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AN EVALUATION OF PROJECT SCHEDULING
TECHNIQUES IN A DYNAMIC ENVIRONMENT

THESIS

James D. Martin
Captain, USAF

AFIT/GSM/LSY/87-19

DEPARTMENT OF THE AIR FORCE

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AN EVALUATION OF PROJECT SCHEDULING

TECHNIQUES IN A DYNAMIC ENVIRONMENT

THESIS

Presented to the Faculty of the

School of Systems and Logistics

of the Air Force Institute of Technology

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Systems Management

James O. Martin, B.S.

Captain, USAF

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Preface

The purpose of this study was to investigate the sensitivity of differences in project arrival distributions on the performance of due date assignment rules and scheduling heuristics previously investigated by others. The experiment was accomplished by a computer simulation of the dynamic, multi-project, multiple constrained resources project scheduling environment.

In performing the simulation experiment and writing this thesis I have had a great deal of help from others. I am deeply indebted to my thesis advisor, Lt Col John Dumond, for accepting the responsibility of guiding me through this thesis. His continuing patience and assistance helped considerably in the successful completion of this research effort.

I wish to thank my wife, Barbara for her support and encouragement during these last 15 months. I have promised not to take such an academic adventure again until I have returned the favor by supporting her in the completion of her undergraduate degree.

Finally, I wish to thank my son, James, and my daughter, Christina, for their patience and understanding while I spent a large portion of my time studying and working on this thesis. I have promised to take them camping and fishing and this time there will be no homework.

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Abstract

This research addresses the issue of what impact
differences in project arrival distribution may have on
procedures for setting due dates and scheduling project
activities to meet those due dates in a dynamic, multi-
project, constrained multiple resource, environment. In
general it was found that different project arrival
distributions do affect the performance of scheduling
heuristics and due date setting rules in an absolute sense,
but not in a relative sense. Because of this, the project
manager does not really need to be concerned about the
arrival distribution of new projects because the relative
performance of the tested heuristics and due date assignment
rules is the same.

The best results are obtained when the Scheduled Finish
Time (SFT) due date setting rule is applied. Not only does
it provide the most accurate due dates, it provides
significantly better results when used with any scheduling
heuristic than the other due date setting rules, and it is
virtually not affected at all by differences in project
arrival distribution. Every project manager probably dreams
of such a procedure being available, however there is a
price to pay for the SFT due date assignment rule. The SFT
due date setting rule requires a finite scheduling system,
the current status of all projects in the system, and a

historical data base to establish the due date compensation factor ("k" value). Not all project managers could implement this procedure due to the computer hardware/software requirements, financial constraints, project duration uncertainty, resource constraints, etc.. If they could use the SFT rule to set the due date of the arriving project, they would be wise to use the very simple First-In-First-Served (FIFS) scheduling heuristic to allocate resources to the project.

An alternative to project managers would be to choose the easier to implement CPTIME due date rule. If this is the case then the manager would want to choose one of the due date oriented heuristics to schedule the activities. The SASP[DD] and MINLFT[DD] produce similar results using the CPTIME due date rule. The CPTIME due date setting rule ignores the current project load when estimating activity completion times and therefore lacks the "self-compensating" feature of the SFT due date assignment rule.

Recall that the goals of the project manager are to first of all determine reasonable due dates for each project in order to make a promised completion date to the customer and then schedule those projects accordingly so that due dates are met on time. This research has determined that the relative performance of the tested scheduling heuristics and due date setting rules is unaffected by the project arrival distribution. For the project manager, this

confirms that certain scheduling heuristics, due date assignment rules, and combinations thereof will perform better than others regardless of the project arrival distribution. Therefore, the alternatives to management are 1) accept the decrease in performance capability for the easier to implement CPTIME due date assignment rule used with the due date oriented heuristics; or 2) make the necessary commitments and investments to implement at least one of these heuristics combined with the SFT due date assignment procedure or better yet; 3) implement the FIFS/SFT combination for assured performance.

AN EVALUATION OF PROJECT SCHEDULING
TECHNIQUES IN A DYNAMIC ENVIRONMENT

I. Introduction

Projects have been part of the human scene since
civilization started yet the practice of project management
is, on the historical timescale, almost brand new. Only in
the last couple of decades has the subject appeared to any
extent in management literature. Current budgeting and
planning methods are all relatively recent, Perhaps the
reason for emphasis on project management is that it is
concerned with the management of resources, including the
most expensive resource of all - namely the human resource.
It is no longer the case that a few thousand slaves can be
deployed to build some architectural extravagance regardless
of their welfare and safety. Almost everything now depends
on time and cost constraints. Moreover, there is
competition. If one contractor fails to meet its obligations
or targets, no doubt twenty others will be ready to jump in
to take its place when the next job comes up. Management
has been described as "getting results through people".
Amend that definition to "achieving successful project
completion with the resources available" and you have
a succinct definition of project management, the

resources being time, money, materials and equipment, and people (12:3).

General Issue

Efficient project management requires more than good planning. It requires that relevant information be obtained, analyzed, and reviewed in a timely manner. This can provide early warning of pending problems and impacts on related project activities thereby providing the opportunity for alternate plans and management actions. Today, project managers have access to a vast array of software packages to assist them in the difficult task of planning, tracking, and controlling projects. Many of the more sophisticated project scheduling software packages that previously required mainframe computer support are now available for microcomputers.

Most, if not all, academic and commercial software designed for project scheduling solve only the static, unconstrained resource, project scheduling problem. The static scenario consists of scheduling a set of known activities, such that each activity begins only after its preceding activity is completed. Resources to accomplish each task are unconstrained. The problem of interest to most project managers, in this scenario, is sequencing the activities to minimize the project's duration (using critical path methodology). However, resources in reality

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are constrained which may cause concurrent activities to be
delayed and cause an increase in project duration.

The static, multi-project, constrained resources
problem is characterized as having many projects present,
each having the same starting point but having different
stopping times for the different projects. As an example,
a construction company planning to build several buildings
at the same time is faced with the static, multi-project,
constrained resources problem. The solution to this
particular type of scheduling problem is a schedule which
allocates the limited resources to the activities of the
multiple projects so as to minimize the individual project
completion times (5:6).

A much more challenging class of project scheduling
problems confronting today's managers consists of multiple
projects that arrive indefinitely over time with a given
level of resources available to the project manager. In
this dynamic environment the project manager must estimate a
project completion date (due date) for each project as it
arrives and then take scheduling actions to meet this date.
This task is relatively simple in the static, multiple
project environment with unlimited resources and the
technique used to ensure the due dates are met in the
minimum amount of time is most likely a critical path
methodology. However, the task of meeting due dates and/or
minimizing project completion times becomes much more

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complex in the dynamic, multiple project with constrained resources environment.

Many organizations face the problem of managing multiple projects requiring multiple resources. One common planning factor they all face is deciding a completion date (due date) for each individual project that is attainable and can be promised to a customer, recognizing new projects will arrive in the future which will add to the existing set of projects and compete with the organization's limited resources. Each organization has some historical basis for estimating completion times of familiar projects and therefore develops a technique for estimating project due dates. Once the due date is established, activity control decisions (scheduling) need to be made on the assignment of resources to minimize deviations from the promised due date (6:4).

Research in this area of project scheduling has not been pursued as extensively as the static, multiple project scheduling problem. Some techniques have been developed for scheduling multiple projects in a dynamic arrival environment where the resources are limited. Various due date setting rules are available and scheduling heuristics are used in meeting due dates. A computer simulation model has been developed to evaluate the effectiveness of techniques for scheduling multiple projects in a dynamic, multi-project, constrained resources environment (5).

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Background

Planning, scheduling, and control are three of
the most important functions of management and project
managers strive for techniques to accomplish these
functions more effectively, especially when a complex set of
activities, functions, and relationships is involved.
Networking models have proven to be extremely useful in the
static project environment for the purpose of tracking the
performance of large and complex projects.

Two networking tools that have been used frequently
by managers are: 1) the Program Evaluation and Review
Technique (PERT); and 2) the Critical Path Method (CPM).
PERT/CPM was designed to eliminate or reduce production
delays, conflicts, and interruptions in order to coordinate
and control the various activities within a given project
and to assure completion of the project on the scheduled
date. Many projects are complex and consist of many highly
interrelated activities and events which make coordination
and control of the entire project difficult. Today, project
managers have access to a large array of PERT/CPM software
packages to help in the difficult task of tracking and
controlling projects (11:89).

Origin of Pert (8:7). PERT was developed in 1958
by the U.S. Navy for the Polaris missile program. The
Polaris program had over 60,000 definable activities which
had to be accomplished by over 3800 contractors, suppliers,

and government agencies. A project of this magnitude and complexity had never been attempted before, making it very difficult to predict completion times of critical tasks or track the progress of the overall project. Therefore, PERT was specifically designed to handle uncertainties in activity duration times. PERT requires three estimates of the duration for each activity (optimistic, most likely, and the pessimistic). By the use of a Beta distribution function, these three estimates are refined to one expected time and its variance.

Origin of CPM (8:8-9). CPM was developed in 1957 primarily by DuPont Corporation and Remington Rand. The chemical industry was interested in being able to provide time and cost trade-offs in building, overhauling, and maintaining chemical plants. If there are unlimited resources, the longest direct route through the project network is the critical path. The minimum time required to complete the project is the sum of the durations of all the activities along the critical path. Any delay in these critical activities will delay the final project completion date. The program manager's task is to ensure that the resources required for the critical activities are available on a timely basis and that the project is completed in its critical path time. Proper control and direction of the activities comprising the critical path give managers innight to the time and costs involved in a project of any

size. The CPM technique makes an assumption that activity
duration times are deterministic (single time estimate for
each activity). It offers the option of increasing
resources, usually at increased costs, to decrease certain
activity times. The distinguishing feature between PERT and
CPM is that CPM provides time and cost trade-offs for
activities within the project.

Network Applications (8:11-13). In both the PERT
and CPM models the basic procedure consists of five steps:
1) analyze and break down the project in terms of specific
activities and/or events; 2) determine the interrelation-
ships and sequence of activities and produce a network; 3)
assign estimates of time, costs, or both to all activities
of the network; 4) identify the longest or critical path
through the network; and 5) monitor, evaluate, and control
the progress of the project by replanning, rescheduling and
reassignment of resources. The primary task is to
determine the critical path through the network (minimum
project duration time). If the project must be completed in
less time than the critical path, those activities along the
critical path must be re-analyzed in terms of what resources
must be dedicated to expedite one or more activities along
the critical path. Non-critical paths are more flexible in
scheduling and distribution of resources, because they take
less time to complete than the critical path. The
networking process signals the project manager when the

critical path of the project is placed in jeopardy. The manager must then take the appropriate actions in order to compensate for any delays.

PERT and CPM can be used for many types of projects, but the emphasis of these models is on the static project environment (single or multiple one-time projects).

Resource Constraints in Static Project Scheduling (13:191-213). Resource availabilities are not considered in the basic PERT/CPM scheduling process and therefore are somewhat limited in producing a detailed project schedule. PERT/CPM procedures implicitly assume that the resources are unlimited and that only precedence relationships between activities constrain activity start/stop times. One consequence of this is that the schedules produced may not be realistic when the resources are constrained. Because of this, the basic time-only PERT/CPM forward-backward pass procedure has been called by some "a feasible procedure for nonfeasible schedules."

Resource constraints alter and complicate some of the basic principles of PERT/CPM. For example, the longest sequence of activities through any one project when resources are constrained may not be the same critical path determined by the basic time-only PERT/CPM technique. While under resource constraints many different Early Start time (ES) schedules may exist, whereas there is only one unique ES schedule in the basic time-only PEHT/CPM approach. To

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understand these differences it is necessary to see how limited resources affect schedule slack (float).

How Limited Resources Affect Schedule Slack. Figure 1 shows a simple activity network with activity times indicated beside each node. Figure 2a shows the all-ES bar chart schedule for this network, assuming that the resources are unlimited. The project duration is 18 weeks, the critical path is the activity sequence A-C-I-J-K, and activities B, D, E, F, G, and H all have positive slack.

Now assume that jobs C and G each require the same resource, say a hoist crane, but only one crane is available. Also, assume that jobs E and F require a special bulldozer, but only one is available.

The result of these simple resource constraints is that neither jobs C and G or jobs E and F can be performed at the same time as indicated previously in Figure 2a. One or the other of these activities will be given priority and each pair must be sequenced so there is no overlap (see Figure 2b).

When resources for activities C and G and E and F are constrained, the following results occur:

1. Activities G and H become critical, with slack reduced to zero.

2. Activities D, E, and F have their slack reduced considerably.
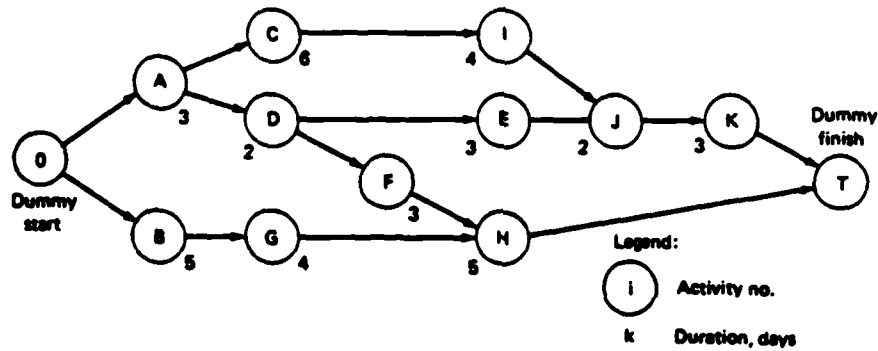
Figure 1.   Simple Activity Network (13:192)
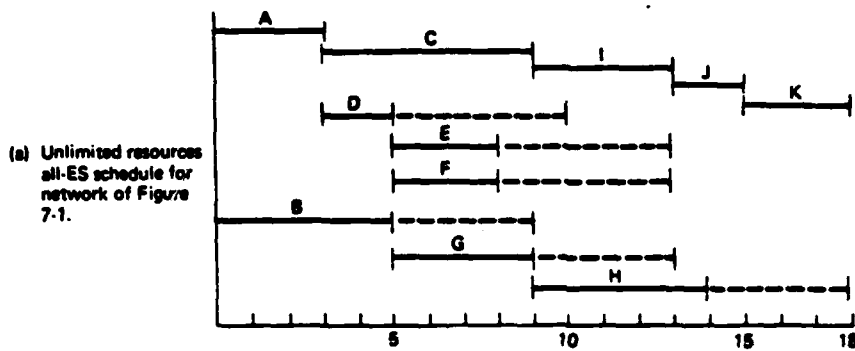
Figure 2a.   Unlimited Resources Schedule (13:193)
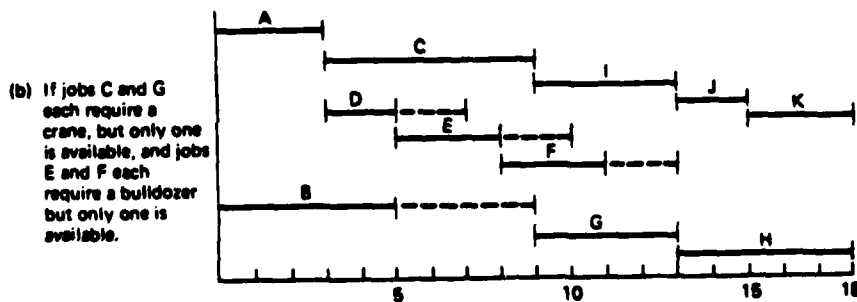
Figure 2b.   Limited Resources Schedule (13:193).

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3. With activity E arbitrarily given priority over F, the slack of jobs D and E become dependent upon job F.

4. No activity can begin earlier than shown, given the resource constraints and precedence relationships, so Figure 2b represents an early start schedule. Note that this solution is not unique because the resource priority could be changed to job F having priority over job E, resulting in another ES schedule for this resource constrained example.

The schedule slack of a project can be affected in significant ways when resources are constrained as illustrated by this simple example. In general, the following is true:

1. Resource constraints reduce total schedule slack.

2. Slack depends both on the precedence relationships and the resource constraints imposed by the project network.

3. Typically, slack times are not unique because the early and late start schedules are not unique, depending on the scheduling rules used for resolving resource conflicts.

4. The critical path in a constrained resource schedule may not be the same as that which occurs in the unlimited resources case. Since activity start times are constrained by both resource availabilities and precedence relationships, the critical path may contain different activities.

Multiple Project Scheduling. Most organizations work on several projects simultaneously. The projects may

be at different locations and may be represented by independent networks. These projects frequently require some of their resources to be drawn from a common pool. Engineers, draftpersons, equipment, etc. are some examples of shared resources within a company (12:403).

When a company is handling several projects at the same time and where the resources must be shared between projects, it is necessary to integrate the planning and control of these multiple projects. Some examples of this situation are (10:131-132):

1. A large chemical company which has several major projects occurring simultaneously, each at various phases in its life cycle and each probably with a different contractor.

2. A contractor who has several projects with different client companies.

3. A factory with a variety of small and medium sized projects, using its own resources and sometimes for large projects, using subcontractors or contractors.

Multi-project scheduling has to accommodate for resource availabilities in the common resource pool and for the resource availabilities assigned to specific projects. When several projects are being scheduled under constrained resources, one has to consider the priority of these projects (12:403).

The impact of resource constraints on scheduling in the single-project illustrated above increases significantly for scheduling multiple projects. Figure 3 shows a hypothetical three-project scheduling scenario involving just three types of resources. To simplify this example, activities requiring a resource use only one unit of any one of the three types of resources, and only one of any type is available.
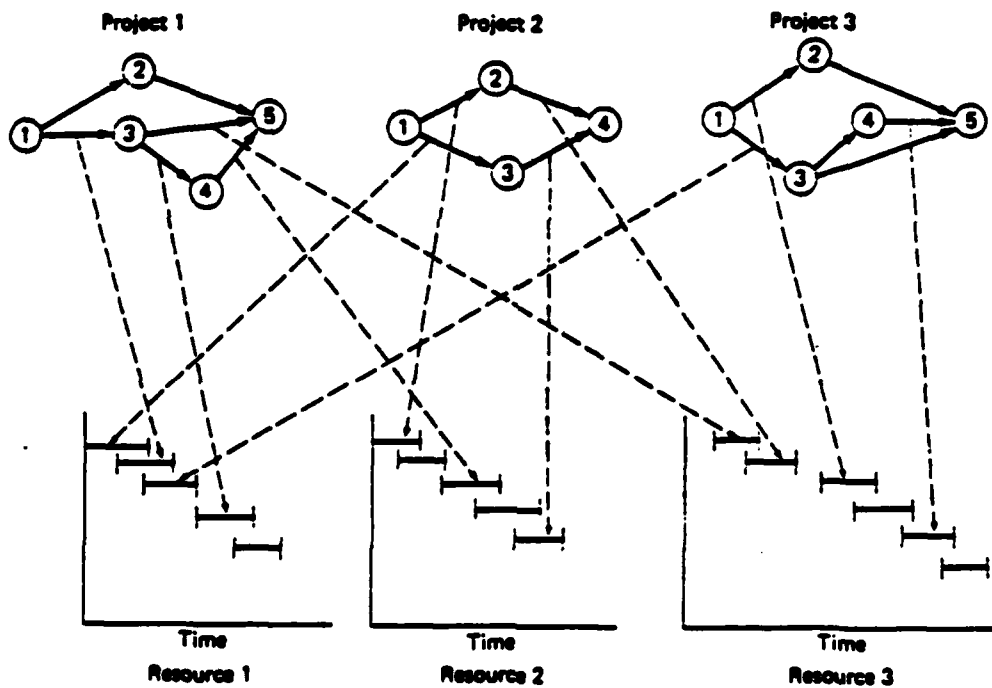
Figure 3. Multiple Project Schedule (13:195).

