuffling. However, for Job Sequence II, the change of job request rate did not show much impact on the final RP schedules. This is because of the order and processing times of the first several jobs in the Job Sequence II. Figure 4.4

shows that Job Sequence II starts with several jobs whose processing times are relatively similar in length. None of these jobs can be finished during one operator-available period, and none of them are large enough (i.e., longer than 24 hours) to span a gap in the operator's schedule. Hence, reshuffling those jobs held little opportunity for reducing the total completion time. The extreme situation would have been that all the jobs would have been of same processing time, which then would make the RP schedule generate the same results as the FIFO schedule. For the job sequences that are composed of jobs whose processing times are widely different, such as those in Job Sequence I (Figure 4.3), the savings are increasingly more prominent as the job request rate increases.

Figures 4.5 through 4.8 show that with more available time in the operator schedule, the system can complete more jobs in less time. Figures 4.5-6 show the effect of an 8AM-5PM operator-schedule, while Figures 4.7-8 show the effect of a 9AM-4PM operator-schedule (with a break between 12 Noon and 1PM), all on the same sequence of jobs. The job schedules in Figures 4.5 and 4.6 are not only shorter than those in Figures 4.7 and 4.8, but they also showed a relatively larger difference between the RP and FIFO schedules. However, this does not indicate that the advantage of the RP schedules increases as the availability of the operator increases. This is because when the operator was available all the time, there would be no difference between the FIFO and RP schedules. The reason that the advantage of the RP schedules increases as the operator's availability increases in the test, could be that (a) the operator-available periods in Figures 4.5-6 are more evenly distributed than in Figures 4.7-8, or (b) the lengths of each operator-available period in both schedules are shorter than the average job processing time.

It is observed that the impact of a particular job request start time on the overall RP scheduling results decreases as more jobs were scheduled. Figures 4.9 and 4.10 show the total completion times for schedules that were generated under the same conditions as those in Figure 4.5 and 4.6, with the exception that the job requests were started at 10AM Friday instead of 10AM Monday. These figures show that the FIFO schedules were consistently affected by this change of start time. When the job start times changed from 10AM Monday to 10AM Friday, the total completion times for the FIFO schedules were

extended by about the duration of one weekend, and the numbers of weekends covered by the FIFO schedules were increased from four to five, as shown in Figures 4.23 and 4.24. However, for the RP job schedules, the total completion times start off with the same delay of about the duration of one weekend; but as more jobs arrive, this delay effectively vanishes. This is because the RP scheduling method reduces the impact of a single gap in the operator schedule through job reshuffling, and as more jobs become available for scheduling, the impact of the gap becomes less significant.

Finally, Table 4.2 shows that the RP job-queue-based search-space-reduction strategy effectively reduced the computation time for the branch-and-bound method. Because of the nature of the branch-and-bound method, there is no guarantee that the computation time can always be reduced successfully. In the worst case, it will still need to search all the nodes in the branch-and-bound search tree to find the best result. However, Table 4.2 shows that the proposed RP job-queue-based strategy worked well for all the cases that were tested. Without this modified strategy, the computation time for the scheduling process would increase very quickly and make the branch-and-bound method impractical. Hence, the RP job-queue based search strategy allows for a practical application of the general branch-and-bound method to the rapid prototyping job-scheduling problem.

Chapter 5

CONCLUSIONS AND CONTRIBUTIONS

This thesis has addressed the machine idle time problem for current rapid prototyping systems. It has proposed a method to reduce the machine idle time by rescheduling the jobs that are pending before the rapid prototyping system. This job scheduling method is based on the branch-and-bound method, and it uses the characteristics of the rapid prototyping job queue to reduce the computation time. The effectiveness of this method has been tested for the FDM 1600 rapid prototyping system. The result from this thesis holds the potential to improve the utilization of remote rapid prototyping facilities.

5.1 CONCLUDING REMARKS

The new RP job scheduling method proposed in this thesis reduces the machine idle time for current rapid prototyping systems by replacing their standard FIFO job queues with optimized job queues. This scheduling method is developed based on the characteristics of the data that is typical most RP systems. First, this new method requires that the processing time of each job is known at the time of job scheduling. Most RP system processors today, including QuickSlice for the FDM RP systems by Stratasys, Inc., generally provide sufficiently accurate estimates. Hence, improving the system utilization through job scheduling is applicable to most RP systems. Second, the RP job scheduling method is based on the general branch-and-bound method, but exploits the characteristics that are common to most RP job queues to reduce the search space for the branch-and-bound method. Specifically, it uses characteristics that are associated with job schedule fragments that do not contain machine idle time. These job schedule fragments (defined as *contiguous sequences* in this thesis) exist in most RP job schedules. The proposed RP job scheduling method can therefore be applied to most current RP systems.

The proposed method holds great promise to benefit remote, network-accessed RP systems, because they more than others would benefit from the improvements in machine

utilization. The test in Chapter 4 shows that the amount of savings tends to be proportional to the number of jobs waiting for processing and the differences in their job processing times. For the two test samples, the standard deviation of job processing times are 11.5 hours for Job Sequence I and 6.4 hours for Job Sequence II. Since remote RP systems typically have more diverse users, these systems will be more likely to be operating with a constant backlog of jobs of large variance, from which they can realize significant savings via the proposed method. We observe this consequence by noting how the average saving in total completion time for Job Sequence I (16.9%) is noticeably larger than that for Job Sequence II (7.1%).

5.2 CONTRIBUTIONS

This thesis has proposed a solution for the machine idle time problem of current rapid prototyping systems. In particular, it has made the following contributions:

Efficient rapid prototyping job management

A method to reduce the machine idle time for current rapid prototyping systems has been demonstrated. This method increases the RP system utilization by replacing the standard FIFO queue with an optimized job queue through job scheduling. The effectiveness of this solution has been demonstrated. Although the machine idle time cannot be eliminated completely, this solution minimizes the needs for extra hardware and human resources, and it is ideal for the remote rapid prototyping systems.

Improved the branch-and-bound method for RP job scheduling

This thesis has proposed a new method to reduce the search space for the branch-and-bound method that particularly addresses the RP job-scheduling problem. This implementation uses the characteristics of RP job queues to reduce the search space for the general branch-and-bound method. It overcomes the difficulty of accurately evaluating the lower bound of the total completion time for the RP job schedules, and hence allows for a practical application of the branch-and-bound method to the rapid prototyping job-scheduling problem.

5.3 RECOMMENDATIONS FOR FUTURE WORK

This thesis has proposed an efficient method to improve the RP system utilization. To ensure its acceptance, the following issues need to be investigated:

The computation overhead of the contiguous sequences

The proposed scheduling method uses the contiguous sequences to reduce the computation time associated with the branch-and-bound method. As discussed in Chapter 3, the current method to expand the contiguous sequences does not explore all combinations of longer contiguous sequences. A brute-force method, which would be able to consider all such combinations, could be used; but it would add a significant computational cost each time the branch-and-bound method generates a branch. However, the resulting longer contiguous sequences might provide more opportunities to reduce the search space and hence the total computation time. The effect of adding this completeness and its associated overhead on the overall computational time has not been studied in this thesis. Therefore, a study of the tradeoff between the computation overhead of the contiguous sequences and the overall computation time of the branch-and-bound method is recommended.

Impact of the operator schedule pattern

The results in Chapter 4 show that the improvements of the RP schedules changed as the operator schedules changed. It is believed that the pattern of the operator schedules will affect the improvement that can be achieved by the proposed RP scheduling method. It is possible that under certain conditions the job scheduling might have little effect on the system's overall utilization. A study of the impact of the operator schedule pattern and the length of each operator-available-period (relative to the average job processing time) would help users make the decision as to whether and when to apply the proposed job scheduling method.

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APPENDIX A

TEST SAMPLE DATA

This appendix lists the two test sequences that were extracted from the usage logs for the FDM 1600 Rapid prototyping system in the Department of Mechanical Engineering at Virginia Tech.

Table A1. Job Processing Times for Test Sequences I and II.

Job ID	Job Processing Time (hours)	
	Sequence I	Sequence II
1	4.37	7.03
2	1.34	18.48
3	24.15	19.58
4	5.14	16.45
5	30.07	17.28
6	10.26	16.69
7	22.23	14.99
8	14.63	13.49
9	25.28	1.14
10	4.21	19.06
11	42.16	11.81
12	2.20	10.65
13	13.30	2.67
14	35.35	9.82
15	18.40	18.37
16	30.64	19.14
17	1.71	2.68
18	1.75	13.74
19	1.86	7.46
20	27.85	7.03
21	5.60	15.98
22	11.29	1.62
23	18.26	1.42
24	7.50	1.56
25	5.15	15.62
26	3.33	5.03
27	4.23	6.15
28	6.84	17.23
29	9.89	18.52
30	16.30	13.72

APPENDIX B

TEST RESULTS

This appendix lists the scheduling results that are displayed graphically in Chapter 4. The queue-make spans (the total completion time for jobs in queue), the machine run times, and the machine idle times listed in these tables are for the current job queue, and do not include those jobs that have been completed. The total completion time in these tables is the time needed for completing all the jobs that have been submitted thus far. This includes those jobs that are currently in the queue and those that have already been completed.

The machine idle times in Figures 4.17 through 4.22 in Chapter 4 differs from those shown in this appendix. The values shown in the figures, T_idle_i , are the total machine idle time when all the jobs that have been submitted thus far are completed, and are derived as follows:

$$T_idle_i = Cmax_i - \sum_{j=1}^i T_j$$

where, i is the number of jobs that have been submitted, $Cmax_i$ is the total completion time for finishing all i jobs, and T_j is the processing time for job j (Table A1).