A domino series of events might occur as a result of delaying activities to resolve resource conflicts as they occur. For example, delaying activity 1-3 of project 1 (to resolve the conflict with activity 1-3 of project 2) might cause the following (13:192-193):

1. Delays in successor activities 3-4, 3-5, and 4-5 of project 1.

2. As a result of (1), the creation of additional resource conflicts among activities requiring resource types 2 and 3 to be resolved.

3. As a result of (2), additional delays in projects 2 and 3, and possibly even project 1 again.

Developing and maintaining schedules for multi-project problems, involving many projects, a variety of resource types, and thousands of activities, are possible only with the aid of powerful computers. The point being, the aspect of resource constraints elevates the complexity of the multi-project problem from a relatively simple exercise using the basic time-only PERT/CPM approach to a much more challenging problem of immense proportions that requires sophisticated computational routines and powerful computers to solve.

Resource Loading. The network model for project scheduling lends itself readily to information about resource requirements over the duration of the project. The only condition for obtaining this information is that

the resource requirements associated with each project

activity shown on the network be identified separately (see

Figure 4).

Figure 4 is the same network as shown in Figure 1 with

resource requirements of two different types indicated above

each activity. By using these resource requirements

together with an early start (see Figure 2) and a late start

schedule (not shown) a plot of resource usage over time can

be developed as shown in Figure 5. These plots are referred

to as resource loading diagrams. Such diagrams are very

useful in project management; they highlight the period-by-

period resource usage of a specific project schedule and

provide a basis for managers to improve scheduling

decisions.

Basic Scheduling Procedures for the Resource

Problem (13:202). Scheduling procedures for dealing with

the resource constrained problem can be divided into two

basic categories: 1) resource leveling, and 2) constrained-

resource scheduling. Resource leveling occurs when

sufficient total resources are available, the project must

be completed by a promised due date, but it is desired to

reduce resource usage variance over the duration of the

project. A constant level of resource usage is desired and

the project duration is not allowed to increase in this

case.
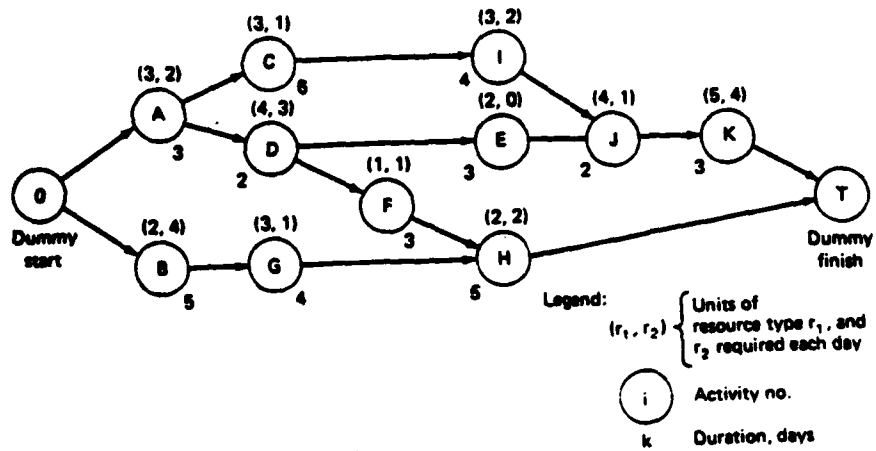
Figure 4.   Activity Network with Resources (13:196).
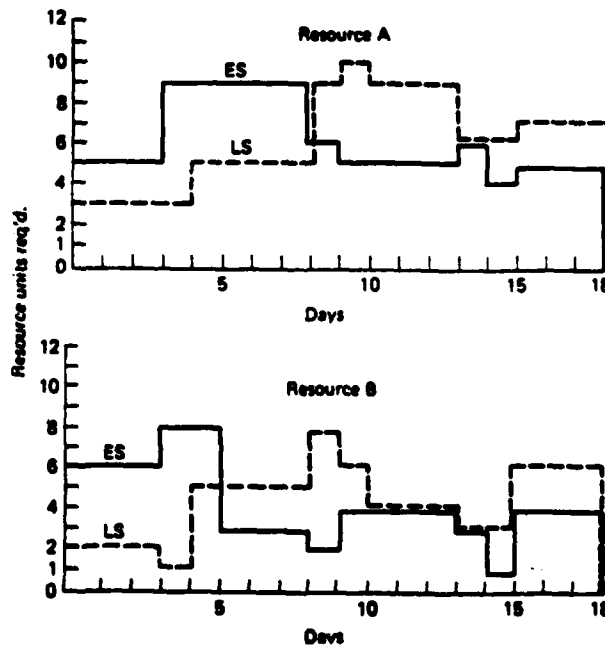
Figure 5.   Resource Usage Over Time (13:196).

The more common and most interesting problem arises when resources are constrained. The scheduling objective in this case is to meet project due dates as much as possible, subject to the fixed limits on resource availability. Thus, project duration may increase beyond the initial due date determined by time-only PERT/CPM calculations. The scheduling objective is to minimize the duration of the project (or projects) being scheduled, subject to the constraints imposed by limited available resources. This problem can be further subdivided into two categories according to whether the fixed limits on resource availabilities are constant at some level or allowed to change over activity or project duration. Further subdivisions are possible according to whether approximate, rule-of-thumb procedures, or mathematical exact procedures are used to solve the scheduling problem.

Heuristic Scheduling (13:202-217). The task of scheduling a set of project activities such that both resource constraints and precedence relationships are satisfied is not easy. The difficulty is increased in the multi-project environment. The limited resources, project scheduling problem falls into a category of mathematical problems called combinatorial problems. Analytical methods such as mathematical programming have not proven very successful on this class of problems. Instead, heuristic

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procedures have been developed and are being used to solve these problems.

Heuristics are "rules-of-thumb" that reduce the computational effort involved in project scheduling. They may not always provide the optimal solution in every case, but they are very useful in finding a good solution with minimum effort.

Simple heuristics such as "shortest job first" or "minimum slack first" are effective in establishing priorities on many types of resource-constrained scheduling problems. More sophisticated heuristic procedures exist and are described in further detail in the literature review.

Although individual studies have indicated the general best effectiveness of a particular heuristic, or combination of due date assignment rule and scheduling heuristic, it must be emphasized that it has been shown that no one heuristic-or combination of heuristics-always produces the best results on every problem. This is perhaps the greatest disadvantage of using scheduling heuristics. In practice, even with very sophisticated procedures, it is not possible to guarantee the performance across the board of any one heuristic or combination thereof.

Despite this disadvantage, heuristic scheduling procedures are used often in practice. The schedules produced by these techniques may not be optimal, but they

are good enough for planning and control purposes in view of
the uncertainties associated with activity durations,
resource constraints and requirements. Some very powerful,
computer-based solution procedures incorporating a variety
of creative heuristics have been developed which
produce schedules for large, complex projects under a
variety of assumptions. The most challenging problem of
course is the dynamic, multi-project, multiple resource
project scheduling problem which has received very little
academic attention.

The Dynamic Versus Static, Multiple Resource, Multi-
Project Scheduling Problem (5:1-13). Resource-
constrained project scheduling research has been limited
almost exclusively to the static problem where all aspects
of the projects are assumed a priori. The emphasis being on
finding scheduling techniques which minimize project
completion time. The result is a master schedule which
allocates specified quantities of the required resources to
certain activities at certain times. In reality, the
project scheduling environment is dynamic; new projects
arrive but the exact arrival times of future projects, their
activity duration times, and their resource requirements are
uncertain and not known until it arrives. These major
differences delineate the static versus the dynamic,
multiple resource, multi-project scheduling problem.
Standard project scheduling techniques are inadequate in the

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dynamic environment because they are unable to schedule resources to projects for which there is no information.

In general, project managers are faced with two problems in project scheduling. First, they must estimate a realistic and minimum expected project completion date (due date). Second, they must schedule this project to meet this due date while not seriously jeopardizing the completion of ongoing projects.

Estimating a realistic due date for a project involves detailed knowledge of the project and depends on:

1. The characteristics of the project (number of activities, successor-predecessor relationships, activity duration times, resource requirements, etc.).

2. The current load of projects in the organization.

3. The future load in the system (as impacted by additional projects).

4. The scheduling heuristics used to allocate the resources to the projects.

The goal of a project manager is to make good estimates of project completion times and deliver the product or service on time to the customer.

Good due date setting rules and scheduling heuristics have been explored recently by simulating the dynamic, multiple resource, multi-project problem with a computer based model (5). The focus of this research is a continued exploration of the performance of these due date

setting rules and scheduling heuristics under variations in the assumptions of the arrival rate distribution.

Specific Problem Statement

Many organizations, both commercial and government, operate in a multiple project environment where their resources are constrained and new projects arrive on a continuing basis. These organizations are expected to estimate a completion date on each of these new projects and then take scheduling (management) actions to meet these estimated completion dates.

The specific problem of estimating due dates and scheduling multiple projects in a dynamic, resource constrained environment has not received much attention academically or commercially. Because of the difficulty of the problem, previous research has focused almost exclusively on the static project environment with the purpose of finding scheduling methods that minimize the completion time of the project. Project managers have access to a large assortment of commercial software programs which basically provide a common schedule, allocating specified amounts of resources to activities at the required time in order to meet the minimum project completion date. However, these techniques require that all aspects of all projects be known in advance. Realistically, in a dynamic environment, the requirements and arrival time of new projects are not known in advance. This basic difference

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makes standard project scheduling models inadequate in a dynamic environment. There are three significant differences between the static and dynamic project environment (5:6).

Static	Dynamic
1. Finite number of projects in advance.	1. Unknown set of projects to be scheduled over time.
2. All projects start at time zero and all character- istics (activities, durations, resources, etc.) are known in advance.	2. Projects arrive at any time and the character- istics are unknown until their arrival.
3. Start with resource at zero, go to a peak resource level, and return to zero.	3. Resources are con- strained at a given level and remain constant throughout time.

Dumond identified several areas of future research on the dynamic, multi-project scheduling problem. A particular area of interest to this researcher is the environments used by Dumond to evaluate due date setting rules and scheduling heuristics in a simulated dynamic project arrival environment. The problem of interest is to examine the sensitivity of the performance of these due date setting rules and scheduling heuristics under variations in the assumptions regarding the project arrival distribution.

Research Objective

The overall objective of this research is to investigate the impact of differences in project arrival distributions during a simulation of the dynamic,

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multi-project scheduling environment on the performance of the due date assignment rule and scheduling heuristic combinations investigated previously by others. To achieve this objective, the following research questions should be answered:

1. Are scheduling heuristics, investigated in previous research, impacted by whether new projects arrive according to a uniform, exponential or triangular distribution?

2. Are due date setting rules, investigated in previous research, impacted by whether new projects arrive according to a uniform, exponential or triangular distribution?

3. Is any combination of scheduling heuristic and due date setting rule, investigated in previous research, impacted by whether new projects arrive according to a uniform, exponential or triangular distribution?

Scope of the Research

The scope of this research concentrates first on reviewing the due date setting rules and scheduling heuristics evaluated by Dumond and others (5). Then an investigation of the details of the computer-simulation model used to evaluate the effectiveness of these dynamic scheduling techniques will be conducted. Finally, the major thrust of this research effort will be to explore various dynamic project environments to test the generalizability of the results presented in (5, 6) and answer the research

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questions identified above. The investigation and
simulation of other project arrival distributions will
hopefully add to the robustness of the existing results and
demonstrate the sensitivity of the due date assignment rule
and scheduling heuristic combinations to project arrival
distributions.

II. Research Methodology

The general methodology will focus on collection of
data pertaining to the evaluation of the effect of different
project arrival distributions on the performance of selected
due date assignment rules and scheduling heuristics in the
dynamic, multiple resource, multi-project scheduling
environment. The initial portion of the research will be an
extensive review of the literature on the dynamic, multiple
resource, multi-project scheduling problem to determine if
this problem is being actively pursued and what types of
project scheduling criteria or rules are being developed to
address the dynamic project environment. Since a simulation
model has already been developed (5), it will be of
interest to the researcher to determine how the model must
be modified and installed on the local computer facility in
order to simulate the effect of different project arrival
distributions on the performance of several combinations of
interest of due-date assignment rules and scheduling
heuristics. The objective being to determine if there is
any significant difference in the performance of these due
date assignment rules and scheduling techniques and if so,
are these differences attributable to the difference in the
project arrival environment.

This chapter further establishs a rationale for
investigating the problem, provides a review of current
literature in this field of study, proposes an appropriate

experimental design to address the problem and collect data, describes the fundamental characteristics of the computer simulation model to be employed in this investigation, and finally, addresses the method of data analysis proposed for this experiment.

Experimental Approach

The primary rationale for investigating this problem is based upon the recommendation by Dumond for further exploration of the environments used in his experimentation (5). The arrival distribution and mean interarrival rate was held fixed during the experiments and the recommendation was made to pursue other distributions and arrival rates (5:195). Dumond used a uniform project arrival distribution with a mean interarrival rate of one new project every 8 days. The main experiment consisted of a two-factor full factorial design to determine the performance of four due date setting rules and seven scheduling heuristics under one set of environmental conditions (5:70). The project arrival distribution and mean interarrival rate were not factors in Dumond's experimental results.

Project Arrival Distributions. In order to make a comparison of experimental results with Dumond's previous study, a replication of the experiment using a selection of two due date setting rules and four scheduling heuristics will be performed using three different project arrival

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distributions (uniform, exponential, and triangular).

Pritsker states the following on the uniform distribution

(17:696-697):

The uniform density function specifies that every value between a minimum and a maximum value is equally likely. The use of the uniform distribution often implies a complete lack of knowledge concerning the random variable other than that it is between a minimum value and a maximum value. Thus, the probability of a value being in a specified interval is proportional to the length of the interval. Another name for the uniform distribution is the rectangular distribution.

Figure 6 gives the density function and its graph for the

uniform distribution.

$$f(x) = \frac{1}{b-a} \; ; \; a \leq x \leq b$$

$$\mu = \frac{a+b}{2} \; ; \; \sigma^2 = \frac{(b-a)^2}{12}$$
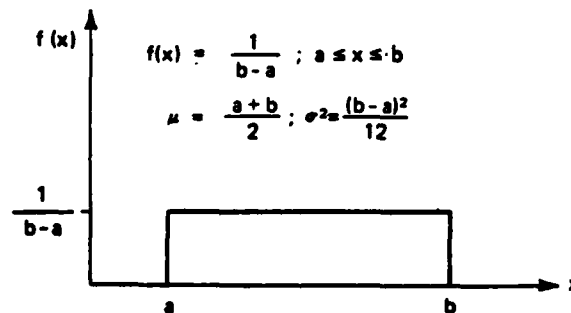
Figure 6.   Uniform Density Function (17:696)

Most of the queuing theory literature pertains to the

special case when job interarrival times are a series of

independent observations from an exponential distribution.

Meaning, the number of arrivals in a given period of time is

a random variable with a Poisson distribution. This is

referred to as the Poisson process and in queuing theory is

referred to as Poisson arrivals. Poisson arrivals are used

quite frequently in queuing models because it is a reason-

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able representation of many physical processes, but a more

important reason is because of the tremendous analytical

convenience that the Poisson process provides (4:142-151).

Pritsker states the following about the exponential

distribution (17:697-698):

> If the probability that one and only one outcome will
> occur during a small time interval is proportional to this
> small time interval and if the occurrence is independent of
> the occurrence of other outcomes then the time between
> occurrences of outcomes is exponentially distributed.
> Another way of saying the above is that an activity
> characterized by an exponential distribution has the same
> probability of being completed in any subsequent period of
> an equal small time interval. Thus, if the activity has
> been ongoing for t time units, the probability that it will
> end in the next time interval is the same as if it had just
> been started. This lack of conditioning of remaining time
> on past time is called the Markov or forgetfulness property.
> There is direct association between the assumption of an
> exponential activity duration and Markovian assumptions.
> The use of an exponential distribution assumes a large
> variability as the variance is the square of the mean. The
> exponential has one of the largest variances of the standard
> distribution types. The exponential distribution is easy to
> manipulate mathematically and is assumed for many studies
> because of this property.

Figure 7 gives the density function for the exponential

distribution and a graph of the distribution.
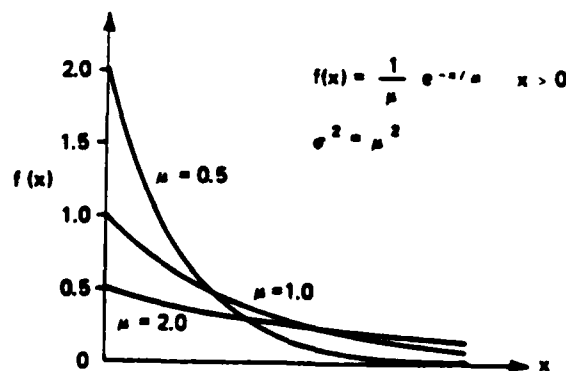
Figure 7. Exponential Density Function (17:698)

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Therefore a rationale can be established for exploring
the performance of due date setting rules and scheduling
heuristics assuming a Poisson arrival process and,
therefore, an exponential project arrival environment.

An argument can also be made that job arrival times are
perhaps a sequence of independent observations from a fixed
normal distribution. An environment may exist which closely
resembles the static, multiple resource, multi-project
problem such that the nature of project arrivals are fairly
repetitive and predictable for a particular organization,
however some uncertainty remains in the variability of
project arrivals. Therefore, one may assume that a normal
distribution of project arrival times is appropriate for
modelling the dynamic, multiple resource, multi-project
problem. The difficulty remains in selecting the
appropriate variance and, hence, standard deviation for a
normal process of project arrival times. Also, a
complicating feature of the normal distribution is the
infinite tails of the distribution which could be solved by
truncating the distribution. A triangular probability
distribution can be used as a reasonable approximation of
the normal distribution that does not require knowledge of
the variance or standard deviation, only the minimum, mode,
and maximum value of probable project arrival times. The
triangular distribution resolves the need for truncating the

normal distribution. Pritsker states the following on the

triangular distribution function (17:697):

> The triangular distribution contains more information
> about a random variable than the uniform distribution. For
> this distribution, three values are specified: a minimum,
> mode, and a maximum. The density function consists of two
> linear parts: one part increases from the modal value to the
> maximum value; and the other part decreases from the modal
> value to the maximum value. The average associated with a
> triangular density is the sum of the minimum, mode, and
> maximum values divided by 3. The triangular distribution is
> used when a most likely value can be ascertained along with
> minimum and maximum values, and a piecewise linear density
> function seems appropriate.

Figure 8 gives the density function and its graph for the

triangular distribution.

$$f(x) = \begin{cases} \dfrac{2(x-a)}{(m-a)(b-a)} ; & a \le x \le m \\[2mm] \dfrac{2(b-x)}{(b-m)(b-a)} ; & m \le x \le b \end{cases}$$

$$\mu = \frac{a+m+b}{3} ;$$

$$\sigma^2 = \frac{a(a-m) + b(b-a) + m(m-b)}{18}$$
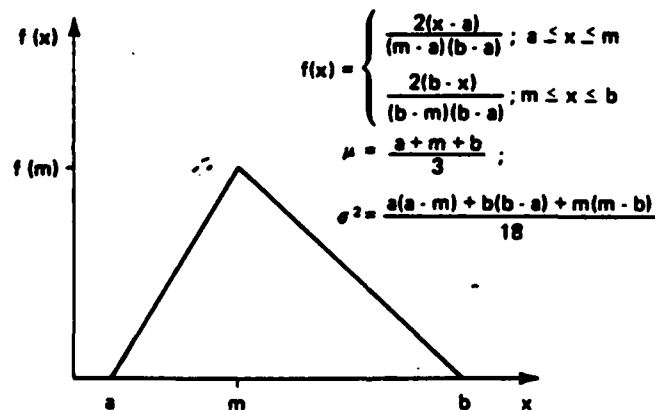
Figure 8. Triangular Density Function (17:698)

The investigation of the sensitivity of the performance

of due date setting rules and scheduling heuristics to

project arrival distributions will be an important

contribution to this area of research because the desired

effect would be a relative insensitivity to the project

arrival distribution. This would demonstrate that the

combinations of due date setting rule and scheduling
heuristic would not need to be compensated for the
particular type of project arrival distribution and, hence,
would remain good rules of thumb for scheduling projects in
the dynamic, multiple resource, multi-project environment.

Limitations. The most significant hurdle anticipated
will be trying to install the simulation model on an
accessible mainframe computer, debugging the model, and
conducting a pretest of the model using existing data. Once
the simulation is installed, it should be a reasonably
straightforward process to acquire new data (different
project environments, scheduling rules, etc.) and to
evaluate the effectiveness of various due date assignment
rules and scheduling techniques in a dynamic project arrival
environment.

Literature Review

A review of current literature has revealed that very
little research effort has been directed towards the
dynamic, multiple resource, multi-project scheduling
problem. Several related articles were discovered that
addressed heuristics and due date rules for resource
constrained scheduling problems, but none specifically
addressed the dynamic, multiple resource, multi-project
scheduling problem (1, 2, 3, 7, 9, 16, 18). The most
relevant current research effort was conducted by Dumond

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which provides the foundation of this experimental
investigation (5).

The remaining discussion will be an overview of the due
date setting rules, scheduling heuristics, and performance
measures that apply to the methodology to be incorporated in
the experimental design.

Due-Date Assignment Rules. A due date is defined
as the present date plus an estimate of the amount of time
required to complete a project. Meeting an assigned due date
is considered a major performance criterion in project
management. Due date assignment rules can vary from simple
to sophisticated depending on the degree of information
known and used about a project's characteristics and the
status of the system at the time of project arrival. Dumond
investigated the following four due date rules (6:10-12):

1. Mean Flow Due Date Rule (FLOW).

2. Number of Activities Due Date Rule (NUMACT).

3. Critical Path Time Due Date Rule (CPTIME).

4. Scheduled Finish Time Due Date Rule (SFT).

The latter two rules are the more sophisticated and are
considered as the two treatments for the due date rule
factor of the three-factor experimental design.

Critical Path Time Due Date Rule (6:11). The
critical path of a project determines the time to complete
the project given that resources are not constrained. This
rule considers the activity predecessor relationships of the

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project and the duration of the critical activities of that project. Since resources are constrained in this problem an adjustment is made to the critical path time due date estimate by multiplying the critical path time estimate by a delay factor based on historical data. This adjusted value becomes a more realistic estimate of the project's completion time and is used to set a due date for that particular project. CPTIME is given by the following:

$$DD_i = TNOW + k_2 * CPTIME_i \qquad (1)$$

where

CPTIME_i = critical path time of project i

k_2 = parameter representing expected delay

Scheduled Finished Time (6:11-12). This rule finitely schedules a new project into the system along with current projects in the system before setting a due date. Therefore, start and stop times of each activity of each project is established. The scheduled finished time of the last activity of the arriving project is an excellent estimate of the completion time of the new project provided no new projects arrive. In the dynamic project environment new projects will continue to arrive and the scheduled finish time is usually not met. Therefore, the estimate must be compensated by an appropriate delay factor.

The SFT technique involves the following three steps in order to set the due date for a new arriving project:

1. Temporarily set the due date of the new incoming

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project as the current date plus the computed critical path time of the new project, without regarding resource needs.

2. Schedule the remaining activities of all current projects in the system plus those activities of the new project using the selected scheduling heuristic (i.e., first-in-first-served, shortest activity of shortest project, etc.).

3. Set the permanent due date of the new project as the present date plus a delay factor (k2) times the estimated completion time for the new project.

The SFT due date rule is given as follows:

$$DD_i = TNOW + k_e(SFT(E)_i - TNOW) \qquad (2)$$

where

k_e = the expected delay factor

$SFT(E)_i$ = the estimated scheduled finish time for project i after loading

$(SFT(E)_i - TNOW)$ = estimated completion time for the new project

The SFT due date rule determines the early activity start times of the new project based upon resource constraints at the time. Therefore, the same project arriving at different times but using the same SFT heuristic would be assigned two different estimates of their completion times. In other words, if the system is relatively empty a shorter due date will be assigned than if the system is relatively full.

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<u>Scheduling Heuristics</u> (6:6-9). Project
scheduling heuristics allocate the constrained available
resources based on a prioritized list of the competing
activities from one or more projects. Some heuristics
perform better than others in reducing the mean completion
time of projects. By assuming that the dynamic, multiple
resource, multi-project problem consists of a series of
static problems, then one can use these same heuristics in
the dynamic environment. Dumond investigated the
performance of several scheduling heuristics, some that
ignore the due date and some that are sensitive to the due
date. Four of the more successful heuristics will be
investigated in combination with the above due date
assignment rules in this study. They are as follows:

1. First in System, First Served (FIFS).

2. Shortest Activity from Shortest Project (SASP).

3. Shortest Activity from Shortest Project-Based on
the Due Date (SASP[DD]).

4. Minimum Late Finish Time-Based on the Due Date
(MINLFT[DD]).

<u>First in System, First Served (FIFS)</u> (6:6-7).
This heuristic is commonly found in the static environment
and many queuing applications as well as the dynamic
scheduling environments. The project first in the system,
hence which has been in the system the longest, receives
priority on available resources. The index used to

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determine an activity's priority is based on the arrival time of the project (ties are broken randomly). Every time a new schedule is developed, the competing activities priority index is recalculated. The FIFS rule ignores the due date assigned to the project and is given as follows:

$$I(FIFS)_{ij} = Min_j(ta_i) \qquad (3)$$

where

ta_i = time of arrival of project i

j = set of competing activities

$I(FIFS)_{ij}$ = index value for activity i on project j using FIFS.

Shortest Activity from Shortest Project (SASP)

(6:7). This rule was found to be effective in the static environment and can be used in the dynamic scheduling environment. This rule, like FIFS, ignores the due date assigned to the project and determines an activity's priority based on the critical path time plus the activity's duration. This rule is given as follows:

$$I(SASP)_{ij} = Min_{ij}(d_{ij} + CPTIME_i) \qquad (4)$$

where

$CPTIME_i$ = critical path time remaining for project i.

d_{ij} = duration of activity j for project i.

Shortest Activity from Shortest Project-Based on the Due Date (SASP[DD])

(6:9). This heuristic is a modified version of SASP which accounts for the due date assigned to a project when computing the activity priority index. The SASP[DD] heuristic is given as follows:

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$$I(SASP[DD])_{i,j} = Min_{i,j} \begin{cases} I(NSLK[DD])_{i,j} & \text{if } I(NSLK[DD])_{i,j} < 0 \\ (d_{i,j}+CPTIME_i) & \text{otherwise} \end{cases} \quad (5)$$

where

$CPTIME_i$ = critical path time remaining for project i

$d_{i,j}$ = duration of activity j of project i

$I(NSLK[DD]_{i,j})$ = $Min_j(Min_{i,j}(LST_{i,j}, LST[DD]_{i,j}-EST_{i,j}))$

$LST[DD]_{i,j}$ = LST of activity j based on project i's
established due date

$LST_{i,j}$ = late start time of activity j of project i
based upon project i's best completion time

$EST_{i,j}$ = early start time of activity j of project i

This rule gives priority to all activities that have
negative slack (late). Once all of the late activities have
been allocated resources, then all remaining available
resources are allocated by the familiar SASP rule.

**Minimum Late Finish Time-Based on the Due Date
(MINLFT[DD])** (6:8-9). This modified version of the minimum
late finish time heuristic uses the project's set due date
or the currently computed late finish time of the project's
last activity as the priority index. The activity with the
earliest adjusted late finish time is given the priority
for available resources. In other words, the earliest due
date project activities receive priority. The MINLFT[DD]
rule is given as follows:

$$I(MLFTD)_{i,j} = Min_j(Min_{i,j}(LFT_{i,j}, LFT[DD]_{i,j}) \quad (6)$$

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where

LFT$_{i,j}$ = late finish time of activity j of project i

LFT[DD]$_{i,j}$ = late finish time of activity j based on project i's due date

Performance Measures (5:69-70). As each project is completed during a simulation run several performance parameters are collected. The dependent variables of interest in this experiment will be the following performance measures:

1. Project Mean Completion Time - the average project completion time. It is calculated as follows:

$$[\sum_{i=1}^{p} (tc_i - ta_i)]/p \qquad (7)$$

where

tc$_i$ = time of completion of project i

ta$_i$ = arrival time of project i

p = total number of projects

2. Project Mean Lateness - the average difference between the actual project completion time and the estimated due date. Mean lateness is calculated as follows:

$$[\sum_{i=1}^{p} (tc_i - dd_i)]/p \qquad (8)$$

where

dd$_i$ = due date of project i

3. Standard Deviation of Project Mean Lateness - the measure of the variability in the project lateness

distribution. Measures the ability of a scheduling
heuristic to consistently meet project due dates. It is
calculated as follows:

$$\{[\sum_{i=1}^{p}(tc_i-dd_i)^2]/(p-1) - [\sum_{i=1}^{p}(tc_i-dd_i)]^2 p/(p-1)\}^{1/2} \quad (9)$$

4. Project Mean Tardiness (mean positive lateness) -
measures the average time by which due dates are exceeded.
Provides a measure of how late, on the average, projects
will be completed using a particular combination of
scheduling heuristic and due date assignment rule. Mean
tardiness is computed as follows:

$$\sum_{i=1}^{L}(tardiness)_i/L \quad (10)$$

where

$(tardiness)_i = 0$ if $(tc_i - dd_i) <= 0$, early

$(tardiness)_i = tc_i-dd_i$, otherwise

L = total number of projects tardy

5. Average Resource Utilization Rate - the measure of
the average usage rate of all resource types during the
simulation of the dynamic project scheduling problem.

Experimental Design

The purpose of this experiment is to determine the
relative performance of four scheduling heuristics and two
due date setting rules under three different assumptions of
dynamic project arrival distributions. The experiment will
be a three-factor full factorial balanced design to analyze

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the effects of due date rule, scheduling heuristic, and project arrival distribution. Many other due date rules and scheduling heuristics exist, but the purpose of this experiment is to explore those which performed the best in Dumond's earlier study and examine their behavior under various project arrival distributions. Many different distributions exist as well, however, three have been selected and justified for the purposes of this experimental investigation. Those three are the uniform, exponential, and triangular distributions. The general experimental approach will be as follows:

1. Select a project stream from the Patterson problems set (15).

2. Run a pilot simulation test run to determine the quantity of resources required to maintain an average resource utilization rate of approximately 85 per cent for the selected project stream.

3. Keeping the resource quantities fixed, run another pilot simulation run to determine the appropriate "historical" k-factors for the two due date setting rules.

4. Run the simulation and collect data for the full factorial, three-factor experiment.

A more detailed description of this procedure is provided in the following sections.

Project Stream. The projects to be used in the simulation are obtained from a host of projects used in

other project scheduling research and are contained in the
Patterson problem set (15). Twenty projects were
selected from this available set of projects in order to
represent a heterogeneous population of projects. The
specific projects to be selected are Problems 7, 9, 10, 13,
14, 20, 31, 37, 44, 54, 59, 61, 63, 70, 73, 92, 97, 98, 101,
and 104.

An observation will consist of 2000 days of operation.
The mean interarrival rate will be the same for each project
arrival distribution, which is eight days. Therefore,
approximately 250 projects must be selected in sequence to
satisfy 2000 days of project scheduling. This sequence of
projects during the a simulation is referred to as the
project stream. The project stream is developed by making a
random selection from the previously selected 20 different
projects repeatedly until approximately 250 projects have
been sequenced.

Resource Quantity Determination. In order to make a
reasonable representation of resource usage in the real
world, an average resource utilization rate of approximately
85% is desired. Dumond also discovered that as one exceeds
the 85% rate, the amount of processing time begins to
increase dramatically due to "tightening" of available
resources. The projects selected for this study require as
many as three different types of resources. The quantity of
each resource required to achieve the desired resource

utilization rate depends on the project stream selected. A pilot simulation run is performed in order to determine the amount of resources required in order to maintain the desired resource utilization rate. A tradeoff between simulation run time and resource utilization rate will be made in order to obtain a reasonable simulation run time.

Due Date Compensation Factor Determination (6:13-14). The full factorial experiment will be preceded by a pretest to determine the compensation parameters (k values) for the due date assignment rules of CPTIME and SFT. These k values are sensitive to many different factors (e.g., resource levels, project arrival rate, project stream characteristics, scheduling heuristic, etc.) and therefore are unique for each combination of due date assignment rule, scheduling heuristic, and project arrival distribution.

A pretest simulation will be used to provide an estimate of mean completion time (MCT) for each combination of due date rule and scheduling heuristic using an initial value of $k_i=1$. This will provide a MCT value similar to knowing MCT from historical data. Based on this data, the initial k values are determined as follows:

CPTIME: k_i = MCT/(mean critical path time per project)

SFT: k_s = MCT/(MCT - mean lateness)

where

$$\text{mean lateness} = (\sum_{i=1}^{p} TC_i - SFT(E)_i)/p \quad (11)$$

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TC_i = time of completion of project i

$SFT(E)_i$ = initial due date estimate of project i when it arrived

p = total number of projects

Values of k which produce near zero lateness are desired and will be obtained by varying the k value between runs in order to determine the appropriate k value for each combination of scheduling heuristic and due date assignment rule.

Experimental Procedure and Data Collection. The complete experiment will examine three factors: 1) scheduling heuristic; 2) due date assignment rule; and 3) project arrival distribution. The scheduling heuristic factor will have four levels of treatment (FIFS, SASP, SASP[DD], MINLFT[DD]). The due date rule factor will have two levels of treatment (CPTIME, SFT). The third factor, project arrival distribution, will consider three levels of treatment (uniform, exponential, triangular). The complete experimental design will involve 24 possible combinations of treatments (cells) with each cell having the same number of observations per cell (balanced design). The number of observations per cell can be determined by conducting an initial simulation run and using the power test to estimate the required sample size. Dumond's main experimental phase was successful with 15 observations per cell and his sensitivity experiment produced meaningful results at 8 observations per cell. An important factor to consider in

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determining the sample size is that the simulation runs may take a long time to complete and there may be some limitations in the amount of computer time accessible to the researcher. Therefore, for this experiment, 8-10 observations per cell will be assumed to be a reasonable sample size.

Randomization will be introduced in the observations per cell by changing the random number seed between runs. This will generate different random variates from the project arrival distribution for each observation per cell. The same sequence of random number seeds will be used between cells so that no random effects are introduced between comparisons of treatment combinations.

Upon completion of each simulation run, several performance criteria are collected. The primary data of interest will be:

1. Project mean completion time (days)

2. Project mean delay (lateness in days)

3. Standard deviation of mean lateness (days)

4. Project mean tardiness (mean positive lateness)

5. Average resource utilization rate (percent)

Simulation Model Description (5:203-210)

The simulation model is designed to simulate a dynamic project scheduling environment in which there is a continuous flow of stochastically arriving projects into the system. As each new project arrives it is assigned a due

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date by a selected due date rule and then it is scheduled into the system using a selected scheduling heuristic. This schedule establishes start and stop times for all activities (currently existing in the system and newly arriving activities). The activity duration times are assumed to be deterministic and, therefore, the schedule is not changed until a new project arrives. Basically, the simulation of the dynamic scheduling problem is a continuous series of static, multiple resource, multi-project scheduling problems where the new project arrival time is randomly drawn from a project arrival distribution.

Figure 9 shows that the simulation model is divided into two sections. The dynamic simulator section creates the dynamic project arrival environment. The simulation is a discrete-event oriented simulation and advances the clock to each successive event. The events are: 1) activity start; 2) activity finish; 3) project completion; 4) new project arrival; and 5) end of the simulation. The interarrival time of new projects is a random variate generated from a probability distribution. In this case, three different distributions will be examined, but the distribution remains fixed during a simulation run. As a new project arrives the model updates all projects in the system and provides a new schedule of activity start and stop times, developed by the scheduler, which is then placed on the event calendar. As the system clock advances to the next event, activities are

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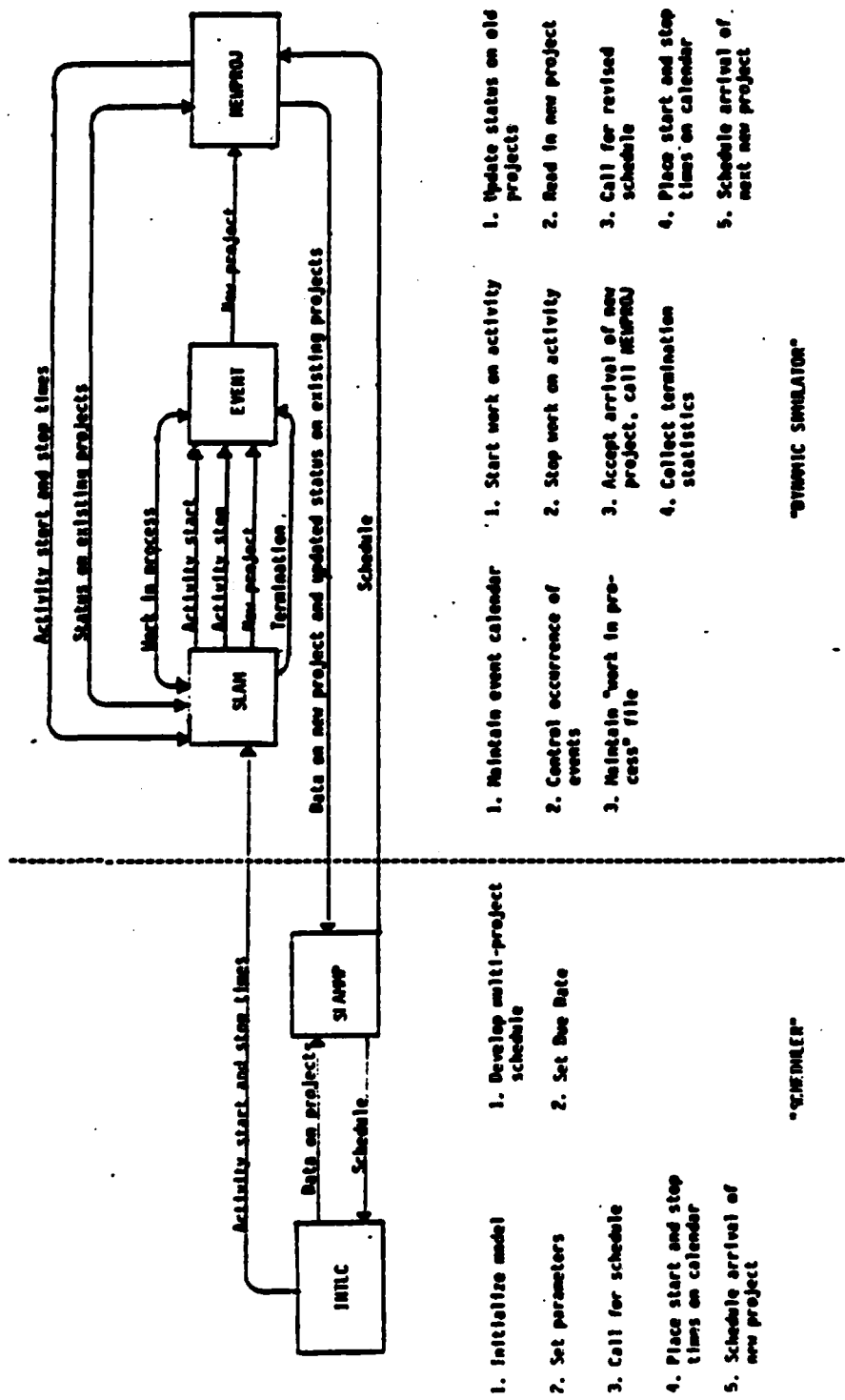
Figure 9. Simulation Model Diagram (5:205)

RESPROU
1. Update status on old projects
2. Read in new project
3. Call for revised schedule
4. Place start and stop times on calendar
5. Schedule arrival of next new project

EVENT
1. Start work on activity
2. Stop work on activity
3. Accept arrival of new project, call RESPROU
4. Collect termination statistics

"DYNAMIC SIMULATOR"

SLAM
1. Maintain event calendar
2. Control occurrence of events
3. Maintain "work in process" file

Activity start and stop times
Status on existing projects
Next in project
Activity start
Activity stop
New project
Termination
Schedule
Data on new project and updated status on existing projects
New project

SLAMP
1. Develop multi-project schedule
2. Set Due Date

"SCHEDULER"

INTLC
1. Initialize model
2. Set parameters
3. Call for schedule
4. Place start and stop times on calendar
5. Schedule arrival of new project

Activity start and stop times
Data on projects
Schedule

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started and placed in a work-in-process file. Each activity
is worked on until it is completed or until it is
interrupted by the arrival of a new project. When the new
project arrives the status of each activity is updated and
the work remaining to be done on each activity is updated.
Activities are not preempted. In other words, once an
activity is allocated resources, the activity is allowed to
be completed and the resources required will not be
available until that activity is finished. As the last
activity of each project is finished, the project is
completed, and statistics are collected on the project
completion time and its deviation from the assigned due
date.