Follows is an example for calculating T_idle_i using Table A1 and B1 after three jobs from Sequence I are completed.

$$i = 3$$

$$T_idle_3 = Cmax_3 - \sum_{j=1}^3 T_j = 48.5 - (4.37 + 1.34 + 24.15) = 18.64 \text{ (hours)}$$

This value was shown in Figure 4.17 in Chapter 4 as the machine idle time for the FIFO schedule when three jobs were submitted at the rate of one job every 10 hours.

**Table B1. FIFO scheduling results for Sequence I: Issued at 10AM on Monday;
Job Arriving Rate: per 10 hours; Operator Schedule: 8AM-5PM**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	23.8
3	2	26.5	25.5	1.0	48.5
4	2	30.3	29.3	1.0	54.1
5	3	70.2	59.4	10.8	94.0
6	3	117.5	45.5	72.0	166.0
7	3	135.9	62.6	73.3	190.0
8	4	159.9	77.2	82.7	214.0
9	5	185.7	102.5	83.2	239.8
10	6	190.4	106.7	83.7	244.5
11	6	240.0	118.8	121.2	334.0
12	7	242.7	121.0	121.7	336.7
13	8	264.0	134.3	129.7	358.0
14	9	312.0	169.6	142.4	406.0
15	10	336.0	188.0	148.0	430.0
16	11	408.0	218.7	189.3	502.0
17	12	410.2	220.4	189.8	504.2
18	12	340.5	211.9	128.6	506.5
19	13	342.8	213.7	129.1	508.8
20	13	360.0	219.3	140.7	550.0
21	14	366.1	224.9	141.2	556.1
22	15	384.0	236.2	147.8	574.0
23	15	384.0	239.9	144.1	598.0
24	16	392.0	247.4	144.6	606.0
25	16	430.2	227.2	203.0	670.0
26	16	429.3	226.3	203.0	673.8
27	17	434.1	230.6	203.5	678.6
28	18	449.5	237.4	212.1	694.0
29	19	473.5	247.3	226.2	718.0
30	20	497.5	263.6	233.9	742.0

Table B2. RP scheduling results for Sequence I: Issued at 10AM on Monday; Job Arriving Rate: per 12 hours; Operator Schedule: 8AM-5PM

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	23.8
3	2	26.5	26.5	0.0	48.5
4	2	30.3	30.3	0.0	54.1
5	3	70.2	60.9	9.3	94.0
6	3	52.1	47.0	5.1	100.6
7	3	111.9	64.1	47.8	166.0
8	3	120.0	68.4	51.6	190.0
9	4	144.0	94.2	49.8	214.0
10	5	144.0	98.9	45.1	214.0
11	6	168.0	141.6	26.4	238.0
12	6	137.4	113.7	23.7	238.0
13	7	161.4	127.5	33.9	262.0
14	8	233.4	163.4	70.1	334.0
15	9	257.4	182.3	75.2	358.0
16	10	281.4	213.4	68.0	382.0
17	11	281.4	215.6	65.8	382.0
18	11	216.0	175.2	40.8	382.0
19	12	216.0	177.6	38.4	382.0
20	13	240.0	205.9	34.1	406.0
21	11	208.3	179.3	29.0	407.0
22	12	231.3	191.1	40.2	430.0
23	11	285.3	192.0	93.3	502.0
24	11	279.2	193.9	85.3	502.0
25	11	264.0	185.7	78.3	502.0
26	10	259.4	185.0	74.4	502.0
27	11	263.3	189.7	73.5	505.8
28	12	263.3	197.1	66.2	505.8
29	12	255.1	179.1	76.0	526.0
30	13	279.1	195.9	83.2	550.0

**Table B3. FIFO scheduling results for Sequence I: Issued at 10AM on Monday;
Job Arriving Rate: per 12 hours; Operator Schedule: 8AM-5PM**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	23.8
3	1	24.7	24.1	0.5	48.7
4	2	30.3	29.3	1.0	54.3
5	3	70.0	59.4	10.6	94.0
6	2	111.7	40.3	71.4	166.0
7	3	135.7	62.6	73.1	190.0
8	4	159.7	77.2	82.5	214.0
9	4	145.8	72.4	73.4	239.8
10	5	150.5	76.6	73.9	244.5
11	6	240.0	118.8	121.2	334.0
12	7	242.7	121.0	121.7	336.7
13	8	264.0	134.3	129.7	358.0
14	9	312.0	169.6	142.4	406.0
15	9	264.0	177.8	86.2	430.0
16	10	336.0	208.4	127.6	502.0
17	10	314.2	187.9	126.3	504.2
18	11	316.5	189.6	126.8	506.5
19	11	294.8	176.9	118.0	508.8
20	12	336.0	204.7	131.3	550.0
21	12	316.3	185.0	131.3	556.1
22	12	329.5	192.1	137.4	574.0
23	13	353.5	210.4	143.1	598.0
24	14	361.5	217.9	143.6	606.0
25	15	425.5	223.0	202.5	670.0
26	16	429.3	226.3	203.0	673.8
27	17	434.1	230.6	203.5	678.6
28	18	449.5	237.4	212.1	694.0
29	18	384.0	205.1	178.9	718.0
30	18	405.3	219.2	186.0	742.0

Table B4. RP scheduling results for Sequence I: Issued at 10AM on Monday; Job Arriving Rate: per 12 hours; Operator Schedule: 8AM-5PM

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	23.8
3	1	24.6	24.6	0.0	48.6
4	2	30.3	30.3	0.0	54.3
5	3	70.0	60.9	9.1	94.0
6	2	111.7	41.3	70.4	166.0
7	3	135.7	64.1	71.7	190.0
8	4	159.7	79.2	80.5	214.0
9	4	144.0	74.4	69.6	238.0
10	5	144.0	79.1	64.9	238.0
11	6	240.0	121.8	118.2	334.0
12	7	240.0	124.5	115.5	334.0
13	8	240.0	138.3	101.7	334.0
14	9	288.0	174.1	113.9	382.0
15	9	240.0	182.3	57.7	406.0
16	10	264.0	213.4	50.6	430.0
17	10	240.0	192.9	47.1	430.0
18	11	240.0	195.1	44.9	430.0
19	11	214.2	171.7	42.5	430.0
20	11	281.5	195.3	86.2	502.0
21	11	264.0	186.3	77.7	502.0
22	11	261.3	195.4	65.9	502.0
23	11	264.0	195.3	68.7	526.0
24	10	255.7	195.0	60.7	526.0
25	11	255.7	200.6	55.1	526.0
26	12	259.5	204.4	55.1	529.8
27	13	262.8	209.2	53.7	533.1
28	14	279.7	216.5	63.2	550.0
29	14	223.1	184.2	38.9	557.1
30	13	235.4	196.4	39.0	574.0

**Table B5. FIFO scheduling results for Sequence I: Issued at 10AM on Monday;
Job Arriving Rate: per 16 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	23.8
3	1	24.7	24.1	0.5	70.7
4	2	30.3	29.3	1.0	76.3
5	3	120.0	59.4	60.6	166.0
6	2	113.7	40.3	73.4	190.0
7	3	137.7	62.6	75.1	214.0
8	4	161.7	77.2	84.5	238.0
9	5	187.5	102.5	85.0	263.8
10	6	192.2	106.7	85.5	268.5
11	7	257.7	148.8	108.9	334.0
12	7	170.7	121.0	49.7	336.7
13	7	168.0	124.0	44.0	358.0
14	8	216.0	159.4	56.6	406.0
15	8	216.0	155.5	60.5	430.0
16	8	264.0	171.5	92.5	502.0
17	9	266.2	173.2	93.0	504.2
18	8	238.0	145.5	92.5	506.5
19	9	240.3	147.4	93.0	508.8
20	10	281.5	175.2	106.3	550.0
21	11	287.6	180.8	106.8	556.1
22	11	240.0	149.9	90.1	574.0
23	11	261.3	166.0	95.3	598.0
24	11	248.0	160.2	87.8	606.0
25	12	312.0	165.4	146.6	670.0
26	13	315.8	168.7	147.1	673.8
27	13	272.6	137.6	135.0	678.6
28	13	264.0	126.0	138.0	694.0
29	14	288.0	135.9	152.1	718.0
30	15	312.0	152.2	159.8	742.0

Table B6. RP scheduling results for Sequence I: Issued at 10AM on Monday; Job Arriving Rate: per 16 hours; Operator Schedule: 8AM-5PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	23.8
3	1	24.6	24.6	0.0	70.7
4	2	30.3	30.3	0.0	76.3
5	3	120.0	60.9	59.1	166.0
6	2	113.7	41.3	72.4	190.0
7	3	137.7	64.1	73.7	214.0
8	4	161.7	79.2	82.5	238.0
9	5	185.7	105.0	80.7	262.0
10	6	185.7	109.7	76.0	262.0
11	7	257.7	152.3	105.4	334.0
12	7	168.0	124.5	43.5	334.0
13	7	168.0	127.5	40.5	358.0
14	8	216.0	163.4	52.6	406.0
15	8	216.0	159.5	56.5	430.0
16	8	262.2	164.9	97.3	502.0
17	8	257.5	162.4	95.1	502.0
18	7	237.3	146.8	90.5	502.0
19	8	237.3	149.2	88.1	502.0
20	9	237.3	177.5	59.8	502.0
21	10	239.6	183.6	55.9	504.2
22	10	192.0	152.7	39.3	526.0
23	9	211.4	166.9	44.5	550.0
24	9	183.1	146.6	36.5	550.0
25	9	170.2	138.4	31.8	552.2
26	10	173.7	142.3	31.4	555.6
27	10	160.9	115.9	45.0	574.0
28	11	163.0	123.2	39.8	576.1
29	10	159.9	108.6	51.3	598.0
30	11	162.0	125.4	36.6	600.1

**Table B7. FIFO scheduling results for Sequence I: Issued at 10AM on Monday;
Job Arriving Rate: per 20 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	23.8
3	1	24.7	24.1	0.5	70.7
4	2	30.3	29.3	1.0	76.3
5	1	72.0	30.1	41.9	166.0
6	2	96.0	40.3	55.7	190.0
7	3	120.0	62.6	57.4	214.0
8	4	144.0	77.2	66.8	238.0
9	5	169.8	102.5	67.3	263.8
10	5	102.5	76.6	25.9	268.5
11	5	144.0	108.5	35.5	334.0
12	5	122.7	88.5	34.2	336.7
13	5	120.0	87.2	32.8	358.0
14	6	168.0	122.5	45.5	406.0
15	5	161.5	111.4	50.1	430.0
16	6	233.5	142.1	91.5	502.0
17	7	235.7	143.8	92.0	504.2
18	6	169.8	101.2	68.6	506.5
19	6	150.8	89.7	61.1	508.8
20	7	192.0	117.6	74.4	550.0
21	8	198.1	123.2	74.9	556.1
22	8	168.0	99.1	68.9	574.0
23	8	168.0	99.0	69.0	598.0
24	9	176.0	106.5	69.5	606.0
25	10	240.0	111.6	128.4	670.0
26	11	243.8	114.9	128.9	673.8
27	8	169.7	83.2	86.5	678.6
28	9	185.2	90.1	95.1	694.0
29	8	161.9	66.5	95.4	718.0
30	8	168.0	71.5	96.5	742.0

Table B8. RP scheduling results for Sequence I: Issued at 10AM on Monday; Job Arriving Rate: per 20 hours; Operator Schedule: 8AM-5PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	23.8
3	1	24.6	24.6	0.0	70.7
4	2	30.3	30.3	0.0	76.3
5	1	72.0	30.6	41.4	166.0
6	2	96.0	41.3	54.7	190.0
7	3	120.0	64.1	55.9	214.0
8	4	144.0	79.2	64.8	238.0
9	5	168.0	105.0	63.0	262.0
10	5	96.0	79.1	16.9	262.0
11	5	144.0	111.0	33.0	334.0
12	5	120.0	91.0	29.0	334.0
13	5	118.2	79.0	39.2	358.0
14	5	161.5	110.1	51.4	406.0
15	4	165.3	111.2	54.1	430.0
16	5	237.3	142.3	95.0	502.0
17	6	237.3	144.6	92.7	502.0
18	6	168.0	104.1	63.9	502.0
19	6	144.0	92.7	51.3	502.0
20	7	168.0	121.1	46.9	526.0
21	8	171.2	127.2	44.1	529.2
22	7	141.8	100.8	40.9	550.0
23	6	135.0	88.9	46.1	574.0
24	7	135.0	96.9	38.1	574.0
25	8	137.7	102.5	35.1	576.6
26	9	141.5	106.4	35.1	580.5
27	8	89.9	73.9	16.0	598.0
28	7	65.2	54.3	10.9	600.2
29	6	114.3	47.3	67.1	670.0
30	5	94.0	41.5	52.5	672.2

**Table B9. FIFO scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 10 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	22.0	7.0	15.0	22.0
2	2	46.0	25.5	20.5	46.0
3	3	70.0	45.1	24.9	70.0
4	3	72.0	54.5	17.5	94.0
5	4	144.0	71.8	72.2	166.0
6	4	144.0	70.0	74.0	190.0
7	5	168.0	85.0	83.0	214.0
8	5	168.0	78.9	89.1	238.0
9	6	169.6	80.0	89.6	239.6
10	7	192.0	99.1	92.9	262.0
11	7	240.0	94.5	145.5	334.0
12	8	264.0	105.1	158.9	358.0
13	9	267.2	107.8	159.4	361.2
14	10	288.0	117.6	170.4	382.0
15	11	312.0	136.0	176.0	406.0
16	12	336.0	155.1	180.9	430.0
17	13	339.2	157.8	181.4	433.2
18	13	336.0	154.2	181.8	502.0
19	14	344.0	161.7	182.3	510.0
20	14	336.0	152.0	184.0	526.0
21	15	360.0	168.0	192.0	550.0
22	16	362.1	169.6	192.5	552.1
23	16	340.0	156.1	184.0	554.0
24	17	342.1	157.6	184.5	556.1
25	16	334.4	158.6	175.7	574.0
26	17	339.9	163.7	176.2	579.5
27	18	358.4	169.8	188.6	598.0
28	18	408.0	168.0	240.0	670.0
29	19	432.0	186.5	245.5	694.0
30	20	456.0	200.2	255.8	718.0

**Table B10. RP scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 10 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	22.0	7.5	14.5	22.0
2	2	46.0	26.5	19.5	46.0
3	3	70.0	46.6	23.4	70.0
4	3	72.0	56.0	16.0	94.0
5	4	144.0	73.8	70.2	166.0
6	4	144.0	72.0	72.0	190.0
7	5	168.0	87.5	80.5	214.0
8	5	168.0	81.4	86.6	238.0
9	6	168.0	83.0	85.0	238.0
10	7	192.0	102.6	89.4	262.0
11	7	240.0	98.0	142.0	334.0
12	8	264.0	109.1	154.9	358.0
13	9	264.0	112.3	151.7	358.0
14	10	288.0	122.6	165.4	382.0
15	11	312.0	141.5	170.5	406.0
16	12	336.0	161.1	174.9	430.0
17	13	336.0	164.3	171.7	430.0
18	13	336.0	160.7	175.3	502.0
19	14	336.0	168.7	167.3	502.0
20	14	312.0	159.0	153.0	502.0
21	15	336.0	175.5	160.5	526.0
22	16	336.0	177.6	158.4	526.0
23	15	310.4	162.4	147.9	526.0
24	16	310.4	164.5	145.9	526.0
25	16	312.0	166.6	145.4	550.0
26	17	312.0	172.2	139.8	550.0
27	18	312.0	178.8	133.2	550.0
28	16	305.6	170.6	135.0	574.0
29	16	327.5	187.5	140.0	598.0
30	17	399.5	201.7	197.8	670.0

**Table B11. FIFO scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 12 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	22.0	7.0	15.0	22.0
2	2	46.0	25.5	20.5	46.0
3	2	48.0	38.1	9.9	70.0
4	3	72.0	54.5	17.5	94.0
5	3	120.0	53.3	66.7	166.0
6	4	144.0	70.0	74.0	190.0
7	4	144.0	65.4	78.6	214.0
8	5	168.0	78.9	89.1	238.0
9	5	145.6	63.6	82.0	239.6
10	6	168.0	82.6	85.4	262.0
11	7	240.0	94.5	145.5	334.0
12	8	264.0	105.1	158.9	358.0
13	9	267.2	107.8	159.4	361.2
14	10	288.0	117.6	170.4	382.0
15	10	240.0	118.7	121.3	406.0
16	11	264.0	137.8	126.2	430.0
17	11	243.2	123.8	119.4	433.2
18	12	312.0	137.6	174.4	502.0
19	12	296.0	130.0	165.9	510.0
20	13	312.0	137.1	174.9	526.0
21	12	310.4	138.4	172.0	550.0
22	13	312.5	140.0	172.5	552.1
23	13	292.0	122.4	169.6	554.0
24	14	294.1	123.9	170.1	556.1
25	15	312.0	139.6	172.4	574.0
26	16	317.5	144.6	172.9	579.5
27	17	336.0	150.7	185.3	598.0
28	18	408.0	168.0	240.0	670.0
29	18	360.0	174.7	185.3	694.0
30	19	384.0	188.4	195.6	718.0

**Table B12. RP scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 12 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	22.0	7.5	14.5	22.0
2	2	46.0	26.5	19.5	46.0
3	2	48.0	39.1	8.9	70.0
4	3	72.0	56.0	16.0	94.0
5	3	120.0	54.8	65.2	166.0
6	4	144.0	72.0	72.0	190.0
7	4	144.0	67.4	76.6	214.0
8	5	168.0	81.4	86.6	238.0
9	5	144.0	66.1	77.9	238.0
10	6	168.0	85.7	82.3	262.0
11	7	240.0	98.0	142.0	334.0
12	8	264.0	109.1	154.9	358.0
13	9	264.0	112.3	151.7	358.0
14	10	288.0	122.6	165.4	382.0
15	10	240.0	123.7	116.3	406.0
16	11	264.0	143.3	120.7	430.0
17	11	240.0	129.3	110.7	430.0
18	12	312.0	143.6	168.4	502.0
19	11	286.4	134.4	152.0	502.0
20	12	286.4	141.9	144.4	502.0
21	12	288.0	144.4	143.6	526.0
22	13	288.0	146.5	141.5	526.0
23	13	264.0	128.9	135.1	526.0
24	14	264.0	130.9	133.1	526.0
25	15	288.0	147.1	140.9	550.0
26	16	288.0	152.6	135.4	550.0
27	17	288.0	159.2	128.8	550.0
28	18	312.0	177.0	135.0	574.0
29	18	264.0	183.7	80.3	598.0
30	17	329.6	191.6	138.1	670.0

**Table B13. FIFO scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 16 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	22.0	7.0	15.0	22.0
2	2	46.0	25.5	20.5	46.0
3	2	48.0	38.1	9.9	70.0
4	2	48.0	36.0	12.0	94.0
5	3	120.0	53.3	66.7	166.0
6	3	120.0	50.4	69.6	190.0
7	3	120.0	49.0	71.0	214.0
8	4	144.0	62.4	81.6	238.0
9	5	145.6	63.6	82.0	239.6
10	6	168.0	82.6	85.4	262.0
11	7	240.0	94.5	145.5	334.0
12	7	192.0	87.8	104.2	358.0
13	7	171.2	73.8	97.4	361.2
14	8	192.0	83.6	108.4	382.0
15	8	192.0	87.0	105.0	406.0
16	7	190.4	91.5	98.8	430.0
17	8	193.5	94.2	99.3	433.2
18	8	240.0	88.9	151.1	502.0
19	9	248.0	96.3	151.6	510.0
20	10	264.0	103.4	160.6	526.0
21	11	288.0	119.3	168.7	550.0
22	11	218.1	109.2	109.0	552.1
23	12	220.0	110.6	109.5	554.0
24	11	194.9	98.8	96.1	556.1
25	11	192.0	104.6	87.4	574.0
26	12	197.5	109.6	87.9	579.5
27	12	192.0	97.4	94.6	598.0
28	12	240.0	95.5	144.5	670.0
29	12	260.8	111.4	149.5	694.0
30	13	284.8	125.1	159.7	718.0