A large portion of the model is written in FORTRAN code
consisting of approximately 1500 lines of code which is
interfaced with the SLAM II simulation language developed by
Pritsker (17). The SLAM II portion of the code maintains
the event calendar, controls the occurrence of each event
and maintains the activity work in process file. The
remaining control of the simulation is governed by the user-
written FORTRAN interface code.

The original model was installed on a CDC 855 series
computer using FORTRAN IV and an earlier version of the SLAM
language. The model will be modified so that it may be
installed on the ELXSI 6400 using the UNIX operating system.
The SLAM II, version 3.2, language has been designed

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to be upwardly compatible with earlier versions of SLAM.
Therefore, modification of the existing model should be
relatively straightforward. One must also be careful of the
FORTRAN compiler available on the computer system. SLAM is
a FORTRAN based language and accommodates user-written
FORTRAN interfaces quite readily. However, some
modifications to the code may be necessary to insure
compatibility with the existing FORTRAN compiler.

Verification and validation of the model was
accomplished earlier by Dumond, therefore an extensive
reverification and revalidation of the model should not
be required. However, because some modifications are being
made to the model for installation purposes and to simulate
the effect of different project arrival distributions, the
model should be checked for reasonableness to ensure the
code is being implemented properly and that the model is
providing accurate output data.

Data Analysis

The dependent variables, mean completion time, mean
lateness, standard deviation of lateness, mean tardiness,
and average resource utilization will be analyzed using a
univariate analysis of variance (ANOVA) to determine
the overall significant difference between factors. All
main and interaction effects will be examined. Independent
observations within each cell will be obtained and common
random numbers will be used between cells so that

significant differences between the various scheduling heuristics, due date assignment rules, and project arrival distributions may be observed.

When the experiment is completed, the data will be assimilated and analyzed using the SAS software system (19). The PROC ANOVA routine will be used to test for significant differences in main and interaction effects and multiple comparison tests will be performed to determine which treatment levels are significantly different from one another.

The main goal of this experiment is to investigate the effect of different project arrival distributions on the performance of due date assignment rules and scheduling heuristics. If the data analysis shows no significance attributable to this factor then it may be assumed that the due date rules, scheduling heuristics, and combinations are insensitive to the project arrival environment. On the other hand, it will be important to learn the sensitivity of these scheduling techniques if the results indicate that there is a significant difference attributable to the project arrival distribution used in the simulation.

III. Experimental Results and Data Analysis

This chapter presents the results of the computer simulation runs that were described in Chapter 2 as part of the experimental design. These results are analyzed and presented in the following sections. This chapter begins with a description of the actual experiment, followed by a presentation of the experimental results and data analysis, and concludes with a summary of the results.

Description of the Actual Experiment

Recall that the objective of this research was to investigate the impact of differences in project arrival distributions on the performance of due date assignment rules and scheduling heuristics, during a simulation of the dynamic, multi-project scheduling environment. The questions addressed by this research involve the performance of scheduling heuristics, due date rules, and combinations thereof when subjected to different project arrival distributions.

Performance is measured by the following four criteria: 1) mean completion time; 2) mean delay (lateness); 3) standard deviation of lateness; and 4) mean tardiness. Also, the average resource utilization rate is measured as a secondary criteria to observe differences in resource utilization during the experiment.

This experiment was conducted using a three factor full factorial design to analyze the effects of differences in due date assignment rules, scheduling heuristics, and project arrival distributions during a simulation of a dynamic, multi-project, constrained resources environment. The two levels of the due date assignment rule factor selected for this experiment were the Critical Path Time Due Date Rule (CPTIME) and the Scheduled Finish Time Due Date Rule (SFT). The four levels of the scheduling heuristic factor selected for this experiment were: 1) First in System, First Served (FIFS); 2) Shortest Activity from Shortest Project (SASP); 3) Shortest Activity from Shortest Project-Based on the Due Date (SASP[DD]); and 4) Minimum Late Finish Time-Based on the Due Date (MINLFT[DD]). The three levels of the project arrival distribution factor were uniform, exponential, and triangular distributions.

The experimental approach is summarized below:

1. First, the simulation code was installed on an ELXSI 6400 mainframe computer and modified somewhat in order to make it compatible with the Fortran compiler and SLAM II software using the UNIX 4.2 operating system. Several test runs were made using a pseudo project stream in order to debug the program and verify that the code was performing well.

2. A project stream consisting of twenty projects was
selected from the Patterson problem set in order to
represent a heterogeneous population of projects (15).

3. A pilot simulation test run was performed to
determine the resource levels required to maintain an
average resource utilization rate of approximately 85 per
cent.

4. Once the resource quantities were determined and
fixed, another pilot test run was performed to determine the
due date rule compensation factors ("k" values) required for
the two due date setting rules used in this experiment.

5. Finally, the simulation was run several times in
order to collect data on all possible combinations of due
date assignment rule, scheduling heuristic, and project
arrival distribution for the full factorial experiment.

- The experiment was conducted using a full factorial
design (4 heuristics, 2 due date rules, and 3 project
arrival distributions) with 24 cells. Each cell contains 8
observations; this resulted in a total of 192 observations
for the experiment.

Each observation consisted of the simulation of 2000
days of project scheduling in a dynamic, multi-project,
constrained resources environment. The mean project
interarrival rate for each project arrival distribution was
eight days resulting in approximately 250 projects arriving
during the 2000 days. The ranges for each project arrival

distribution were 0-16 days for the uniform distribution, 0-16 days for the triangular distribution, and 0 to infinity for the exponential distribution. Each project consisted of a number of activities, ranging from 6 to 49. The average number of activities per project for the project streams used in this experiment was 27.46. The average critical path time per project for the project streams was 33.26 days. The projects selected for this experiment are contained in the Patterson problem set (15) and they were selected as defined in Chapter 2. A random selection process was used to determine the sequence of projects for the project stream used in each simulation run. Eight project streams were used for each cell so that variations in the performance measurements between cells were not attributable to the project streams themselves.

The resource levels chosen for this experiment were selected in order to obtain an average resource utilization rate of approximately 85 per cent. Resource one was set at 37 available units per day, resource 2 was set at 33 available units per day, and resource 3 was set at 32 available units per day. The resources were assumed to be fixed at these levels throughout the simulation run.

The due date compensation factors were determined by pretest simulation runs to obtain a historical data base for the calculation of the k values required for each

combination of due date rule, scheduling heuristic, and
project arrival distribution. This required an iterative
process in order to obtain k values that produced near zero
lateness. Tables 1 and 2 presents the k value results of
the simulation. The k_1 values are shown for the CPTIME due
date rule according to scheduling heuristic and project
arrival distribution. Likewise, the k_2 values are shown for
the SFT due date rule.

Experimental Results and Data Analysis

The results and data analysis for this experiment are
presented below in terms of each of the performance criteria
described in Chapter 2. For each performance criteria, the
data is presented in tabular format as well as graphically
in order to present the data in a concise and understandable
manner.

In this section, for each performance criterion the
data has been reduced to the average values obtained for
each cell in the experimental design. The data is then
presented in two sets of tabular and graphical formats so
that all possible main effects and interaction effects can
be illustrated for each performance criteria.

The first set of data is presented according to
performance measurement and due date rule. Each table shows
the performance results for each combination of scheduling
heuristic versus project arrival distribution for each due
date rule used. Likewise the data is presented graphically

Table 1

CPTIME Due Date Rule

Selected k_1 Values

Project Interarrival Distribution

Heuristic	Uniform	Exponential	Triangular
FIFS	1.92	2.27	1.84
SASP	1.72	1.93	1.66
SASP[DD]	1.93	2.24	1.80
MINLFT[DD]	1.86	2.22	1.76

Table 2

SFT Due Date Rule

Selected k_2 Values

Project Interarrival Distribution

Heuristic	Uniform	Exponential	Triangular
FIFS	1.03	1.03	1.03
SASP	1.44	1.51	1.40
SASP[DD]	1.31	1.40	1.28
MINLFT[DD]	1.32	1.36	1.31

in terms of the performance results obtained for each
scheduling heuristic versus the project arrival distribution
(according to the due date rule).

The second set of data presents the results according
to performance measurement and scheduling heuristic. Each
of these tables shows the performance results for each
combination of due date assignment rule and project arrival
distribution for each scheduling heuristic investigated in
this experiment. Likewise, the data from each of these
tables is presented in graphical form in terms of the
performance results obtained for each due date assignment
rule versus the project arrival distribution (according to
scheduling heuristic).

A three-factor analysis of variance (ANOVA) was
performed for each performance parameter to test for main
factor effects, two-factor interactions, and three-factor
interactions according to the methodology presented by Neter
and Wasserman (14:788-825). The three main effects in this
experiment are scheduling heuristic, due date rule, and
project arrival distribution. The three two-factor
interaction effects are as follows: 1) scheduling heuristic
and due date rule combinations; 2) scheduling heuristic and
arrival distribution combinations; and 3) due date rule and
arrival distribution combinations. The three-factor
interaction effects are the combination of scheduling
heuristic, due date rule, and arrival distribution.

In order to provide a family level of significance of .05 for the seven possible effects tests, the Kimball inequality equation is used to calculate the level of significance required for each test in order to provide the desired family level of significance (14:819). The significance level for each test in the ANOVA was found to be .0073 in order to assure that there will be only a 5 per cent chance for one or more of the seven tests to lead to the conclusion of the presence of factor effects.

Multiple comparison tests (Tukey, Bonferroni, and Scheffe) were performed to identify which levels of each factor, for the performance measure under investigation, were significantly different from one another. These tests were conducted according to the methodology presented by Neter and Wasserman and the computations were performed using the SAS statistical software package (10). Appendix A contains the SAS computer programs, data inputs, and ANOVA statistical tests conducted for each of the performance criteria measured in this experiment.

Mean Completion Time. The mean completion time is a measure of the average time to complete each project. It is calculated as follows (8:80):

$$\left[\sum_{i=1}^{p} (tc_i - ta_i)\right]/p \qquad (7)$$

where

    ta - time of arrival of project i

    tc - time of completion of project i

    p = number of projects

The minimization of completion time is a primary criterion
because it reflects the capability to finish the projects as
early as possible.

Table 3 presents the mean completion time results of
the simulation for the CPTIME due date rule. These results
are graphed and presented in Figure 10. Table 4 presents
the mean completion times for the SFT due date rule and
Figure 11 presents these results in graph form. The project
interarrival distributions are plotted on the X-axis with
"1" representing the uniform arrival distribution, "2"
representing the exponential distribution, and "3"
representing the triangular distribution. The mean
completion times for each scheduling heuristic are plotted
on the Y-axis.

The mean completion times for the FIFS, SASP, SASP[DD],
and MINLFT[DD] scheduling heuristics are presented in Tables
5, 6, 7, and 8, respectively. These results are then
presented in graphical form in Figures 12, 13, 14, and 15.
The project arrival distributions are plotted on the X-axis
and the mean completion times for each due date rule are
plotted on the Y-axis.

The first observation to be made is that the SASP
scheduling heuristic mean completion time performance is
better than the other three heuristics for both due date
rules. In fact, the other three heuristics, FIFS, SASP[DD],
and MINLFT[DD], perform almost identically in each case.
Secondly, for all four heuristics, it is apparent that the
mean completion times are sensitive to the difference in
project interarrival distributions. The results for the
uniform and triangular distributions are similar, but are
somewhat higher for the exponential interarrival
distribution. Also, it is apparent that there is
virtually no difference in mean completion times between the
two due date rules investigated. Finally, because all of
the lines in the graphs shown above remain parallel between
graphs it is assumed that there was no interaction effects
present for the mean completion time results. Only the
scheduling heuristic and arrival distribution main effects
are present in the mean completion time results shown above.

A three-factor ANOVA was conducted for the above mean
completion time results and it was determined that there
is a significant difference in the mean completion times
between the main factors of scheduling heuristic and the
arrival distribution, but not for the due date rule main
factor in this phase of the experiment. Also, all of the
two-factor and three-factor interactions were not

Table 3

Mean Completion Time (Days)

CPTIME Due Date Rule

Project Arrival Distribution

Heuristic	Uniform	Exponential	Triangular	Row Mean
FIFS	64.24	76.51	60.76	66.84
SASP	56.96	64.06	56.11	56.71
SASP[DD]	62.80	74.36	59.36	65.51
MINLFT[DD]	61.84	73.71	58.28	64.51
Column Mean	61.39	71.91	58.38	63.89
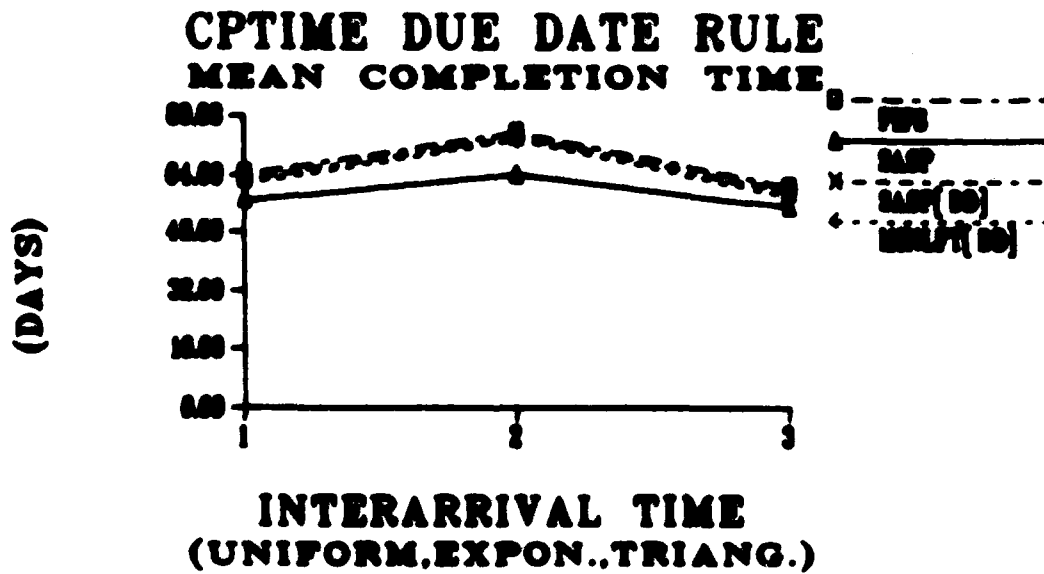
Figure 10. Mean Completion Time – CPTIME Due Date Rule

Table 4

Mean Completion Time (Days)

SFT Due Date Rule

Project Arrival Distribution

Heuristic	Uniform	Exponential	Triangular	Row Mean
FIFS	64.24	76.61	60.78	66.84
SASP	56.96	64.06	55.11	58.71
SASP(DD)	63.43	74.70	59.85	65.99
SINLFT(DD)	63.89	76.31	60.26	66.82
Column Mean	62.13	72.65	59.00	64.59
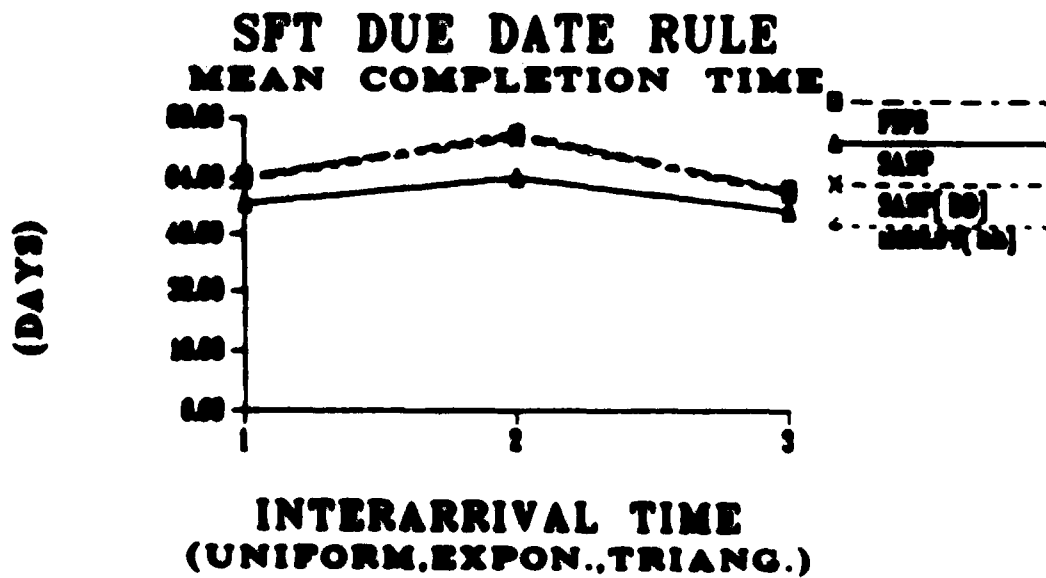
Figure 11. Mean Completion Time - SFT Due Date Rule

Table 5

Mean Completion Time (Days)

FIFS Scheduling Heuristic

Due Date Rule	Project Arrival Distribution			
	Uniform	Exponential	Triangular	Row Mean
CPTIME	64.24	75.51	60.76	66.84
SFT	64.24	75.51	60.76	66.84
Column Mean	64.24	75.51	60.76	66.84

FIFS HEURISTIC
MEAN COMPLETION TIME

Y-axis: (DAYS) — 0.00, 16.00, 32.00, 48.00, 64.00, 80.00

X-axis: 1, 2, 3

INTERARRIVAL TIME
(UNIFORM,EXPON.,TRIANG.)