**Table B14. RP scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 16 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	22.0	7.5	14.5	22.0
2	2	46.0	26.5	19.5	46.0
3	2	48.0	39.1	8.9	70.0
4	2	48.0	37.0	11.0	94.0
5	3	120.0	54.8	65.2	166.0
6	3	120.0	51.9	68.1	190.0
7	3	120.0	50.5	69.5	214.0
8	4	144.0	64.5	79.5	238.0
9	5	144.0	66.1	77.9	238.0
10	6	168.0	85.7	82.3	262.0
11	7	240.0	98.0	142.0	334.0
12	7	192.0	91.3	100.7	358.0
13	7	168.0	77.3	90.7	358.0
14	8	192.0	87.6	104.4	382.0
15	7	190.4	89.4	101.0	406.0
16	7	192.0	95.0	97.0	430.0
17	8	192.0	98.2	93.8	430.0
18	8	240.0	92.9	147.1	502.0
19	9	240.0	100.8	139.2	502.0
20	10	240.0	108.4	131.6	502.0
21	11	264.0	124.8	139.2	526.0
22	11	192.0	114.7	77.3	526.0
23	11	188.8	113.4	75.4	526.0
24	10	164.8	101.1	63.7	526.0
25	10	168.0	98.4	69.6	550.0
26	10	160.0	96.0	64.1	550.0
27	9	136.5	84.8	51.7	550.0
28	9	144.0	88.2	55.8	574.0
29	8	164.0	103.2	60.7	598.0
30	9	236.0	117.4	118.5	670.0

**Table B15. FIFO scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 20 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	22.0	7.0	15.0	22.0
2	2	46.0	25.5	20.5	46.0
3	2	48.0	38.1	9.9	70.0
4	2	48.0	36.0	12.0	94.0
5	2	96.0	33.7	62.3	166.0
6	2	96.0	34.0	62.0	190.0
7	3	120.0	49.0	71.0	214.0
8	4	144.0	62.4	81.6	238.0
9	5	145.6	63.6	82.0	239.6
10	5	96.0	65.4	30.6	262.0
11	5	144.0	60.5	83.5	334.0
12	5	144.0	56.1	87.9	358.0
13	4	121.5	44.2	77.3	361.2
14	5	142.4	54.0	88.4	382.0
15	5	144.0	53.3	90.7	406.0
16	6	168.0	72.5	95.5	430.0
17	7	171.2	75.1	96.0	433.2
18	7	168.0	77.1	90.9	502.0
19	7	152.0	73.9	78.1	510.0
20	7	164.8	78.2	86.6	526.0
21	7	168.0	84.4	83.6	550.0
22	7	146.1	67.6	78.5	552.1
23	6	120.9	47.2	73.6	554.0
24	7	122.9	48.8	74.1	556.1
25	8	140.8	64.4	76.4	574.0
26	9	146.3	69.5	76.9	579.5
27	8	88.0	54.4	33.6	598.0
28	8	144.0	64.6	79.4	670.0
29	5	137.9	62.6	75.4	694.0
30	4	138.5	55.6	82.9	718.0

**Table B16. RP scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 20 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	22.0	7.5	14.5	22.0
2	2	46.0	26.5	19.5	46.0
3	2	48.0	39.1	8.9	70.0
4	2	48.0	37.0	11.0	94.0
5	2	96.0	34.7	61.3	166.0
6	2	96.0	35.0	61.0	190.0
7	3	120.0	50.5	69.5	214.0
8	4	144.0	64.5	79.5	238.0
9	5	144.0	66.1	77.9	238.0
10	5	96.0	67.9	28.1	262.0
11	5	144.0	63.0	81.0	334.0
12	4	142.4	57.0	85.4	358.0
13	4	120.0	46.2	73.8	358.0
14	5	144.0	56.5	87.5	382.0
15	5	144.0	55.8	88.2	406.0
16	6	168.0	75.5	92.5	430.0
17	7	168.0	78.6	89.4	430.0
18	6	164.8	77.4	87.4	502.0
19	6	144.0	74.2	69.8	502.0
20	7	144.0	81.7	62.3	502.0
21	6	140.8	84.7	56.1	526.0
22	5	112.0	60.0	52.0	526.0
23	4	88.5	40.2	48.3	526.0
24	5	88.5	42.2	46.3	526.0
25	6	112.5	58.3	54.1	550.0
26	7	112.5	63.9	48.6	550.0
27	4	47.4	44.8	2.7	555.5
28	3	41.4	39.4	2.0	574.0
29	2	42.5	36.8	5.7	598.0
30	2	96.0	33.2	62.8	670.0

**Table B17. FIFO scheduling results for Sequence I: Issued at 10AM on Monday;
Job Arriving Rate: per 10 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	24.8
3	2	26.5	25.5	1.0	49.5
4	2	46.2	29.3	16.9	71.0
5	3	76.7	59.4	17.4	101.6
6	3	117.5	45.5	72.0	167.0
7	4	141.5	67.7	73.8	191.0
8	5	165.5	82.3	83.2	215.0
9	5	169.8	102.5	67.3	240.8
10	6	174.5	106.7	67.8	245.5
11	7	264.0	148.8	115.2	335.0
12	7	236.1	121.0	115.2	337.7
13	8	257.4	134.3	123.2	359.0
14	9	305.4	169.6	135.8	407.0
15	10	329.4	188.0	141.4	431.0
16	11	401.4	218.7	182.8	503.0
17	12	403.6	220.4	183.3	505.2
18	12	340.5	211.9	128.6	507.5
19	13	342.8	213.7	129.1	509.8
20	14	384.0	241.6	142.4	551.0
21	14	366.1	224.9	141.2	557.1
22	15	384.0	236.2	147.8	575.0
23	15	384.0	239.9	144.1	599.0
24	16	456.0	247.4	208.6	671.0
25	17	461.6	252.5	209.1	676.6
26	16	449.5	226.3	223.2	695.0
27	17	454.2	230.6	223.7	699.7
28	18	473.5	237.4	236.1	719.0
29	19	497.5	247.3	250.2	743.0
30	20	521.5	263.6	257.9	767.0

Table B18. RP scheduling results for Sequence I: Issued at 10AM on Monday; Job Arriving Rate: per 10 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	24.8
3	2	26.5	26.5	0.0	49.5
4	2	46.2	30.3	15.9	71.0
5	3	75.8	60.9	14.9	100.6
6	3	117.5	47.0	70.5	167.0
7	4	141.5	69.7	71.8	191.0
8	5	165.5	84.8	80.7	215.0
9	6	189.5	110.6	78.9	239.0
10	7	189.5	115.3	74.2	239.0
11	7	168.0	127.4	40.6	263.0
12	7	162.4	124.5	37.9	263.0
13	8	234.4	138.3	96.1	335.0
14	9	258.4	174.1	84.2	359.0
15	10	282.4	193.0	89.3	383.0
16	11	330.4	224.2	106.2	431.0
17	12	330.4	226.4	104.0	431.0
18	12	264.0	186.0	78.0	431.0
19	13	264.0	188.3	75.7	431.0
20	14	336.0	216.7	119.3	503.0
21	14	312.0	200.0	112.0	503.0
22	15	312.0	211.8	100.2	503.0
23	15	310.2	204.8	105.4	527.0
24	15	329.5	208.1	121.4	551.0
25	15	312.0	203.0	109.0	551.0
26	14	307.1	201.9	105.2	551.0
27	15	307.1	206.6	100.5	551.0
28	14	305.9	188.9	117.0	575.0
29	15	329.9	199.3	130.6	599.0
30	16	401.9	216.1	185.8	671.0

**Table B19. FIFO scheduling results for Sequence I: Issued at 10AM on Monday;
Job Arriving Rate: per 12 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	24.8
3	2	26.5	25.5	1.0	49.5
4	2	46.2	29.3	16.9	71.0
5	3	76.7	59.4	17.4	101.6
6	3	117.5	45.5	72.0	167.0
7	3	120.0	62.6	57.4	191.0
8	4	144.0	77.2	66.8	215.0
9	5	169.8	102.5	67.3	240.8
10	5	143.9	76.6	67.3	245.5
11	6	233.4	118.8	114.7	335.0
12	7	236.1	121.0	115.2	337.7
13	8	257.4	134.3	123.2	359.0
14	9	305.4	169.6	135.8	407.0
15	9	264.0	177.8	86.2	431.0
16	10	336.0	208.4	127.6	503.0
17	10	314.2	187.9	126.3	505.2
18	11	316.5	189.6	126.8	507.5
19	11	294.8	176.9	118.0	509.8
20	12	336.0	204.7	131.3	551.0
21	13	342.1	210.3	131.8	557.1
22	12	329.5	192.1	137.4	575.0
23	13	353.5	210.4	143.1	599.0
24	14	425.5	217.9	207.6	671.0
25	15	431.2	223.0	208.1	676.6
26	16	449.5	226.3	223.2	695.0
27	17	454.2	230.6	223.7	699.7
28	18	473.5	237.4	236.1	719.0
29	18	408.0	205.1	202.9	743.0
30	18	429.3	219.2	210.1	767.0

Table B20. RP scheduling results for Sequence I: Issued at 10AM on Monday; Job Arriving Rate: per 12 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	24.8
3	2	26.5	26.5	0.0	49.5
4	2	46.2	30.3	15.9	71.0
5	3	75.8	60.9	14.9	100.6
6	3	117.5	47.0	70.5	167.0
7	4	141.5	69.7	71.8	191.0
8	5	165.5	84.8	80.7	215.0
9	5	144.0	80.0	64.0	239.0
10	5	138.4	79.1	59.2	239.0
11	6	234.4	121.8	112.6	335.0
12	7	234.4	124.5	109.9	335.0
13	8	234.4	138.3	96.1	335.0
14	9	282.4	174.1	108.2	383.0
15	9	240.0	182.3	57.7	407.0
16	10	336.0	213.4	122.6	503.0
17	10	312.0	192.9	119.1	503.0
18	11	312.0	195.1	116.9	503.0
19	12	312.0	197.5	114.5	503.0
20	11	281.5	195.3	86.2	503.0
21	11	264.0	186.3	77.7	503.0
22	11	285.3	195.4	89.9	527.0
23	11	288.0	200.4	87.6	551.0
24	9	305.2	201.5	103.6	575.0
25	10	305.2	207.2	98.0	575.0
26	11	305.2	211.0	94.2	575.0
27	12	305.2	215.8	89.4	575.0
28	13	329.2	223.1	106.1	599.0
29	13	336.0	190.8	145.2	671.0
30	14	360.0	207.6	152.4	695.0

**Table B21. FIFO scheduling results for Sequence I: Issued at 10AM on Monday;
Job Arriving Rate: per 16 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	24.8
3	1	24.7	24.1	0.5	71.7
4	2	30.3	29.3	1.0	77.3
5	3	120.0	59.4	60.6	167.0
6	2	113.7	40.3	73.4	191.0
7	3	137.7	62.6	75.2	215.0
8	4	161.7	77.2	84.5	239.0
9	5	187.5	102.5	85.0	264.8
10	6	192.2	106.7	85.5	269.5
11	7	257.7	148.8	108.9	335.0
12	7	170.7	121.0	49.7	337.7
13	7	168.0	124.0	44.0	359.0
14	8	216.0	159.4	56.6	407.0
15	8	216.0	155.5	60.5	431.0
16	8	264.0	171.5	92.5	503.0
17	9	266.2	173.2	93.0	505.2
18	8	238.0	145.5	92.5	507.5
19	9	240.3	147.4	93.0	509.8
20	10	281.5	175.2	106.3	551.0
21	11	287.6	180.8	106.8	557.1
22	11	240.0	149.9	90.1	575.0
23	11	261.3	166.0	95.3	599.0
24	11	312.0	160.2	151.8	671.0
25	12	317.6	165.4	152.3	676.6
26	13	336.0	168.7	167.3	695.0
27	13	292.7	137.6	155.2	699.7
28	13	288.0	126.0	162.0	719.0
29	14	312.0	135.9	176.1	743.0
30	15	336.0	152.2	183.8	767.0

Table B22. RP scheduling results for Sequence I: Issued at 10AM on Monday; Job Arriving Rate: per 16 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	24.8
3	1	24.6	24.6	0.0	71.7
4	2	30.3	30.3	0.0	77.3
5	3	120.0	60.9	59.1	167.0
6	2	113.7	41.3	72.4	191.0
7	3	137.7	64.1	73.7	215.0
8	4	161.7	79.2	82.5	239.0
9	5	185.7	105.0	80.7	263.0
10	6	185.7	109.7	76.0	263.0
11	7	257.7	152.3	105.4	335.0
12	7	168.0	124.5	43.5	335.0
13	7	168.0	127.5	40.5	359.0
14	8	216.0	163.4	52.6	407.0
15	8	216.0	159.5	56.5	431.0
16	9	288.0	190.7	97.3	503.0
17	8	257.5	162.4	95.1	503.0
18	7	237.3	146.8	90.5	503.0
19	8	237.3	149.2	88.1	503.0
20	9	261.3	177.5	83.8	527.0
21	10	261.3	183.6	77.7	527.0
22	10	216.0	152.7	63.3	551.0
23	11	240.0	171.5	68.5	575.0
24	10	237.8	163.5	74.3	599.0
25	11	237.8	169.1	68.6	599.0
26	11	209.4	144.6	64.8	599.0
27	12	209.4	149.4	60.1	599.0
28	12	240.0	120.8	119.2	671.0
29	12	257.9	125.1	132.8	695.0
30	13	281.9	141.9	140.0	719.0

**Table B23. FIFO scheduling results for Sequence I: Issued at 10AM on Monday;
Job Arriving Rate: per 20 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	24.8
3	1	24.7	24.1	0.5	71.7
4	2	30.3	29.3	1.0	77.3
5	1	72.0	30.1	41.9	167.0
6	2	96.0	40.3	55.7	191.0
7	3	120.0	62.6	57.4	215.0
8	4	144.0	77.2	66.8	239.0
9	5	169.8	102.5	67.3	264.8
10	5	102.5	76.6	25.9	269.5
11	5	144.0	108.5	35.5	335.0
12	5	122.7	88.5	34.2	337.7
13	5	120.0	87.2	32.8	359.0
14	6	168.0	122.5	45.5	407.0
15	5	161.5	111.4	50.1	431.0
16	6	233.5	142.1	91.5	503.0
17	7	235.7	143.8	92.0	505.2
18	6	169.8	101.2	68.6	507.5
19	6	150.8	89.7	61.1	509.8
20	7	192.0	117.6	74.4	551.0
21	8	198.1	123.2	74.9	557.1
22	8	168.0	99.1	68.9	575.0
23	8	168.0	99.0	69.0	599.0
24	9	240.0	106.5	133.5	671.0
25	10	245.6	111.6	134.0	676.6
26	11	264.0	114.9	149.1	695.0
27	8	189.9	83.2	106.7	699.7
28	9	209.2	90.1	119.1	719.0
29	8	185.9	66.5	119.4	743.0
30	8	192.0	71.5	120.5	767.0

Table B24. RP scheduling results for Sequence I: Issued at 10AM on Monday; Job Arriving Rate: per 20 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	24.8
3	1	24.6	24.6	0.0	71.7
4	2	30.3	30.3	0.0	77.3
5	1	72.0	30.6	41.4	167.0
6	2	96.0	41.3	54.7	191.0
7	3	120.0	64.1	55.9	215.0
8	4	144.0	79.2	64.8	239.0
9	5	168.0	105.0	63.0	263.0
10	5	96.0	79.1	16.9	263.0
11	5	144.0	111.0	33.0	335.0
12	5	120.0	91.0	29.0	335.0
13	6	144.0	104.8	39.2	359.0
14	5	161.5	110.1	51.4	407.0
15	4	165.3	111.2	54.1	431.0
16	5	237.3	142.3	95.0	503.0
17	6	237.3	144.6	92.7	503.0
18	6	168.0	104.1	63.9	503.0
19	6	144.0	92.7	51.3	503.0
20	7	168.0	121.1	46.9	527.0
21	8	174.1	127.2	46.9	533.1
22	7	141.8	100.9	40.9	551.0
23	7	137.4	91.3	46.1	575.0
24	8	161.4	99.3	62.1	599.0
25	9	161.4	104.9	56.5	599.0
26	10	161.4	108.8	52.7	599.0
27	8	95.4	77.8	17.6	603.0
28	7	137.9	60.1	77.8	671.0
29	6	138.3	53.1	85.3	695.0
30	6	143.6	51.1	92.5	719.0

**Table B25. FIFO scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 10 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	23.0	7.0	16.0	23.0
2	2	47.0	25.5	21.5	47.0
3	3	71.0	45.1	25.9	71.0
4	3	72.0	54.5	17.5	95.0
5	4	144.0	71.8	72.2	167.0
6	4	144.0	70.0	74.0	191.0
7	5	168.0	85.0	83.0	215.0
8	6	192.0	98.5	93.5	239.0
9	6	169.6	80.0	89.6	240.6
10	7	192.0	99.1	92.9	263.0
11	7	240.0	94.5	145.5	335.0
12	8	264.0	105.1	158.9	359.0
13	9	268.0	107.8	160.2	363.0
14	10	288.0	117.6	170.4	383.0
15	11	312.0	136.0	176.0	407.0
16	12	336.0	155.1	180.9	431.0
17	13	340.0	157.8	182.2	435.0
18	13	336.0	154.2	181.8	503.0
19	14	360.0	161.7	198.3	527.0
20	15	384.0	168.7	215.3	551.0
21	15	384.0	168.0	216.0	575.0
22	16	386.1	169.6	216.5	577.1
23	16	364.0	156.1	208.0	579.0
24	17	366.1	157.6	208.5	581.1
25	17	360.0	159.8	200.2	599.0
26	17	363.9	163.7	200.2	604.5
27	18	430.4	169.8	260.6	671.0
28	18	432.0	168.0	264.0	695.0
29	19	456.0	186.5	269.5	719.0
30	20	480.0	200.2	279.8	743.0

**Table B26. RP scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 10 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	23.0	7.5	15.5	23.0
2	2	47.0	26.5	20.5	47.0
3	3	71.0	46.6	24.4	71.0
4	3	72.0	56.0	16.0	95.0
5	4	144.0	73.8	70.2	167.0
6	4	144.0	72.0	72.0	191.0
7	5	168.0	87.5	80.5	215.0
8	6	192.0	101.5	90.5	239.0
9	6	168.0	83.0	85.0	239.0
10	7	192.0	102.6	89.4	263.0
11	7	240.0	98.0	142.0	335.0
12	8	264.0	109.1	154.9	359.0
13	9	264.0	112.3	151.7	359.0
14	10	288.0	122.6	165.4	383.0
15	11	312.0	141.5	170.5	407.0
16	12	336.0	161.1	174.9	431.0
17	13	336.0	164.3	171.7	431.0
18	13	336.0	160.7	175.3	503.0
19	14	360.0	168.7	191.3	527.0
20	15	384.0	176.2	207.8	551.0
21	15	384.0	175.5	208.5	575.0
22	16	384.0	177.6	206.4	575.0
23	15	358.4	162.4	195.9	575.0
24	16	358.4	164.5	193.9	575.0
25	16	360.0	166.6	193.4	599.0
26	17	360.0	172.2	187.8	599.0
27	18	360.0	178.8	181.2	599.0
28	17	404.0	173.8	230.2	671.0
29	18	428.0	192.8	235.2	695.0