Legend: CPTIME, SFT
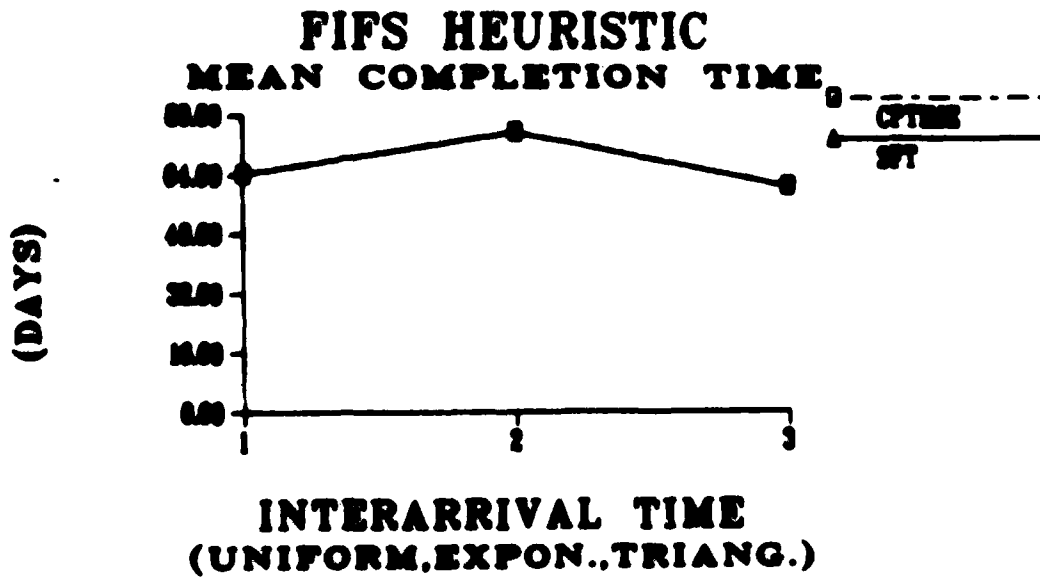
Figure 12. Mean Completion Time - FIFS Heuristic

Table 6

Mean Completion Time (Days)

SASP Scheduling Heuristic

Project Arrival Distribution

Due Date Rule	Uniform	Exponential	Triangular	Row Mean
CPTIME	56.96	64.05	55.11	58.71
SFT	56.96	64.05	55.11	58.71
Column Mean	56.96	64.05	55.11	58.71

SASP HEURISTIC
MEAN COMPLETION TIME
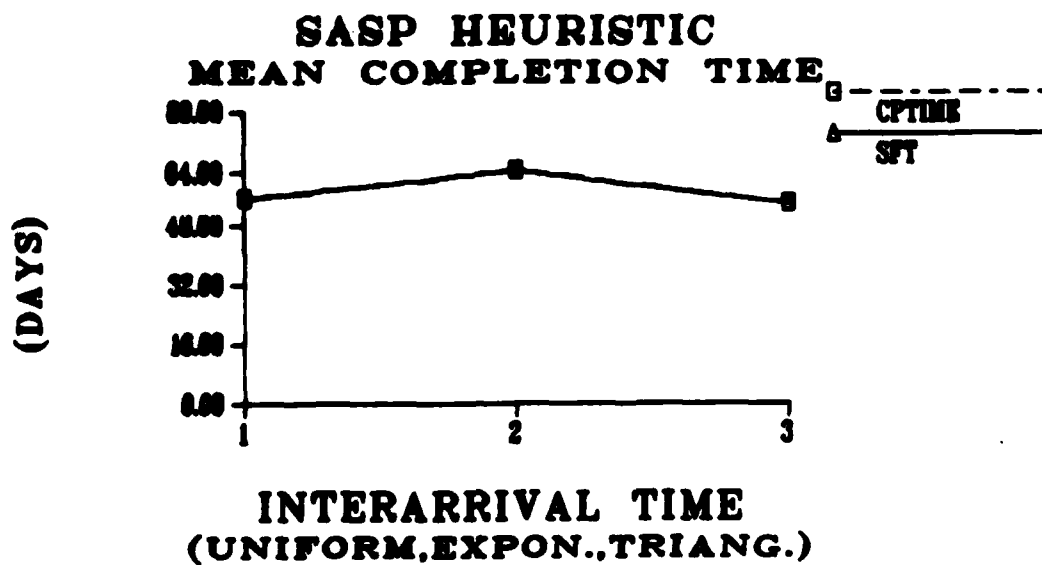
Figure 13.   Mean Completion Time - SASP Heuristic

Table 7

Mean Completion Time (Days)

SASP[DD] Scheduling Heuristic

	Project Arrival Distribution			
	Uniform	Exponential	Triangular	Row Mean
Due Date Rule				
CPTIME	62.80	74.36	59.36	65.51
SFT	63.43	74.70	59.85	65.99
Column Mean	63.17	74.53	59.61	65.75
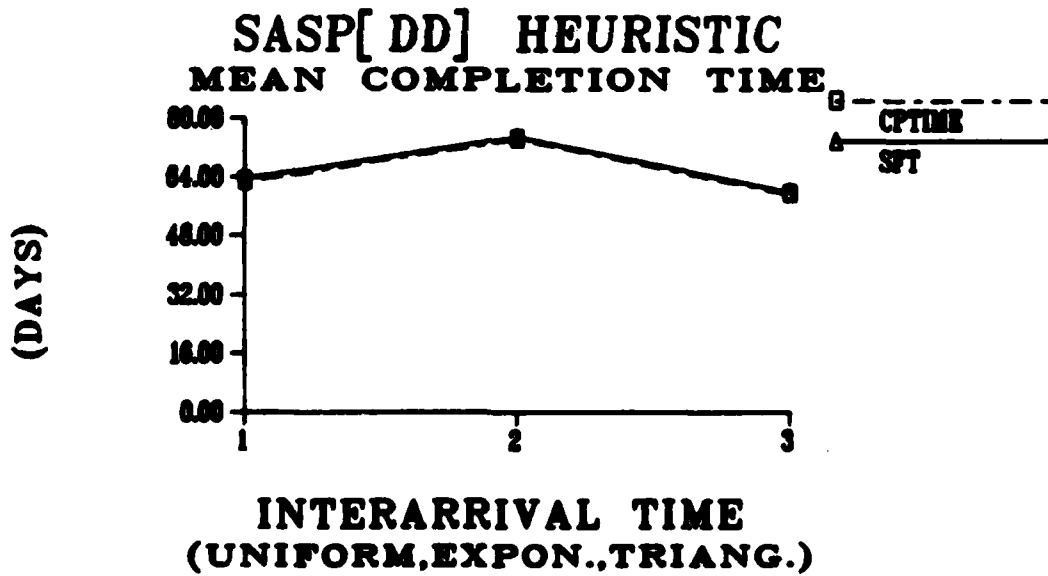
Figure 14. Mean Completion Time - SASP[DD] Heuristic

Table 8

Mean Completion Time (Days)

MINLFT[DD] Scheduling Heuristic

Project Arrival Distribution

Due Date Rule	Uniform	Exponential	Triangular	Row Mean
CPTIME	61.54	73.71	58.28	64.51
SFT	63.89	76.31	60.25	66.81
Column Mean	62.71	75.01	59.27	65.61

MINLFT[DD] HEURISTIC
MEAN COMPLETION TIME
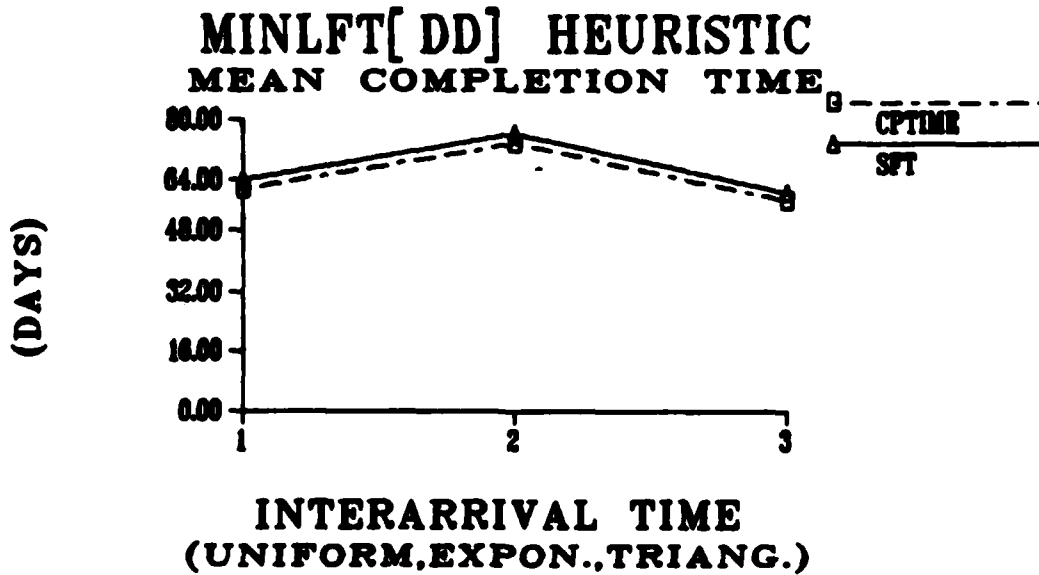
Figure 15. Mean Completion Time - MINLFT[DD] Heuristic

significant for mean completion times at the 0.05 family level of significance (see Appendix A).

Multiple comparison tests were conducted to investigate the significant differences in scheduling heuristic and project arrival distribution and to identify which levels of those factors were significantly different. Tukey, Bonferroni, and Scheffe tests were conducted at the .05 level using the SAS software system for data analysis (19). Significant differences were found at this level which is very conservative. The results indicated that only the SASP scheduling heuristic is significantly different in mean completion time performance out of the four heuristics tested. There were no significant differences in performance attributable to the due date assignment rule used, however, significant differences in mean completion time were found for each level of project arrival distribution.

To summarize the analysis on mean completion time, it was found that the SASP heuristic performs significantly better than the FIFS, SASP[DD], and MINLFT[DD] heuristics which perform on the same level. Additionally, no significant differences in mean completion time were found attributable to the CPTIME or SFT due date rules. At the .05 family level of significance, the mean completion times were found to be significantly different for each of the project arrival distributions investigated. Finally, no

significant two-factor or three-factor interaction effects
for mean completion time were found by this analysis.

   Mean Delay Time. Mean delay time (or mean lateness)
is a measure of the delay (both positive and negative)
between the actual completion time and the estimated
completion time of a project (due date). It is determined
as follows (5:69):

$$[\sum_{i=1}^{p} (tc_i - dd_i)]/p \qquad\qquad (8)$$

where

   dd_i = due date of project i

   tc_i = time of completion of project i

    p = number of projects

Recall that in this experiment the effort was made to
achieve near zero lateness in order to establish good due
date compensation factors ("k" values) for each combination
of due date rule, scheduling heuristic, and project arrival
distribution. These due date compensation factors were
applied to the due date setting rules to improve their
performance. The table of mean lateness values is presented
in Tables 9 and 10. They are presented graphically in
Figures 16 and 17 according to due date rule.

   A three-factor ANOVA was performed to determine if
there were any significant differences in project mean
lateness. No main factor or interaction effects were found
in this experiment at the .05 family level of significance

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Table 9

Mean Delay Time (Days)

CPTIME Due Date Rule

Project Arrival Distribution

Heuristic	Uniform	Exponential	Triangular	Row Mean
FIFS	1.01	0.75	0.45	0.74
SASP	0.32	0.85	0.34	0.50
SASP[DD]	-0.90	0.76	0.28	0.05
MINLFT[DD]	0.43	1.01	0.35	0.60
Column Mean	0.22	0.84	0.36	0.47

CPTIME DUE DATE RULE
MEAN DELAY TIME

Legend:
- FIFS
- SASP
- SASP[DD]
- MINLFT[DD]

(DAYS)

INTERARRIVAL TIME
(UNIFORM,EXPON.,TRIANG.)
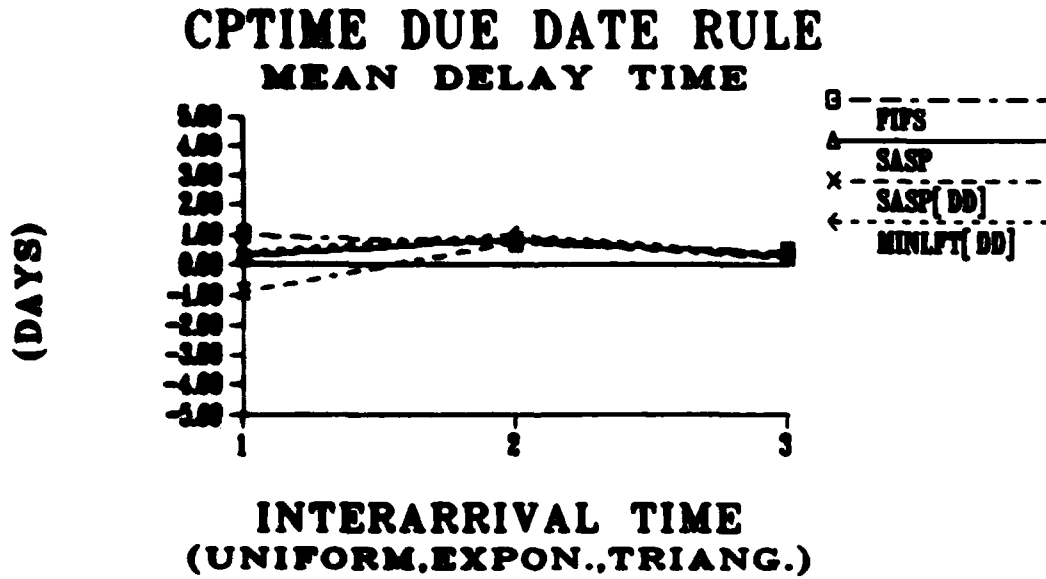
Figure 16. Mean Delay Time - CPTIME Due Date Rule

Table 10

Mean Delay Time (Days)

SFT Due Date Rule

Project Arrival Distribution

Heuristic	Uniform	Exponential	Triangular	Raw Mean
FIFS	0.53	0.57	0.62	0.57
SASP	-0.91	-0.13	-0.24	-0.42
SASP[DD]	0.83	0.44	0.78	0.68
MINLFT[DD]	0.48	0.08	0.22	0.26
Column Mean	0.23	0.24	0.34	0.27

SFT DUE DATE RULE
MEAN DELAY TIME

(DAYS)

INTERARRIVAL TIME
(UNIFORM, EXPON., TRIANG.)
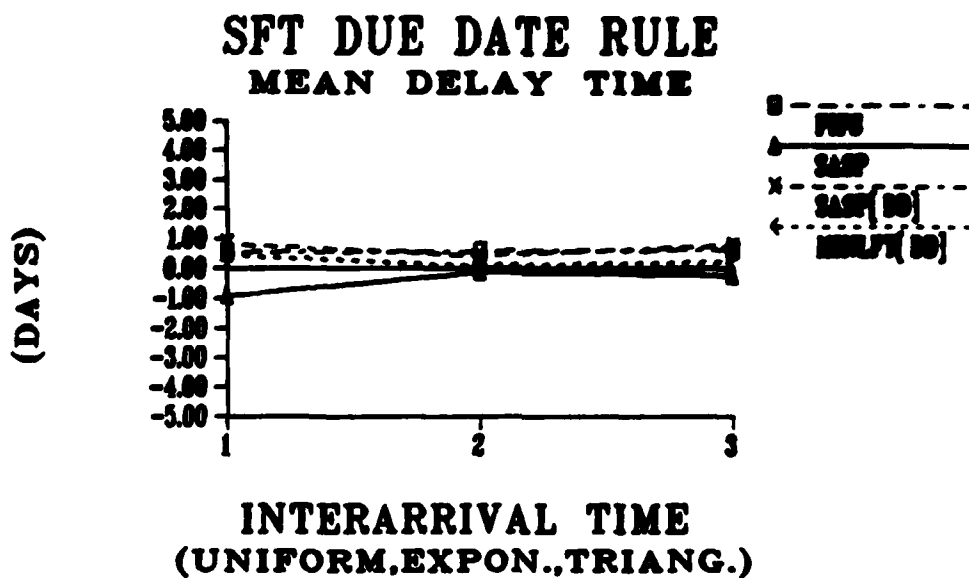
Figure 17. Mean Delay Time - SFT Due Date Rule

This indicates that the choice of h values (see Tables 1 and 2) produced due dates which, in general, resulted in a mean lateness of approximately zero. Again, this result can be expected due to the intentional design of the experiment which was to achieve near zero lateness for all observations (see Appendix A).

Standard Deviation of Lateness. This measure of performance is used to provide some insight into the shape of the lateness distribution. A low standard deviation of lateness demonstrates that most of the projects came close to meeting their due dates while a high standard deviation of lateness indicates that most projects will miss their due dates by a considerable amount of time. The standard deviation of lateness is determined as follows (8:70):

$$\left(\left[\sum_{i=1}^{p}(tc_i - dd_i)^2\right]/(p-1) - \left\{\sum_{i=1}^{p}(tc_i - dd_i)\right\}^2 p/(p-1)\right)^{1/2} \qquad (9)$$

where

    dd_i - due date of project i

    tc_i - time of completion of project i

    p - number of projects

The standard deviation of lateness results are presented according to due date rule in tabular form in Tables 11 and 12, and in graphical form in Figures 18 and 19. Likewise, the results are also presented according to scheduling heuristic in tabular form in Tables 13, 14, 15,

and 16, and in graphical form in Figures 20, 21, 22, and 23. Several observations can be made from the data and are supported by the three-factor ANOVA:

1. The two due date oriented heuristics (SASM(DD) and SIMLFT(DD)) perform about the same but much better for the SFT due date rule.

2. The SASP heuristic performs significantly worse than the others for both due date rules although the performance improves for the SFT due date rule.

3. The FIFS heuristic performs about the same as the two due date oriented heuristics when used with the CPTIME due date rule. However, its performance improves remarkably when used with the SFT due date rule.

4. In general, there is an improvement in the standard deviation of lateness when the more sophisticated SFT due date rule is used.

5. The performance of all four heuristics, for both due date rules, is significantly worse for the exponential project arrival distribution while the performance is the same for the uniform and triangular arrival distributions.

6. An interesting observation can be made with respect to the FIFS/SFT combination. It appears as though this combination of scheduling heuristic and due date assignment rule is insensitive to differences in the project arrival distribution for the measure of standard deviation of lateness. Also, the due date oriented

Table 11

Standard Deviation of Lateness (Days)

CPTIME Due Date Rule

Project Arrival Distribution

Heuristic	Uniform	Exponential	Triangular	Row Mean
FIFS	32.12	46.98	27.08	35.40
SASP	50.00	62.26	44.25	52.17
SASP[DD]	24.74	36.50	20.33	27.19
MINLFT[DD]	21.78	33.75	17.34	24.29
Column Mean	32.16	44.87	27.25	34.76

CPTIME DUE DATE RULE
STD. DEV. OF LATENESS
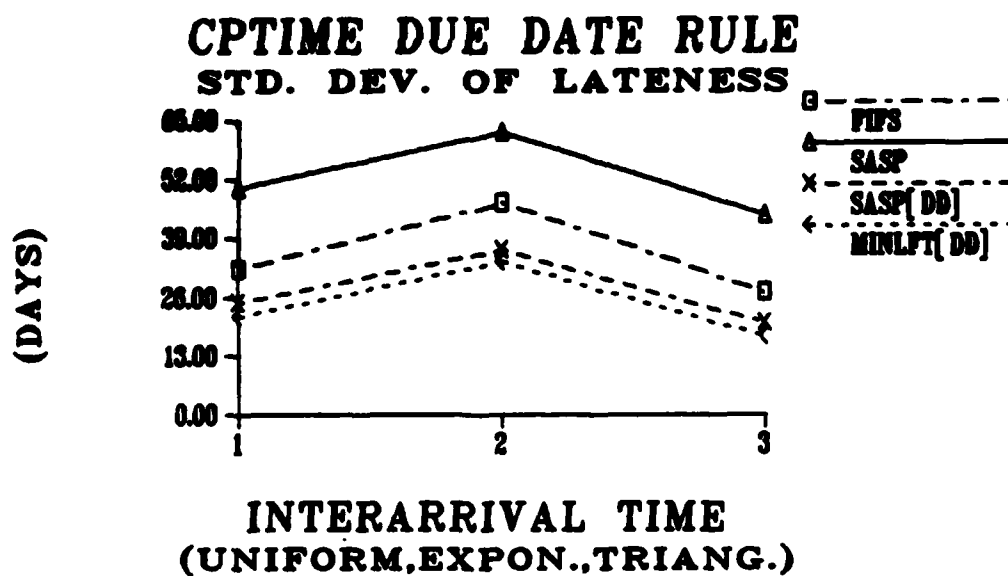
Figure 18. Standard Deviation of Lateness - CPTIME

Heuristic	Uniform	Exponential	Triangular	Row Mean
FIFS	2.88	3.17	2.51	2.75
SASP	41.96	51.71	37.98	43.88
SASP(DD)	9.99	14.88	8.27	10.95
SIMLFT(DD)	9.11	13.61	8.08	10.27
Column Mean	15.91	20.77	14.21	16.96

SFT DUE DATE RULE
STD. DEV. OF LATENESS
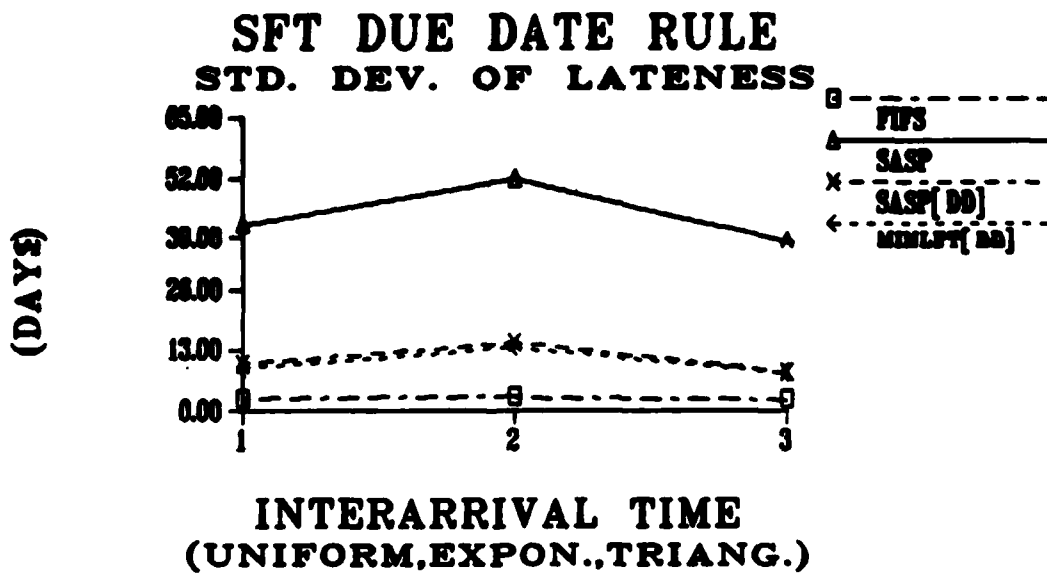
Figure 19. Standard Deviation of Lateness - SFT

Table 13

Standard Deviation of Lateness (Days)

FIFS Scheduling Heuristic

Project Arrival Distribution

Due Date Rule	Uniform	Exponential	Triangular	Row Mean
OPTIMK	22.12	46.96	27.06	35.40
SFT	2.66	3.17	2.51	2.78
Column Mean	17.38	25.07	14.80	19.06

FIFS HEURISTIC
STD. DEV. OF LATENESS
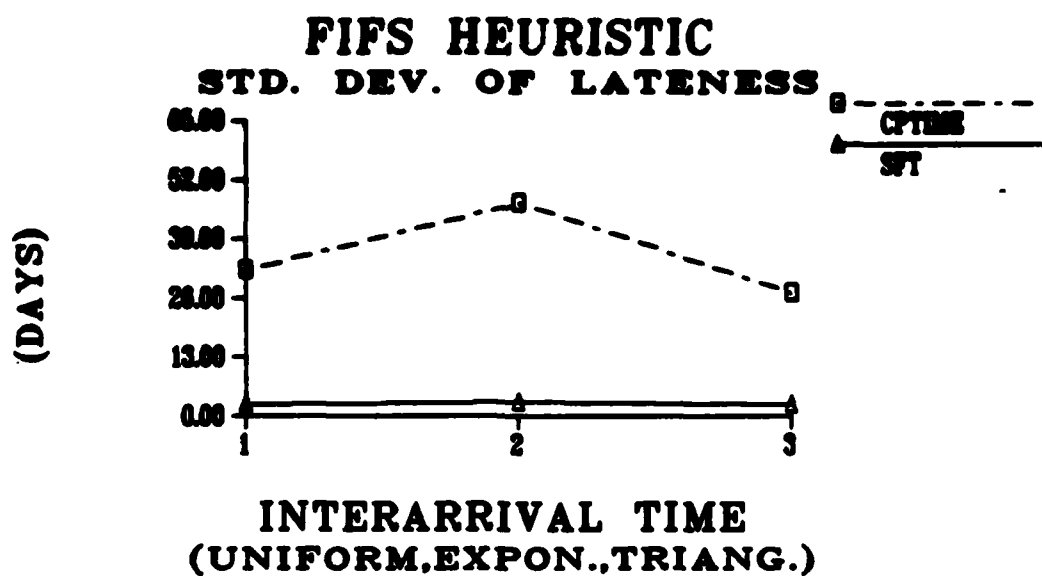
Figure 20.   Standard Deviation of Lateness - FIFS

Table 14

Standard Deviation of Lateness (Days)

SASP Scheduling Heuristic

Project Arrival Distribution

Due Date Rule	Uniform	Exponential	Triangular	Row Mean
OPTIME	50.00	62.26	44.26	52.17
SPT	41.96	51.71	37.96	43.86
Column Mean	46.96	56.99	41.11	46.03

SASP HEURISTIC
STD. DEV. OF LATENESS
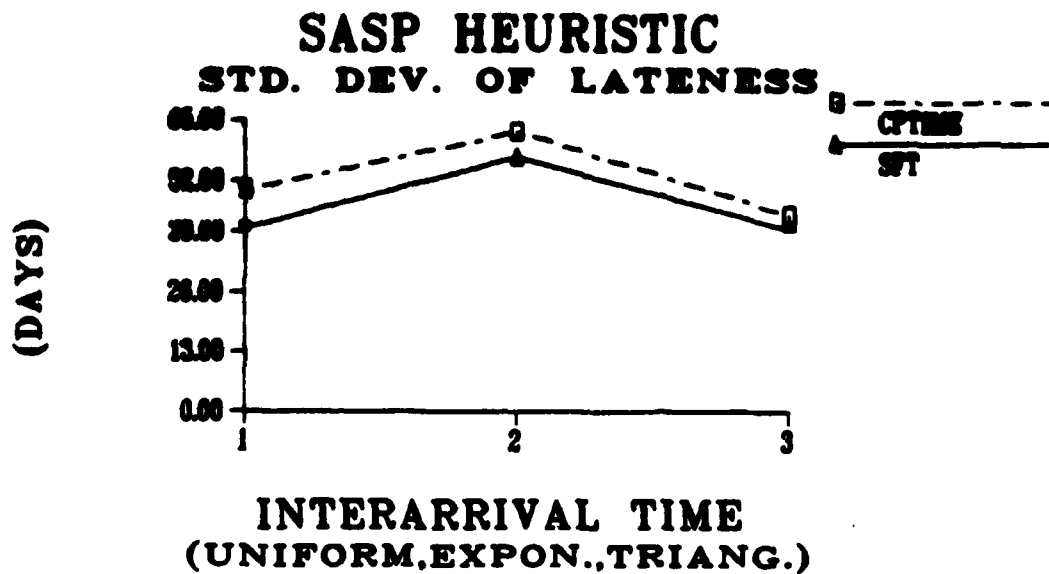
Figure 21.   Standard Deviation of Lateness - SASP

Due Date Rule	Uniform	Exponential	Triangular	Row Mean
OPTIME	24.74	26.80	20.33	27.19
SPT	9.99	14.88	8.27	43.88
Column Mean	17.37	26.84	14.30	19.07

SASP[DD] HEURISTIC
STD. DEV. OF LATENESS
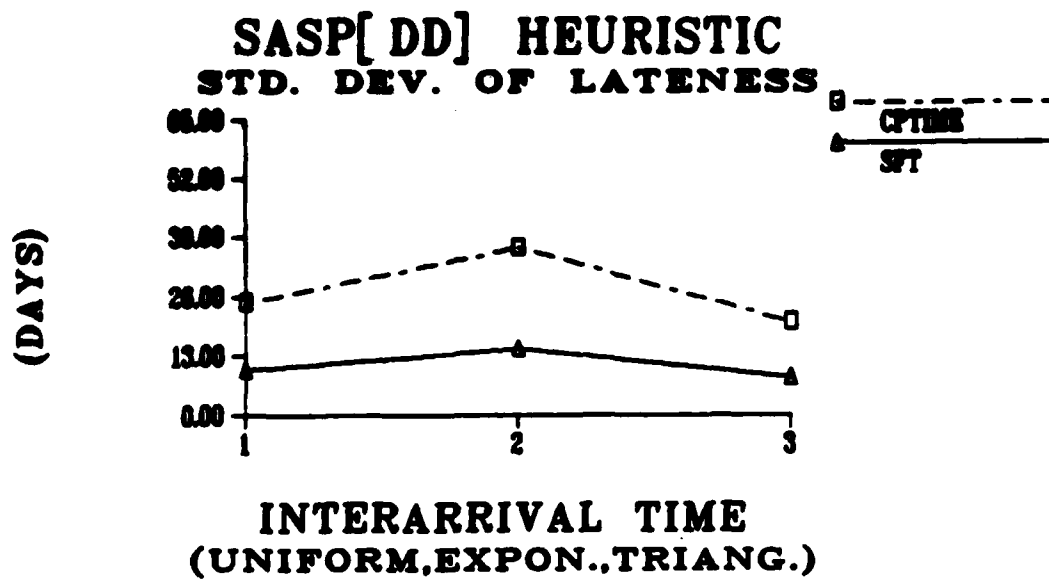
Figure 22.   Standard Deviation of Lateness – SASP[DD]

Table 16

Standard Deviation of Lateness (Days)

MINLFT[DD] Scheduling Heuristic

Project Arrival Distribution

Due Date Rule	Uniform	Exponential	Triangular	Row Mean
OPTIME	21.76	33.76	17.34	24.29
SFT	9.11	13.61	8.08	10.27
Column Mean	15.45	23.68	12.71	17.28
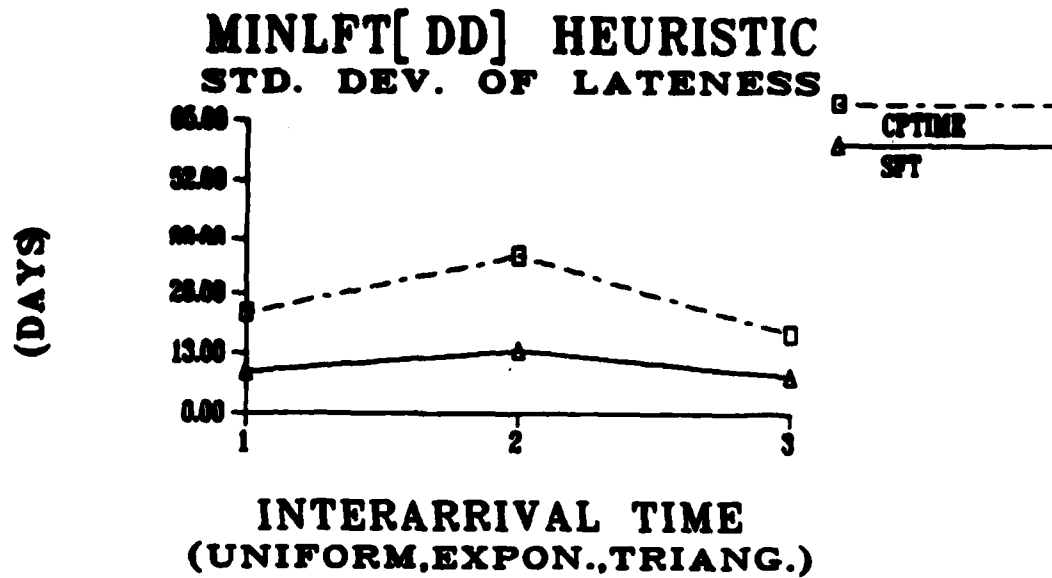
Figure 23. Standard Deviation of Lateness - MINLFT[DD]

scheduling heuristics, when used with the SFT due date rule, become less sensitive to changes in the project arrival distribution, but not as much as the FIFS/SFT combination.

7. There is definitely some interaction effects present between the scheduling heuristic and due date factors as well as some interaction effects between the due date rule and project arrival factors. This can be readily seen in the graphs presented. Note that the parallelism for these factors is no longer present.

The three-factor ANOVA indicates that there are significant main effects present at the 0.05 family level of significance for all factors and there are significant interaction effects between heuristic and due date rule combinations and between due date rule and arrival distribution combinations in the experiment. The results of these statistical tests on the standard deviation of lateness are provided in Appendix A.

Multiple comparison tests were conducted in order to identify which levels of the factors were significantly different from one another. Tukey, Bonferroni, and Scheffe tests were conducted at the 0.0073 level which provides a family level of significance of 0.05. The results indicated that for the scheduling heuristic factor, the SASP heuristic performs significantly worse than all of the other heuristics tested. The due date rule factor tests indicated that the SFT due date rule provided significantly better

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results in terms of the standard deviation of lateness measure for all cases. This is especially true for the FIFS/SFT combination as illustrated in Figure 19. The ANOVA also indicates that all scheduling heuristic and due date rule combinations perform significantly worse for the exponential project arrival distribution level results.

In summary, the standard deviation of lateness results indicate that the SASP heuristic is a very poor performer regardless of the due date rule and the FIFS/SFT combination of scheduling heuristic and due date assignment rule emerges as a remarkable performer. Most importantly, the FIFS/SFT combination proved to be insensitive to the project arrival distribution which is a desired result. The due date oriented scheduling heuristics, when used with the SFT due date rule, demonstrated a decrease in sensitivity to project arrival distribution compared to the due date oriented heuristics using the CPTIME due date rule. In general, the exponential arrival distribution has a significant impact on the standard deviation of lateness, except for the FIFS/SFT heuristic and when the SFT due date rule is used with due date oriented scheduling heuristics.

Mean Tardiness. Project mean tardiness is the average amount of positive lateness for each project that has exceeded its due date. It is determined as follows (5:104):

$$\sum_{i=1}^{L} (tardiness)_i / L \qquad (10)$$

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where

$$(\text{tardiness})_i = 0 \text{ if } (tc_i - dd_i) >= 0$$

$$(\text{tardiness})_i = tc_i - dd_i, \text{ otherwise}$$

$$L = \text{total number of projects tardy}$$

Project managers may be more concerned with how late, on the average, they tend to complete projects when tardy than how often they miss due dates. If tardiness is a more important factor, mean tardiness can provide a "fudge" factor for the project manager when promising due dates to customers. The mean tardiness data is provided in tabular form according to due date rule in Tables 17 and 18 and in graphical form in Figures 24 and 25. Tables 19, 20, 21, 22 and Figures 26, 27, 28, and 29 present the data according to scheduling heuristic. Some general observations can be made from these results in terms of mean tardiness performance:

1. The due date oriented scheduling heuristics (SASP[DD] and MINLFT[DD]) perform characteristically the same for each due date rule and their performance is better for the SFT due date rule than the CPTIME due date rule.

2. The SASP heuristic performs poorly in terms of project mean tardiness.

3. The FIFS heuristic performs remarkably well when combined with the SFT due date rule.

Table 17

Mean Tardiness (Days)

CPTIME Due Date Rule

Project Arrival Distribution

Heuristic	Uniform	Exponential	Triangular	Row Mean
FIFS	12.76	18.28	10.60	13.87
SASP	11.87	15.48	10.74	12.70
SASP(DD)	9.30	14.53	8.20	10.71
MINLFT(DD)	8.66	13.42	6.91	9.66
Column Mean	10.67	15.42	9.11	11.73

CPTIME DUE DATE RULE
MEAN TARDINESS
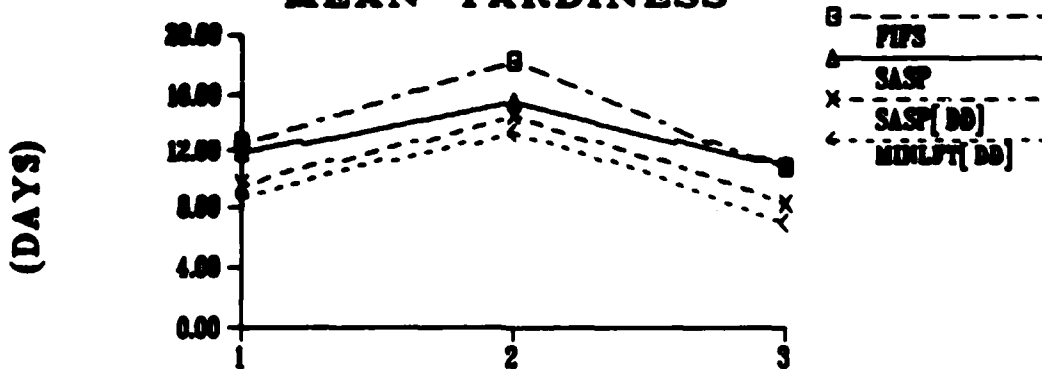
Figure 24.   Mean Tardiness - CPTIME

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Table 16

Mean Tardiness (Days)

SFT Due Date Rule

Project Arrival Distribution

Heuristic	Uniform	Exponential	Triangular	Row Mean
FIFS	1.13	1.27	1.16	1.18
SASP	9.66	12.19	9.17	10.34
SASP[DD]	4.46	6.01	3.85	4.77
MINLFT[DD]	4.03	5.51	3.52	4.35
Column Mean	4.82	6.24	4.42	5.16
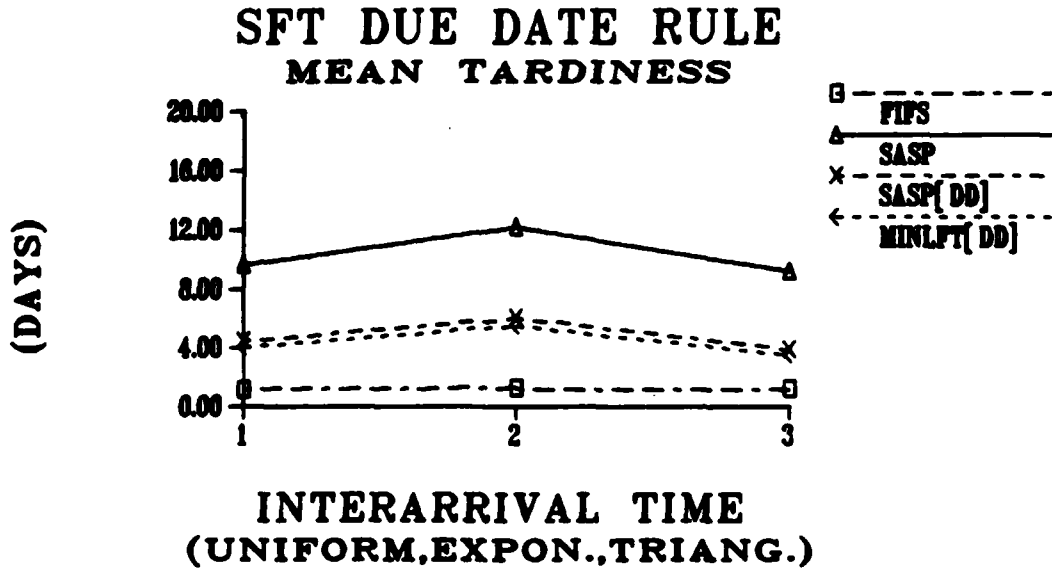
Figure 25. Mean Tardiness - SFT