**Table B27. FIFO scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 12 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	23.0	7.0	16.0	23.0
2	2	47.0	25.5	21.5	47.0
3	2	48.0	38.1	9.9	71.0
4	3	72.0	54.5	17.5	95.0
5	3	120.0	53.3	66.7	167.0
6	4	144.0	70.0	74.0	191.0
7	4	144.0	65.4	78.6	215.0
8	5	168.0	78.9	89.1	239.0
9	5	145.6	63.6	82.0	240.6
10	6	168.0	82.6	85.4	263.0
11	7	240.0	94.5	145.5	335.0
12	8	264.0	105.1	158.9	359.0
13	9	268.0	107.8	160.2	363.0
14	10	288.0	117.6	170.4	383.0
15	10	240.0	118.7	121.3	407.0
16	11	264.0	137.8	126.2	431.0
17	11	244.0	123.8	120.2	435.0
18	12	312.0	137.6	174.4	503.0
19	12	312.0	130.0	182.0	527.0
20	13	336.0	137.1	198.9	551.0
21	13	336.0	139.5	196.5	575.0
22	13	336.5	140.0	196.5	577.1
23	13	316.0	122.4	193.6	579.0
24	14	318.1	123.9	194.1	581.1
25	15	336.0	139.6	196.4	599.0
26	16	341.5	144.6	196.9	604.5
27	17	408.0	150.7	257.3	671.0
28	18	432.0	168.0	264.0	695.0
29	18	384.0	174.7	209.3	719.0
30	19	408.0	188.4	219.6	743.0

**Table B28. RP scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 12 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	23.0	7.5	15.5	23.0
2	2	47.0	26.5	20.5	47.0
3	2	48.0	39.1	8.9	71.0
4	3	72.0	56.0	16.0	95.0
5	3	120.0	54.8	65.2	167.0
6	4	144.0	72.0	72.0	191.0
7	4	144.0	67.4	76.6	215.0
8	5	168.0	81.4	86.6	239.0
9	5	144.0	66.1	77.9	239.0
10	6	168.0	85.7	82.3	263.0
11	7	240.0	98.0	142.0	335.0
12	8	264.0	109.1	154.9	359.0
13	9	264.0	112.3	151.7	359.0
14	10	288.0	122.6	165.4	383.0
15	10	240.0	123.7	116.3	407.0
16	11	264.0	143.3	120.7	431.0
17	11	240.0	129.3	110.7	431.0
18	12	312.0	143.6	168.4	503.0
19	12	312.0	136.0	176.0	527.0
20	12	334.4	141.9	192.4	551.0
21	12	336.0	144.4	191.6	575.0
22	13	336.0	146.5	189.5	575.0
23	13	312.0	128.9	183.1	575.0
24	14	312.0	130.9	181.1	575.0
25	15	336.0	147.1	188.9	599.0
26	16	336.0	152.6	183.4	599.0
27	17	336.0	159.2	176.8	599.0
28	18	408.0	177.0	231.0	671.0
29	18	360.0	183.7	176.3	695.0
30	18	380.0	194.7	185.3	719.0

**Table B29. FIFO scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 16 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	23.0	7.0	16.0	23.0
2	2	47.0	25.5	21.5	47.0
3	2	48.0	38.1	9.9	71.0
4	2	48.0	36.0	12.0	95.0
5	3	120.0	53.3	66.7	167.0
6	3	120.0	50.4	69.6	191.0
7	3	120.0	49.0	71.0	215.0
8	4	144.0	62.4	81.6	239.0
9	5	145.6	63.6	82.0	240.6
10	6	168.0	82.6	85.4	263.0
11	7	240.0	94.5	145.5	335.0
12	7	192.0	87.8	104.2	359.0
13	7	172.0	73.8	98.2	363.0
14	8	192.0	83.6	108.4	383.0
15	8	192.0	87.0	105.0	407.0
16	8	192.0	92.7	99.3	431.0
17	8	194.4	94.2	100.2	435.0
18	8	240.0	88.9	151.1	503.0
19	9	264.0	96.3	167.7	527.0
20	10	288.0	103.4	184.6	551.0
21	11	312.0	119.3	192.7	575.0
22	11	242.1	109.2	133.0	577.1
23	12	244.0	110.6	133.5	579.0
24	11	218.1	98.8	119.3	581.1
25	11	216.0	104.6	111.4	599.0
26	12	221.5	109.6	111.9	604.5
27	12	264.0	97.4	166.6	671.0
28	12	264.0	95.5	168.5	695.0
29	12	284.0	111.4	172.6	719.0
30	13	308.0	125.1	182.9	743.0

**Table B30. RP scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 16 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	23.0	7.5	15.5	23.0
2	2	47.0	26.5	20.5	47.0
3	2	48.0	39.1	8.9	71.0
4	2	48.0	37.0	11.0	95.0
5	3	120.0	54.8	65.2	167.0
6	3	120.0	51.9	68.1	191.0
7	3	120.0	50.5	69.5	215.0
8	4	144.0	64.5	79.5	239.0
9	5	144.0	66.1	77.9	239.0
10	6	168.0	85.7	82.3	263.0
11	7	240.0	98.0	142.0	335.0
12	7	192.0	91.3	100.7	359.0
13	7	168.0	77.3	90.7	359.0
14	8	192.0	87.6	104.4	383.0
15	7	190.4	89.4	101.0	407.0
16	7	192.0	95.0	97.0	431.0
17	8	192.0	98.2	93.8	431.0
18	8	240.0	92.9	147.1	503.0
19	9	264.0	100.8	163.2	527.0
20	10	288.0	108.4	179.6	551.0
21	11	312.0	124.8	187.2	575.0
22	11	240.0	114.7	125.3	575.0
23	11	236.0	113.4	122.6	575.0
24	11	216.0	104.3	111.7	575.0
25	11	216.0	110.1	105.9	599.0
26	12	216.0	115.6	100.4	599.0
27	11	188.0	100.2	87.8	599.0
28	11	240.0	98.3	141.7	671.0
29	12	264.0	117.4	146.6	695.0
30	13	288.0	131.6	156.4	719.0

**Table B31. FIFO scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 20 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	23.0	7.0	16.0	23.0
2	2	47.0	25.5	21.5	47.0
3	2	48.0	38.1	9.9	71.0
4	2	48.0	36.0	12.0	95.0
5	2	96.0	33.7	62.3	167.0
6	2	96.0	34.0	62.0	191.0
7	3	120.0	49.0	71.0	215.0
8	4	144.0	62.4	81.6	239.0
9	5	145.6	63.6	82.0	240.6
10	5	96.0	65.4	30.6	263.0
11	5	144.0	60.5	83.5	335.0
12	5	144.0	56.1	87.9	359.0
13	5	124.0	45.3	78.7	363.0
14	5	142.4	54.0	88.4	383.0
15	5	144.0	53.3	90.7	407.0
16	6	168.0	72.5	95.5	431.0
17	7	172.0	75.1	96.9	435.0
18	7	168.0	77.1	90.9	503.0
19	7	168.0	73.9	94.1	527.0
20	7	188.0	78.2	109.8	551.0
21	7	192.0	84.4	107.6	575.0
22	7	170.1	67.6	102.5	577.1
23	6	144.0	47.2	96.8	579.0
24	7	146.1	48.8	97.3	581.1
25	8	164.0	64.4	99.6	599.0
26	9	169.5	69.5	100.1	604.5
27	9	168.0	61.9	106.1	671.0
28	9	168.0	71.6	96.4	695.0
29	9	168.0	83.1	84.9	719.0
30	7	164.0	77.8	86.1	743.0

**Table B32. RP scheduling results for Sequence II: Issued at 10AM on Monday;
Job Arriving Rate: per 20 hours; Operator Schedule: 9AM-12PM and 1PM-4PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	23.0	7.5	15.5	23.0
2	2	47.0	26.5	20.5	47.0
3	2	48.0	39.1	8.9	71.0
4	2	48.0	37.0	11.0	95.0
5	2	96.0	34.7	61.3	167.0
6	2	96.0	35.0	61.0	191.0
7	3	120.0	50.5	69.5	215.0
8	4	144.0	64.5	79.5	239.0
9	5	144.0	66.1	77.9	239.0
10	5	96.0	67.9	28.1	263.0
11	5	144.0	63.0	81.0	335.0
12	4	142.4	57.0	85.4	359.0
13	4	120.0	46.2	73.8	359.0
14	5	144.0	56.5	87.5	383.0
15	5	144.0	55.8	88.2	407.0
16	6	168.0	75.5	92.5	431.0
17	7	168.0	78.6	89.4	431.0
18	6	164.0	77.4	86.6	503.0
19	6	168.0	74.2	93.8	527.0
20	7	192.0	81.7	110.3	551.0
21	7	192.0	87.9	104.1	575.0
22	6	164.0	68.0	96.0	575.0
23	6	144.0	50.2	93.8	575.0
24	7	144.0	52.3	91.7	575.0
25	8	168.0	68.4	99.6	599.0
26	9	168.0	74.0	94.0	599.0
27	9	96.0	66.4	29.6	599.0
28	6	137.9	70.0	67.9	671.0
29	5	138.5	76.0	62.5	695.0
30	5	144.0	73.7	70.3	719.0