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A
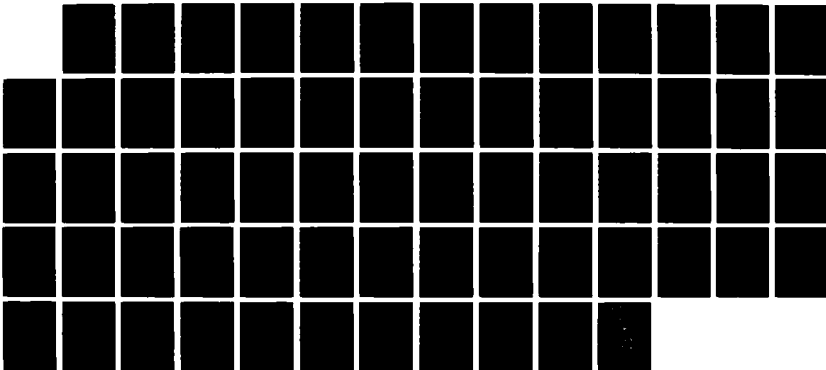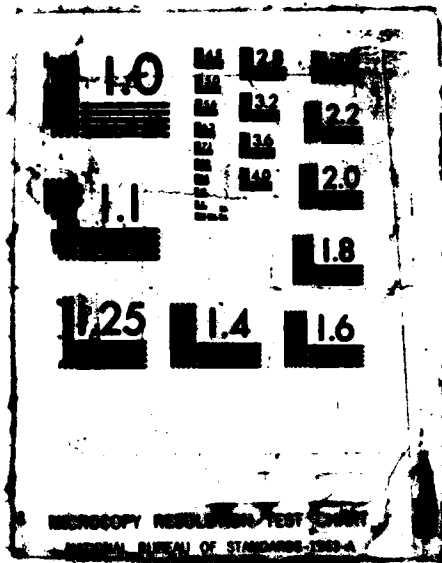
Table 19

Mean Tardiness (Days)

FIFS Scheduling Heuristic

Project Arrival Distribution

Due Date Rule	Uniform	Exponential	Triangular	Row Mean
CPTIME	12.76	18.25	10.60	13.87
SFT	1.13	1.27	1.16	1.18
Column Mean	6.94	9.76	5.88	7.53
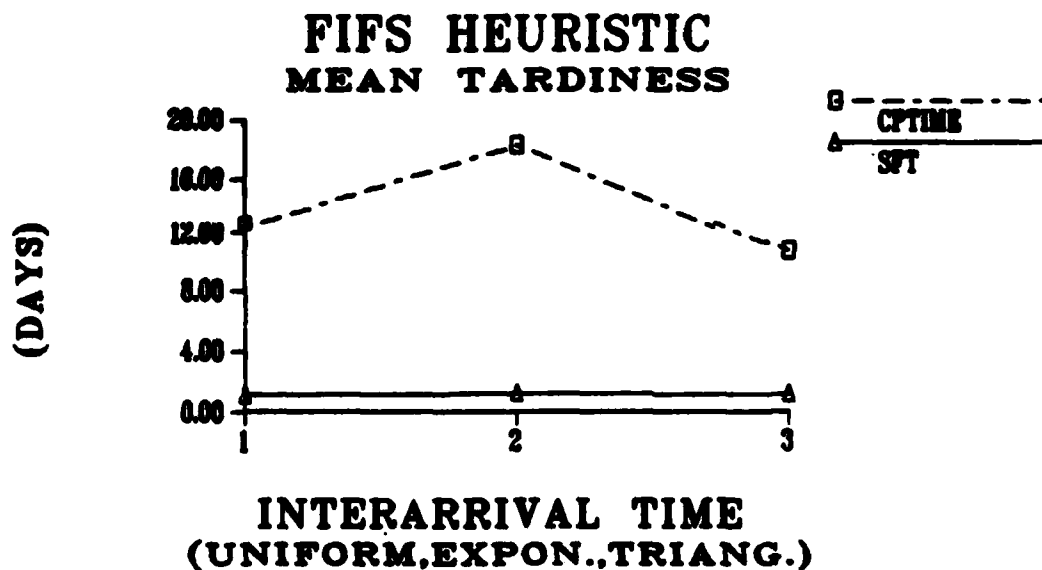
Figure 26. Mean Tardiness - FIFS Heuristic

Table 20

Mean Tardiness (Days)

SASP Scheduling Heuristic

Due Date Rule	Project Arrival Distribution			
	Uniform	Exponential	Triangular	Row Mean
CPTIME	11.87	15.48	10.74	12.70
SFT	9.66	12.19	9.17	10.34
Column Mean	10.77	13.83	9.95	11.52
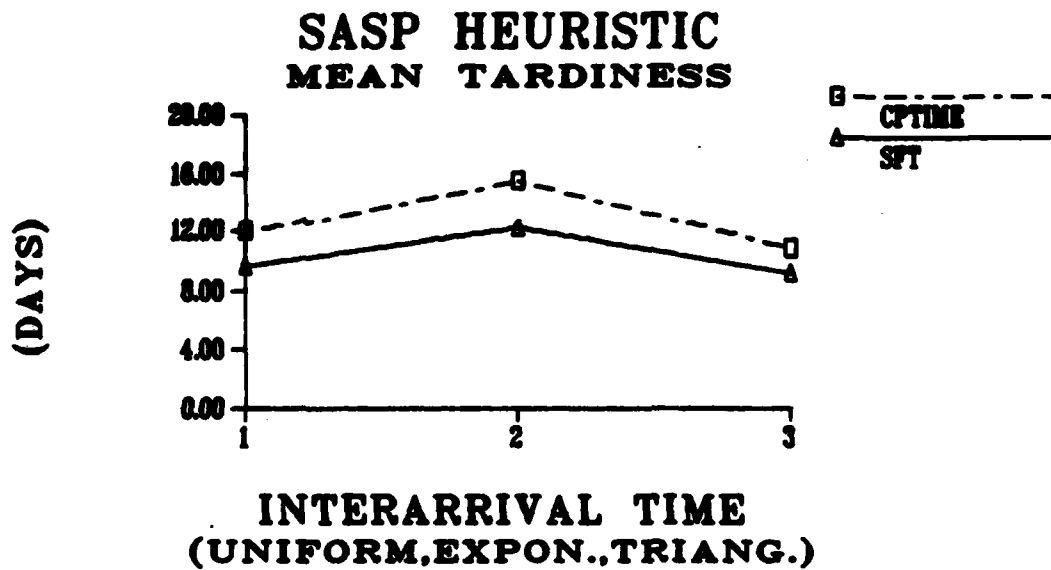
Figure 27. Mean Tardiness - SASP Heuristic

Table 21

Mean Tardiness (Days)

SASP[DD] Scheduling Heuristic

Project Arrival Distribution

Due Date Rule	Uniform	Exponential	Triangular	Row Mean
CPTIME	9.39	14.63	8.20	10.71
SFT	4.46	6.01	3.85	4.77
Column Mean	6.92	10.27	6.02	7.74

SASP[DD] HEURISTIC
MEAN TARDINESS

•INTERARRIVAL TIME
(UNIFORM,EXPON.,TRIANG.)
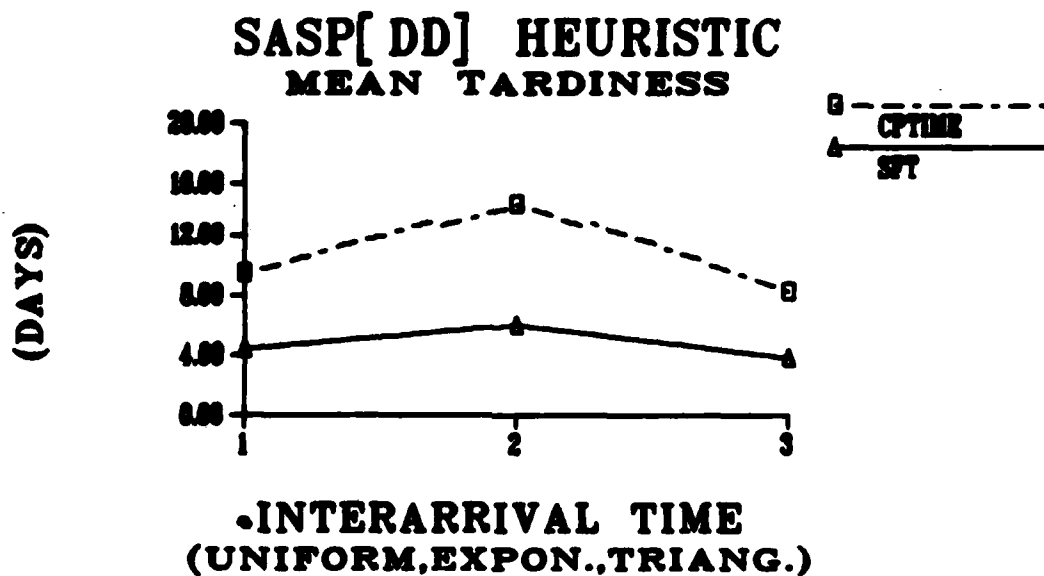
Figure 28.   Mean Tardiness - SASP[DD] Heuristic

Table 22

Mean Tardiness (Days)

MINLFT[DD] Scheduling Heuristic

Due Date Rule	Project Arrival Distribution			
	Uniform	Exponential	Triangular	Row Mean
CPTIME	8.66	13.42	6.91	9.66
SFT	4.03	5.51	3.52	4.35
Column Mean	6.34	9.47	5.22	7.01
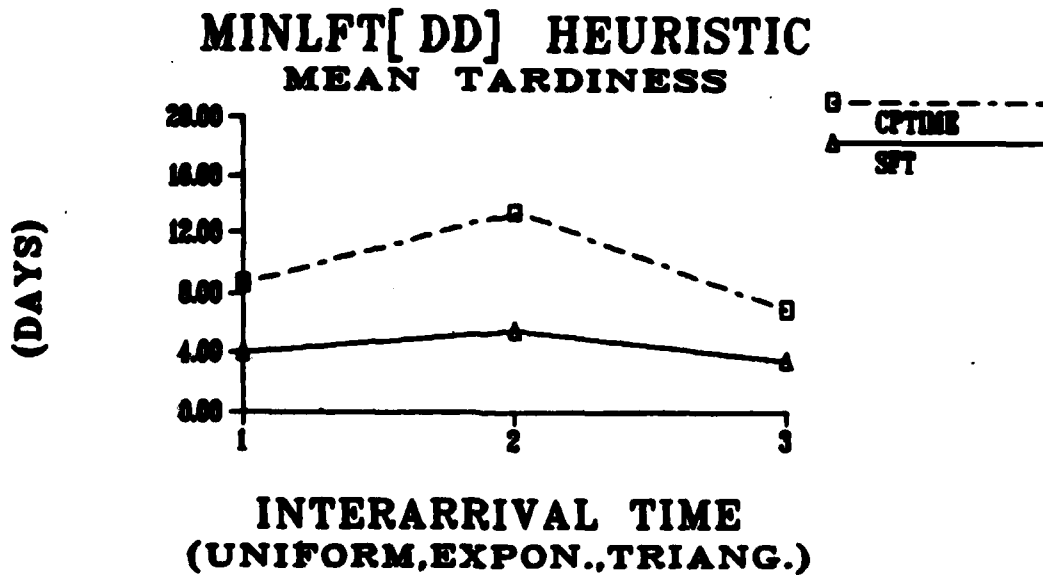
Figure 29.   Mean Tardiness - MINLFT[DD] Heuristic

4. In general, the mean tardiness performance improves across the board when the SFT due date rule is combined with any of the scheduling heuristics tested in this experiment.

5. Again, the mean tardiness results from the exponential arrival distribution tend to be worse than the other two distributions investigated.

These observations are supported by the three-factor ANOVA. Significant main effects for all three factors (heuristic, due date rule, and arrival distribution). Significant two-factor interaction effects were found for the scheduling heuristic and due date rule factor combinations as well as for the due date rule and arrival distribution factor combinations. No other interaction effects were found to be significant in this portion of the experiment.

Multiple comparison tests were conducted at the 0.0073 level to provide a family level of significance of 0.05 for the seven tests. Tukey, Bonferroni, and Scheffe test were conducted at the .05 family level of significance. The results show that the SASP scheduling heuristic mean tardiness performance is significantly worse than the other three heuristics. There is clearly a significant difference between both of the due date rules and the exponential project arrival distribution accounts for the differences in mean tardiness. The ANOVA procedure and

statistical tests for mean tardiness can be found in Appendix A.

In summary, the mean tardiness results indicate that the combination of FIFS scheduling heuristic and SFT due date rule is clearly the best performer while the FIFS/CPTIME combination is the poorest. Most importantly, the FIFS/SFT combination seems to be insensitive to differences in project arrival distribution. The due date oriented heuristics used with the SFT due date rule also demonstrated a decrease in sensitivity to the different arrival distributions. This insensitivity is a desired result because one would not have to be concerned about the potential impact on mean tardiness if the arrival distribution is unknown.

Average Resource Utilization Rate. This research effort did not investigate thoroughly the behavior of the resource utilization rate during the experiment other than to make some general observations to ensure that the overall resource utilization rate was approximately 85 per cent. Upon completion of the simulation of 2000 days per simulation run it was found that the average resource utilization rate was approximately 85 per cent for all three types of project arrival distribution. However, samples of the average resource utilization rate during each simulation run revealed some interesting behavior. The variation in the resource utilization rate appears to be very small for

the uniform project arrival distribution runs. In other words, the project load in the system tends to be fairly constant during the 2000 days of simulation time. Likewise, the triangular project arrival results revealed a small, but somewhat larger than the uniform distribution, variation in the average resource utilization rate during each run. The interesting observation occurred during the exponential project arrival distribution runs. The project interarrival times tend to be very small and very large at times, causing the project load in the system to vary during the simulation and, therefore, the average resource utilization rate varies considerably compared to the other project arrival distribution runs. When the project interarrival time is small the project load in the system is high and therefore the resource utilization rate is high. On the other hand, when the time between project arrivals is long the system project load is low and consequently the resource utilization rate is low. In the long run, the average resource utilization rate for the exponential arrival distribution is still approximately 85 per cent.

Summary of the Results

The purpose of this experiment was to produce data from the simulation of the dynamic, multi-project, constrained resources scheduling environment and analyze the results to search for answers to the research questions posed in Chapter 1. This experiment was an extension to

previous research conducted on the performance of scheduling
heuristics and due date assignment rules in a dynamic,
project scheduling environment. The objective was to
interject another factor into the previous experiments
performed, specifically, different types of project arrival
distributions, and to analyze the impact on the performance
of scheduling heuristics, due date assignment rules, and
combinations of scheduling heuristic and due date rule.

In order to address the research questions posed in
Chapter 1, the results have been grouped according to
project arrival distribution for each of the performance
parameters and presented below. The data is presented below
in both tabular and graphical format in order to clearly
present the differences in each performance measurement due
to differences in project arrival distribution.

The results of this three-factor, full factorial
experiment indicate that the performance of scheduling
heuristics, due date rules, and combinations thereof,
were similar to the two-factor experiments conducted earlier
by others (5). In other words, no new surprises were
discovered for the scheduling heuristic factor or the due
date rule factor. The SFT due date rule provides
significantly better performance on all due date measures
without any penalty in minimizing mean completion times (see
figures 30-38). However, it was discovered that the new
factor, project arrival distribution, impacts the ability of

Table 23

Mean Completion Time (Days)

Uniform Project Arrival Distribution

Due Date Rule

Heuristic	CPTIME	SFT	Row Mean
FIFS	64.24	64.24	64.24
SASP	56.96	56.96	56.96
SASP[DD]	62.80	63.43	63.12
MINLFT[DD]	61.54	63.89	62.71
Column Mean	61.39	62.13	61.76
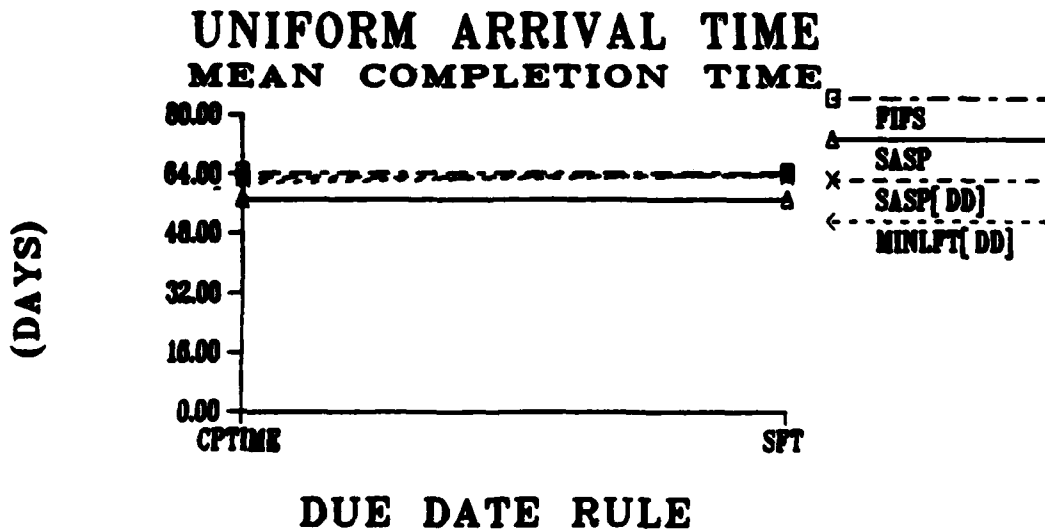
Figure 30. Mean Completion Time
Uniform Arrival Distribution

Table 24

Mean Completion Time (Days)

Exponential Arrival Distribution

Due Date Rule

Heuristic	CPTIME	SFT	Row Mean
FIFS	75.51	75.51	75.51
SASP	64.05	64.05	64.05
SASP[DD]	74.36	74.70	74.53
MINLFT[DD]	73.71	76.31	75.01
Column Mean	71.91	72.65	72.28

EXPONENTIAL ARRIVAL TIME
MEAN COMPLETION TIME
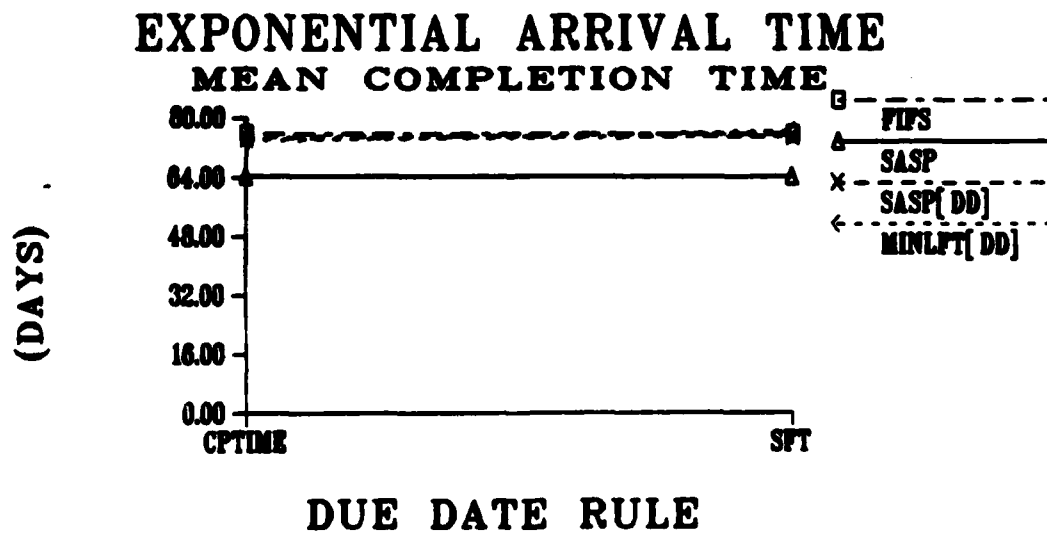
Figure 31. Mean Completion Time
Exponential Arrival Distribution