**Table B33. FIFO scheduling results for Sequence I: Issued at 10AM on Friday;
Job Arriving Rate: per 12 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	71.8
3	2	26.5	25.5	1.0	96.5
4	3	32.1	30.6	1.5	102.1
5	4	72.0	60.7	11.3	142.0
6	5	96.0	71.0	25.0	166.0
7	5	166.2	91.9	74.3	238.0
8	6	190.2	106.5	83.7	262.0
9	7	215.9	131.8	84.2	287.8
10	6	190.4	106.7	83.7	292.5
11	7	233.0	148.8	84.2	335.2
12	8	235.7	151.0	84.7	337.9
13	8	264.0	134.3	129.7	406.0
14	9	312.0	169.6	142.4	454.0
15	9	312.0	177.8	134.2	478.0
16	10	343.1	208.4	134.7	509.1
17	11	408.0	210.1	197.9	574.0
18	12	410.3	211.9	198.4	576.3
19	13	412.6	213.7	198.9	578.6
20	14	441.0	241.6	199.4	607.0
21	14	384.0	224.9	159.1	622.0
22	15	408.0	236.2	171.8	646.0
23	15	408.0	239.9	168.1	670.0
24	16	416.0	247.4	168.6	678.0
25	16	454.2	227.2	227.0	742.0
26	16	453.3	226.3	227.0	745.8
27	17	458.1	230.6	227.5	750.6
28	18	473.5	237.4	236.1	766.0
29	18	454.8	205.1	249.7	790.0
30	18	476.1	219.2	256.9	814.0

Table B34. RP scheduling results for Sequence I: Issued at 10AM on Friday; Job Arriving Rate: per 12 hours; Operator Schedule: 8AM-5PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	71.8
3	2	26.5	26.5	0.0	96.5
4	3	32.1	32.1	0.0	102.1
5	4	72.0	62.7	9.3	142.0
6	5	78.3	73.5	4.8	148.3
7	5	99.2	94.3	4.8	171.0
8	6	166.2	109.5	56.7	238.0
9	7	190.2	135.3	54.9	262.0
10	7	159.6	109.4	50.2	262.0
11	7	168.0	141.3	26.7	286.0
12	8	168.0	144.0	24.0	286.0
13	8	167.3	133.2	34.2	310.0
14	8	257.7	163.4	94.4	406.0
15	9	257.7	182.3	75.5	406.0
16	8	256.3	188.0	68.3	430.0
17	9	256.3	190.2	66.1	430.0
18	10	256.3	192.4	63.9	430.0
19	11	256.3	194.8	61.5	430.0
20	12	280.3	223.1	57.1	454.0
21	12	218.2	186.6	31.6	456.2
22	13	240.0	198.4	41.6	478.0
23	13	238.2	191.3	46.9	502.0
24	13	233.5	194.6	38.9	502.0
25	13	214.6	181.4	33.2	502.0
26	14	218.4	185.2	33.2	505.8
27	15	222.6	189.9	32.7	510.0
28	15	255.5	166.1	89.3	574.0
29	15	240.0	161.4	78.6	574.0
30	14	255.5	169.7	85.8	598.0

**Table B35. FIFO scheduling results for Sequence I: Issued at 10AM on Friday;
Job Arriving Rate: per 16 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	71.8
3	2	26.5	25.5	1.0	96.5
4	3	32.1	30.6	1.5	102.1
5	4	72.0	60.7	11.3	142.0
6	4	94.2	69.6	24.5	166.0
7	5	166.2	91.8	74.3	238.0
8	4	159.9	77.2	82.7	262.0
9	5	185.7	102.5	83.2	287.8
10	5	150.5	76.6	73.9	292.5
11	6	193.2	118.8	74.4	335.2
12	6	171.9	110.7	61.1	337.9
13	7	240.0	124.0	116.0	406.0
14	8	288.0	159.4	128.6	454.0
15	9	312.0	177.8	134.2	478.0
16	9	271.1	186.2	85.0	509.1
17	10	336.0	187.9	148.1	574.0
18	10	314.3	175.0	139.3	576.3
19	10	290.8	151.6	139.3	578.6
20	10	314.5	175.2	139.3	607.0
21	11	329.5	180.8	148.7	622.0
22	11	310.8	149.9	160.9	646.0
23	11	332.1	166.0	166.1	670.0
24	12	340.1	173.5	166.6	678.0
25	13	404.1	178.7	225.5	742.0
26	14	408.0	182.0	226.0	745.8
27	14	344.6	172.9	171.6	750.6
28	15	360.0	179.8	180.2	766.0
29	16	384.0	189.6	194.4	790.0
30	16	360.0	170.6	189.4	814.0

Table B36. RP scheduling results for Sequence I: Issued at 10AM on Friday; Job Arriving Rate: per 16 hours; Operator Schedule: 8AM-5PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	71.8
3	2	26.5	26.5	0.0	96.5
4	3	32.1	32.1	0.0	102.1
5	4	72.0	62.7	9.3	142.0
6	4	76.7	71.6	5.1	148.6
7	5	99.5	94.3	5.1	171.3
8	4	135.9	79.2	56.7	238.0
9	4	144.0	94.2	49.8	262.0
10	5	144.0	98.9	45.1	262.0
11	5	137.4	111.0	26.4	286.0
12	5	116.5	91.0	25.5	287.8
13	6	138.7	104.8	33.9	310.0
14	7	234.7	140.6	94.1	406.0
15	8	234.7	159.5	75.2	406.0
16	8	192.0	148.0	44.0	430.0
17	7	184.6	142.8	41.8	430.0
18	7	168.0	129.9	38.1	430.0
19	7	143.9	106.5	37.4	431.7
20	8	170.5	134.9	35.6	458.2
21	6	163.4	122.5	40.8	478.0
22	7	165.4	134.3	31.1	480.0
23	7	159.0	124.7	34.3	502.0
24	8	163.2	132.7	30.4	506.1
25	9	231.0	138.4	92.6	574.0
26	10	231.0	142.2	88.8	574.0
27	9	161.9	105.0	56.9	574.0
28	9	143.0	93.4	49.6	574.0
29	9	137.2	95.8	41.4	576.2
30	8	138.3	95.2	43.2	598.0

**Table B37. FIFO scheduling results for Sequence I: Issued at 10AM on Friday;
Job Arriving Rate: per 20 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.4	0.5	4.9
2	1	1.8	1.3	0.5	71.8
3	2	26.5	25.5	1.0	96.5
4	3	32.1	30.6	1.5	102.1
5	3	70.2	59.4	10.8	142.0
6	3	69.5	45.5	24.0	166.0
7	3	135.9	62.6	73.3	238.0
8	4	159.9	77.2	82.7	262.0
9	4	145.8	72.4	73.4	287.8
10	4	126.5	66.3	60.1	292.5
11	5	169.2	108.5	60.6	335.2
12	6	171.9	110.7	61.1	337.9
13	6	168.0	101.8	66.2	406.0
14	7	216.0	137.1	78.9	454.0
15	7	216.0	140.9	75.1	478.0
16	6	216.7	142.1	74.6	509.1
17	7	281.5	143.8	137.8	574.0
18	6	238.4	101.2	137.2	576.3
19	7	240.8	103.0	137.8	578.6
20	8	269.1	130.9	138.3	607.0
21	9	284.1	136.5	147.7	622.0
22	9	240.0	134.5	105.5	646.0
23	10	264.0	152.7	111.3	670.0
24	10	224.0	124.9	99.1	678.0
25	10	264.0	111.6	152.4	742.0
26	11	267.8	114.9	152.9	745.8
27	11	241.4	88.5	152.9	750.6
28	12	256.9	95.4	161.5	766.0
29	13	280.9	105.3	175.6	790.0
30	11	235.4	116.2	119.1	814.0

Table B38. RP scheduling results for Sequence I: Issued at 10AM on Friday; Job Arriving Rate: per 20 hours; Operator Schedule: 8AM-5PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	4.9	4.9	0.0	4.9
2	1	1.8	1.8	0.0	71.8
3	2	26.5	26.5	0.0	96.5
4	3	32.1	32.1	0.0	102.1
5	3	70.2	60.9	9.3	142.0
6	3	52.1	47.0	5.1	148.6
7	2	53.3	53.3	0.0	171.3
8	3	120.0	68.4	51.6	238.0
9	3	113.4	63.6	49.8	262.0
10	3	90.7	45.6	45.1	262.0
11	4	138.7	88.3	50.4	310.0
12	5	138.7	91.0	47.7	310.0
13	5	96.0	79.0	17.0	334.0
14	5	163.3	110.1	53.2	406.0
15	4	165.3	111.2	54.1	430.0
16	5	189.3	142.3	47.0	454.0
17	5	144.0	101.9	42.1	454.0
18	4	120.0	83.0	37.0	456.2
19	5	122.4	85.4	37.0	458.6
20	6	148.9	113.7	35.2	485.1
21	7	165.8	119.8	45.9	502.0
22	5	97.5	91.2	6.3	508.1
23	5	135.0	81.6	53.5	574.0
24	5	126.1	75.8	50.3	580.1
25	6	144.0	81.4	62.6	598.0
26	6	116.7	54.1	62.6	601.8
27	5	93.7	39.1	54.6	603.6
28	6	112.0	46.4	65.6	622.0
29	7	117.7	56.8	60.8	627.6
30	6	68.2	51.0	17.2	646.0

**Table B39. FIFO scheduling results for Sequence II: Issued at 10AM on Friday;
Job Arriving Rate: per 12 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	70.0	7.0	63.0	70.0
2	2	94.0	25.5	68.5	94.0
3	3	118.0	45.1	72.9	118.0
4	4	142.0	61.5	80.5	142.0
5	5	166.0	78.8	87.2	166.0
6	6	238.0	95.5	142.5	238.0
7	6	192.0	103.5	88.5	262.0
8	7	216.0	117.0	99.0	286.0
9	7	193.6	99.6	94.0	287.6
10	8	216.0	118.7	97.3	310.0
11	8	216.0	110.9	105.1	334.0
12	9	288.0	121.6	166.4	406.0
13	9	267.2	107.8	159.4	409.2
14	10	288.0	117.6	170.4	430.0
15	10	288.0	118.7	169.3	454.0
16	11	312.0	137.8	174.2	478.0
17	12	315.2	140.5	174.7	481.2
18	13	336.0	154.2	181.8	502.0
19	14	344.0	161.7	182.3	510.0
20	15	408.0	168.7	239.3	574.0
21	15	360.0	168.0	192.0	598.0
22	16	362.1	169.6	192.5	600.1
23	16	340.0	156.1	184.0	602.0
24	17	342.1	157.6	184.5	604.1
25	16	334.4	158.6	175.7	622.0
26	17	339.9	163.7	176.2	627.5
27	17	336.0	150.7	185.3	646.0
28	18	360.0	168.0	192.0	670.0
29	18	408.0	174.7	233.3	742.0
30	19	432.0	188.4	243.6	766.0

Table B40. RP scheduling results for Sequence II: Issued at 10AM on Friday; Job Arriving Rate: per 12 hours; Operator Schedule: 8AM-5PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	70.0	7.5	62.5	70.0
2	2	94.0	26.5	67.5	94.0
3	3	118.0	46.6	71.4	118.0
4	4	142.0	63.5	78.5	142.0
5	5	166.0	81.3	84.7	166.0
6	6	238.0	98.5	139.5	238.0
7	6	192.0	106.5	85.5	262.0
8	7	216.0	120.5	95.5	286.0
9	7	192.0	103.1	88.9	286.0
10	8	216.0	122.7	93.3	310.0
11	8	216.0	114.9	101.1	334.0
12	9	288.0	126.1	161.9	406.0
13	9	264.0	112.3	151.7	406.0
14	10	288.0	122.6	165.4	430.0
15	10	288.0	123.7	164.3	454.0
16	11	312.0	143.3	168.7	478.0
17	12	312.0	146.5	165.5	478.0
18	13	336.0	160.7	175.3	502.0
19	14	336.0	168.7	167.3	502.0
20	15	336.0	176.2	159.8	502.0
21	15	336.0	175.5	160.5	574.0
22	16	336.0	177.6	158.4	574.0
23	15	310.4	162.4	147.9	574.0
24	16	310.4	164.5	145.9	574.0
25	16	312.0	166.6	145.4	598.0
26	17	312.0	172.2	139.8	598.0
27	17	288.0	159.2	128.8	598.0
28	15	303.5	168.5	135.0	622.0
29	15	312.0	175.2	136.8	646.0
30	15	328.0	181.5	146.6	670.0

**Table B41. FIFO scheduling results for Sequence II: Issued at 10AM on Friday;
Job Arriving Rate: per 16 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	70.0	7.0	63.0	70.0
2	2	94.0	25.5	68.5	94.0
3	3	118.0	45.1	72.9	118.0
4	4	142.0	61.5	80.5	142.0
5	5	166.0	78.8	87.2	166.0
6	5	168.0	88.5	79.5	238.0
7	5	168.0	85.0	83.0	262.0
8	6	192.0	98.5	93.5	286.0
9	6	169.6	80.0	89.6	287.6
10	6	168.0	82.6	85.4	310.0
11	7	192.0	94.5	97.5	334.0
12	7	240.0	87.8	152.2	406.0
13	8	243.2	90.5	152.7	409.2
14	9	264.0	100.3	163.7	430.0
15	10	288.0	118.7	169.3	454.0
16	10	240.0	121.1	118.9	478.0
17	11	243.2	123.8	119.4	481.2
18	11	240.0	122.6	117.4	502.0
19	10	222.3	115.4	106.9	510.0
20	11	286.4	122.4	163.9	574.0
21	11	288.0	119.3	168.7	598.0
22	11	266.1	109.2	157.0	600.1
23	12	268.0	110.6	157.5	602.0
24	13	270.1	112.1	158.0	604.1
25	14	288.0	127.8	160.2	622.0
26	15	293.5	132.8	160.7	627.5
27	14	236.8	125.6	111.2	646.0
28	14	240.0	133.0	107.0	670.0
29	15	312.0	151.6	160.4	742.0
30	15	312.0	146.9	165.1	766.0

Table B42. RP scheduling results for Sequence II: Issued at 10AM on Friday; Job Arriving Rate: per 16 hours; Operator Schedule: 8AM-5PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	70.0	7.5	62.5	70.0
2	2	94.0	26.5	67.5	94.0
3	3	118.0	46.6	71.4	118.0
4	4	142.0	63.5	78.5	142.0
5	5	166.0	81.3	84.7	166.0
6	5	168.0	91.0	77.0	238.0
7	5	168.0	87.5	80.5	262.0
8	6	192.0	101.5	90.5	286.0
9	6	168.0	83.0	85.0	286.0
10	6	168.0	85.7	82.3	310.0
11	7	192.0	98.0	94.0	334.0
12	7	240.0	91.3	148.7	406.0
13	8	240.0	94.5	145.5	406.0
14	9	264.0	104.8	159.2	430.0
15	10	288.0	123.7	164.3	454.0
16	10	240.0	126.1	113.9	478.0
17	11	240.0	129.3	110.7	478.0
18	10	238.4	126.4	111.9	502.0
19	10	216.0	120.4	95.6	502.0
20	11	216.0	127.9	88.1	502.0
21	11	264.0	124.8	139.2	574.0
22	11	240.0	114.7	125.3	574.0
23	11	236.8	113.4	123.4	574.0
24	12	236.8	115.5	121.4	574.0
25	13	260.8	131.6	129.2	598.0
26	14	260.8	137.1	123.7	598.0
27	12	186.7	119.6	67.1	598.0
28	12	191.1	117.7	73.4	622.0
29	12	207.1	128.7	78.4	646.0
30	11	208.5	124.3	84.2	670.0

**Table B43. FIFO scheduling results for Sequence II: Issued at 10AM on Friday;
Job Arriving Rate: per 20 hours; Operator Schedule: 8AM-5PM.**

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	70.0	7.0	63.0	70.0
2	2	94.0	25.5	68.5	94.0
3	3	118.0	45.1	72.9	118.0
4	4	142.0	61.5	80.5	142.0
5	4	96.0	71.8	24.2	166.0
6	4	144.0	70.0	74.0	238.0
7	4	144.0	65.4	78.6	262.0
8	5	168.0	78.9	89.1	286.0
9	5	145.6	63.6	82.0	287.6
10	5	144.0	65.4	78.6	310.0
11	6	168.0	77.2	90.8	334.0
12	7	240.0	87.8	152.2	406.0
13	7	171.2	73.8	97.4	409.2
14	8	192.0	83.6	108.4	430.0
15	8	192.0	87.0	105.0	454.0
16	7	190.4	91.5	98.8	478.0
17	7	171.2	75.1	96.0	481.2
18	7	168.0	77.1	90.9	502.0
19	8	176.0	84.5	91.4	510.0
20	9	240.0	91.6	148.4	574.0
21	10	264.0	107.5	156.5	598.0
22	9	191.0	95.8	95.1	600.1
23	9	172.0	87.4	84.6	602.0
24	9	150.1	70.6	79.5	604.1
25	9	144.0	67.1	76.9	622.0
26	9	146.3	69.5	76.9	627.5
27	8	136.0	54.4	81.6	646.0
28	9	160.0	71.6	88.4	670.0
29	10	232.0	90.2	141.9	742.0
30	10	192.0	96.9	95.1	766.0

Table B44. RP scheduling results for Sequence II: Issued at 10AM on Friday; Job Arriving Rate: per 20 hours; Operator Schedule: 8AM-5PM.

Jobs Submitted	Queue Size	Queue Make Span (hours)	Machine Run Time (hours)	Machine Idle Time (hours)	Total Completion Time for Jobs Submitted thus far (hours)
1	1	70.0	7.5	62.5	70.0
2	2	94.0	26.5	67.5	94.0
3	3	118.0	46.6	71.4	118.0
4	4	142.0	63.5	78.5	142.0
5	4	96.0	73.8	22.2	166.0
6	4	144.0	72.0	72.0	238.0
7	4	144.0	67.4	76.6	262.0
8	5	168.0	81.4	86.6	286.0
9	5	144.0	66.1	77.9	286.0
10	5	144.0	67.9	76.1	310.0
11	6	168.0	80.2	87.8	334.0
12	7	240.0	91.3	148.7	406.0
13	7	168.0	77.3	90.7	406.0
14	8	192.0	87.6	104.4	430.0
15	7	190.4	89.4	101.0	454.0
16	7	192.0	95.0	97.0	478.0
17	7	168.0	78.6	89.4	478.0
18	6	164.8	77.4	87.4	502.0
19	7	164.8	85.4	79.5	502.0
20	8	164.8	92.9	71.9	502.0
21	9	236.8	109.4	127.5	574.0
22	9	168.0	100.3	67.7	574.0
23	8	140.8	80.2	60.6	574.0
24	8	120.0	62.6	57.4	574.0
25	7	120.0	60.5	59.5	598.0
26	7	112.5	58.5	54.0	598.0
27	4	95.4	44.8	50.7	603.5
28	5	113.9	62.5	51.4	622.0
29	6	137.9	81.5	56.4	646.0
30	6	96.0	79.3	16.7	670.0

VITA

Yingxiang Wu was born on December 2, 1972 in Beijing, China. He spent his childhood in a small town in the most northwest of China, but grew up in a much warmer place in the south. In 1993, he received a Bachelor's degree in Mechanical Engineering from Beijing University of Posts and Telecommunications, and began to work for a machine tool factory. He came to Virginia Tech because of its reputation in engineering and the beautiful scenes around the Blue Ridge Mountain. He plans to continue his study in Computer Engineering after completing the M.S. program in Mechanical Engineering.