Table 25

Mean Completion Time (Days)

Triangular Arrival Distribution

Due Date Rule

Heuristic	CPTIME	SFT	Row Mean
FIFS	60.78	60.78	60.78
SASP	55.11	55.11	55.11
SASP[DD]	59.36	59.85	59.61
MINLFT[DD]	58.28	60.25	59.27
Column Mean	58.38	59.00	58.69

TRIANGULAR ARRIVAL TIME
MEAN COMPLETION TIME
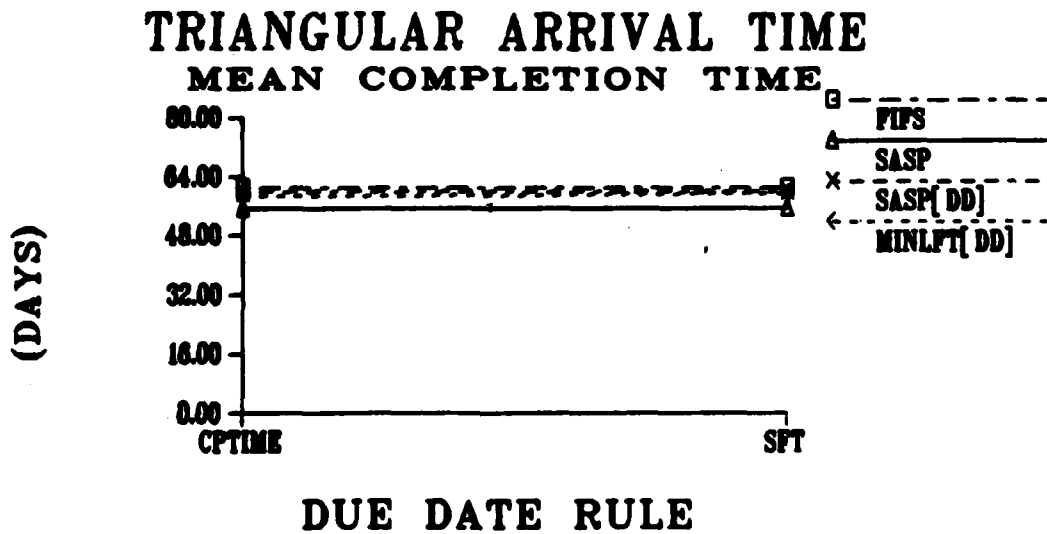
Figure 32. Mean Completion Time
Triangular Arrival Distribution

Table 26

Standard Deviation of Lateness (Days)

Uniform Arrival Distribution

Heuristic	Due Date Rule		
	CPTIME	SFT	Row Mean
FIFS	32.12	2.58	17.35
SASP	50.00	41.96	45.98
SASP[DD]	24.74	9.99	17.37
MINLFT[DD]	21.78	9.11	15.45
Column Mean	32.16	15.91	24.04
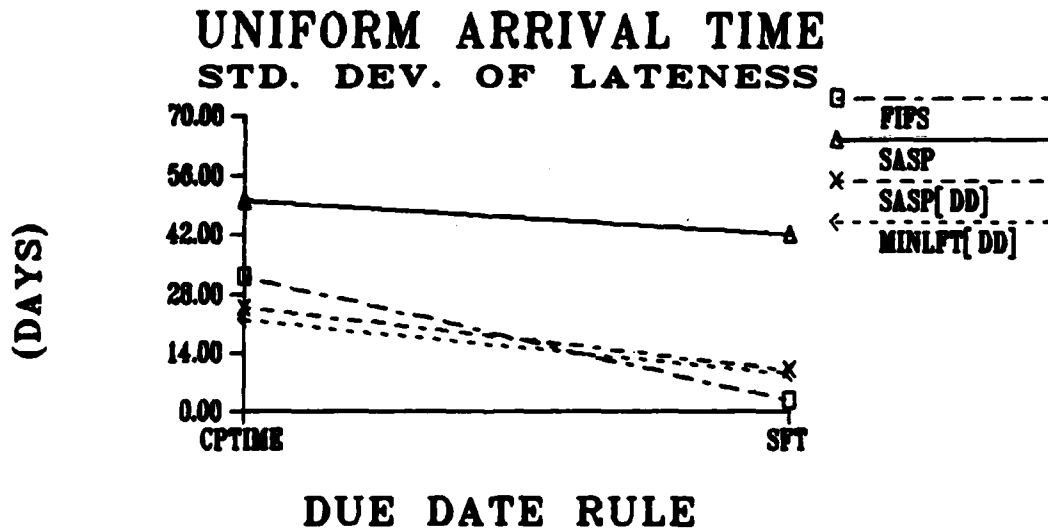
Figure 33.   Standard Deviation of Lateness
Uniform Arrival Distribution

Table 27

Standard Deviation of Lateness (Days)

Exponential Arrival Distribution

Due Date Rule

Heuristic	CPTIME	SFT	Row Mean
FIFS	46.98	3.17	25.07
SASP	62.26	51.71	56.99
SASP[DD]	36.50	14.58	25.54
MINLFT[DD]	33.75	13.61	23.68
Column Mean	44.87	20.77	32.82
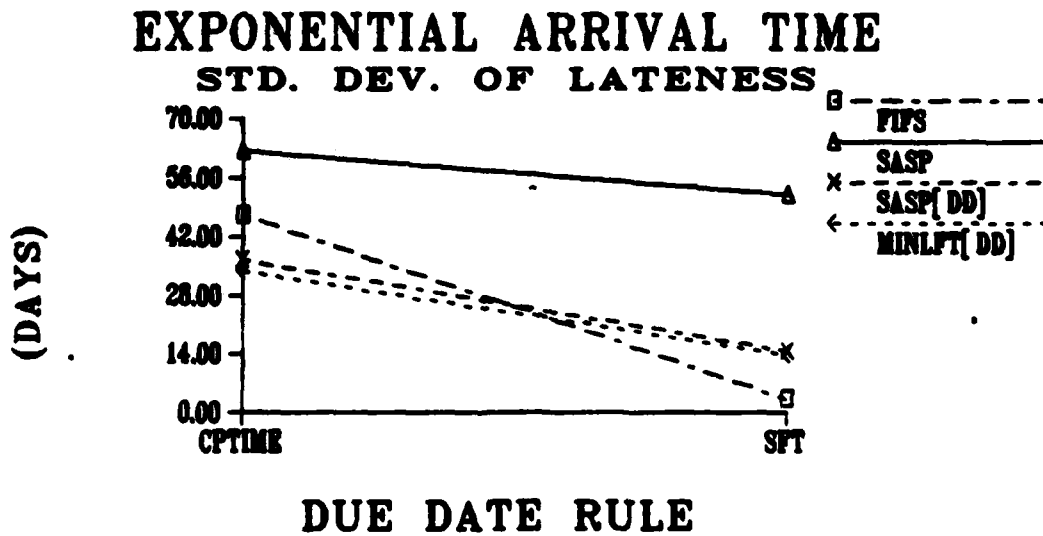
Figure 34. Standard Deviation of Lateness
Exponential Arrival Distribution

Table 28

Standard Deviation of Lateness (Days)

Triangular Arrival Distribution

Due Date Rule

Heuristic	CPTIME	SFT	Row Mean
FIFS	27.08	2.51	14.80
SASP	44.25	37.98	41.11
SASP[DD]	20.33	8.27	14.30
MINLFT[DD]	17.34	8.08	12.71
Column Mean	27.25	14.21	20.73

TRIANGULAR ARRIVAL TIME
STD. DEV. OF LATENESS
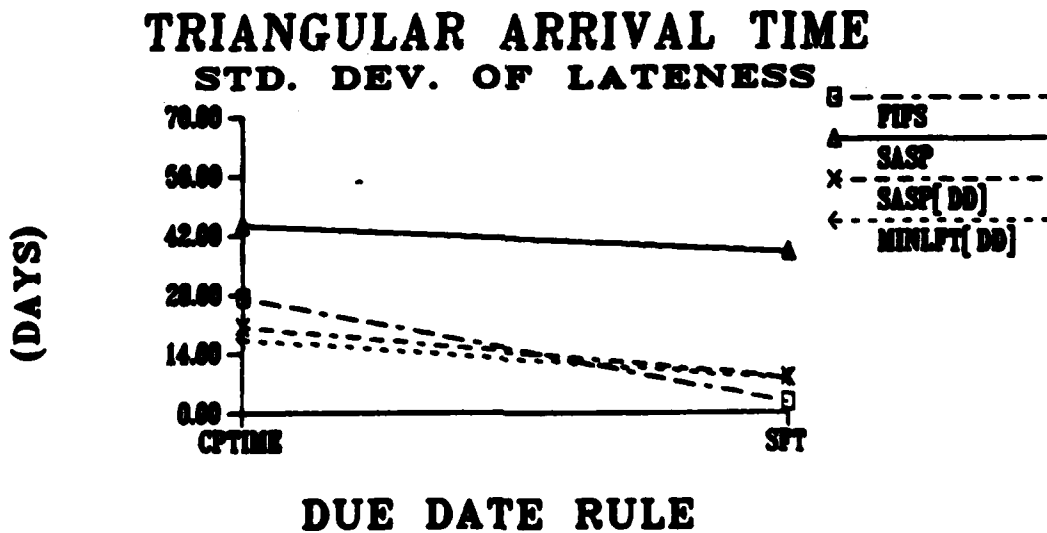
Figure 35. Standard Deviation of Lateness
Triangular Arrival Distribution

Table 29

Mean Tardiness (Days)

Uniform Arrival Distribution

	Due Date Rule		
Heuristic	CPTIME	SFT	Row Mean
FIFS	12.76	1.13	6.94
SASP	11.87	9.66	10.77
SASP[DD]	9.39	4.46	6.92
MINLFT[DD]	8.66	4.03	6.34
Column Mean	10.67	4.82	7.74
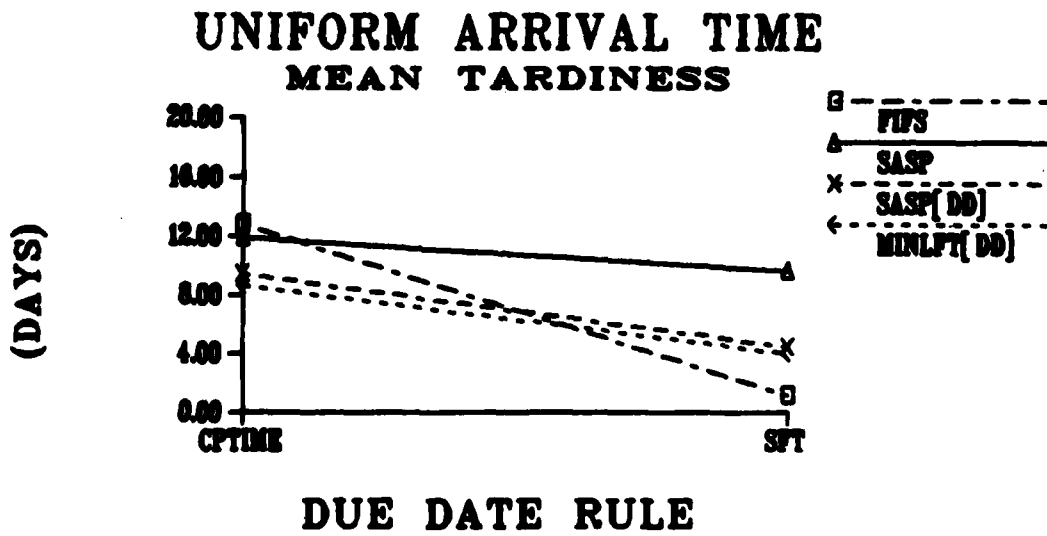
Figure 36. Mean Tardiness
Uniform Arrival Distribution

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Table 30

Mean Tardiness (Days)

Exponential Arrival Distribution

Due Date Rule

Heuristic	CPTIME	SFT	Row Mean
FIFS	18.25	1.27	9.76
SASP	15.48	12.19	13.83
SASP[DD]	14.53	6.01	10.27
MINLFT[DD]	13.42	5.51	9.47
Column Mean	15.42	6.24	10.83
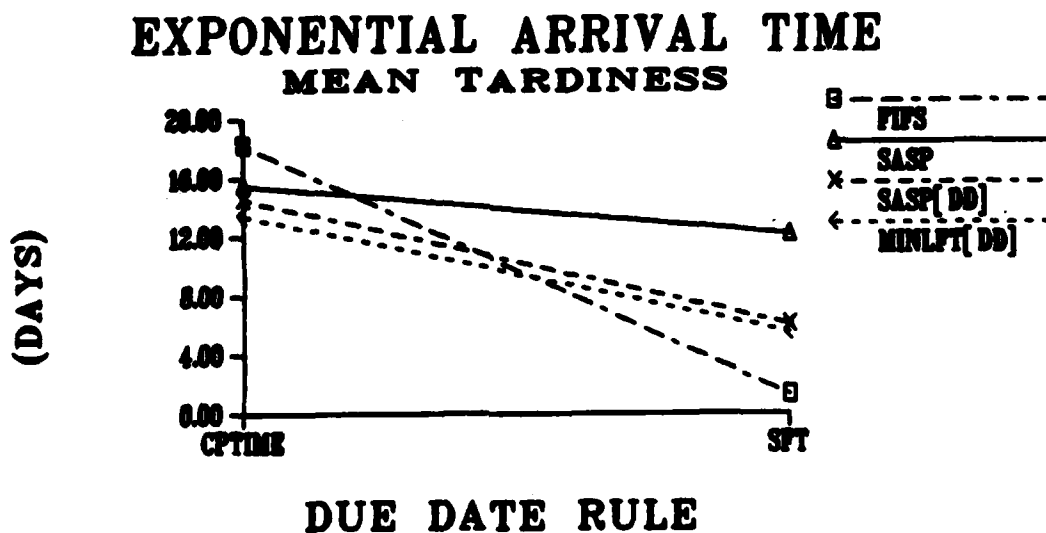
Figure 37. Mean Tardiness
Exponential Arrival Distribution

Table 31

Mean Tardiness (Days)

Triangular Arrival Distribution

Heuristic	CPTIME	SFT	Row Mean
		Due Date Rule	
FIFS	10.60	1.16	5.88
SASP	10.74	9.17	9.95
SASP[DD]	8.20	3.85	6.02
MINLFT[DD]	6.91	3.52	5.22
Column Mean	9.11	4.42	6.77

TRIANGULAR ARRIVAL TIME
MEAN TARDINES
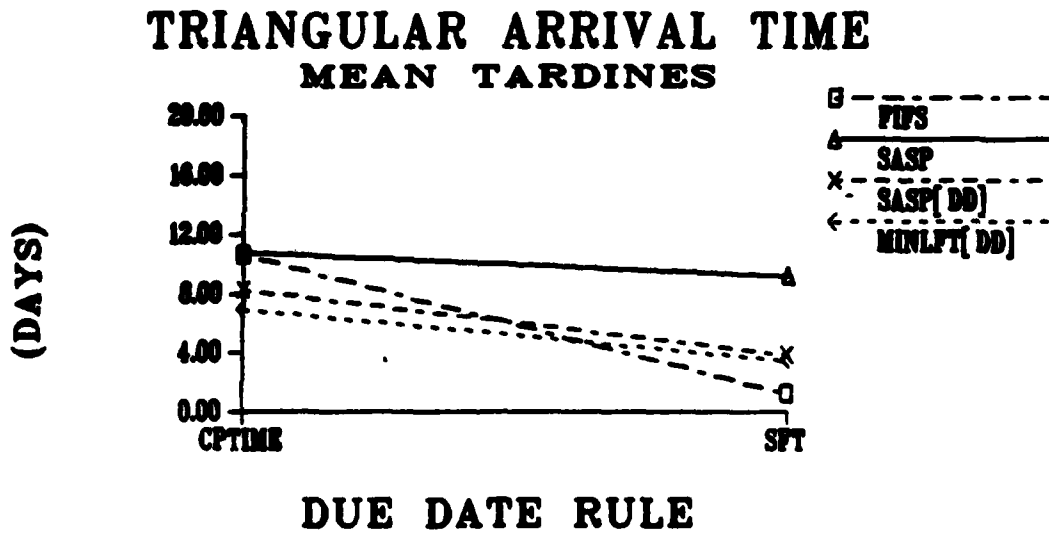
Figure 38. Mean Tardiness
Triangular Arrival Distribution

due date assignment rules and scheduling heuristics to meet
due dates. Therefore, the remainder of this discussion will
focus on the research questions posed in Chapter 1.

Research Question 1. Are scheduling heuristics,
investigated in previous research, impacted by whether new
projects arrive according to a uniform, exponential, or
triangular distribution?

This question is answered in terms of two major
performance criteria: ability to minimize the mean
completion times of projects and ability to meet established
due dates.

If mean completion time is the important factor then
the results show that all of the heuristics tested were
found to be sensitive to each of the different project
arrival distributions. Figures 10 and 11 illustrate
the differences in mean completion time for each project
arrival distribution. The three-factor ANOVA revealed a
significant difference in mean completion times existed and
the multiple comparison tests indicated that all three
project arrival distribution mean completion times were
significantly different from one another. The average mean
completion times for each scheduling heuristic are the
column mean values shown in Tables 3 and 4.

The SASP heuristic is the best performing heuristic in
terms of mean completion time while the other three
heuristics perform equally well but worse than the SASP

heuristic. If the SASP heuristic is chosen based on its mean completion time performance then one needs to be aware that it's exceptional performance is due to its ability to get small projects done very quickly, at the expense of long projects which take longer than normally expected.

The ability of scheduling heuristics to meet established due dates is measured in terms of standard deviation of lateness and mean tardiness. The standard deviation of lateness measures how close to the due date projects are completed. Mean tardiness measures the average tardiness (positive lateness) of a project when it is tardy. The performance of the heuristics relative to these measures is the same and will be discussed together.

The SASP heuristic performs poorly on these due date performance measures. With regard to both standard deviation of lateness and mean tardiness it performed significantly worse than the other three heuristics tested, SASP[DD], MINLFT[DD], and FIFS (see Tables 11, 12, 17 and 18 and Figures 18, 19, 24 and 25). These latter three heuristics performed equally well on both due date measures. The performance of all four heuristics deteriorates when the projects arrive according to an exponential distribution relative to their performance when projects arrive according to a uniform or triangular distribution. It must be noted that, although the absolute performance of the heuristics changes depending on the arrival distribution, the relative

performance of the heuristics is unchanged and similar to that found earlier (5, 6).

In summary, the answer to this research question is that the heuristics do perform differently, in an absolute sense, depending on the arrival distribution of new projects. However, in a relative sense the heuristics perform the same; that is, SASP does better in minimizing mean completion time and worse at meeting due dates than the other three heuristics tested (FIFS, SASP[DD], and MINLFT[DD]), regardless of the arrival distribution. This finding extends the generalizability of the research cited earlier (5, 6).

Research Question 2. Are due date setting rules, investigated in previous research, impacted by whether new projects arrive according to a uniform, exponential, or triangular distribution?

Recall that the due date for each project is set when it arrives to the system and is established by either the CPTIME or SFT due date assignment rule. Figures 30-38 illustrate the comparison of CPTIME and SFT due date assignment rules and their impact on the various performance measures observed in this experiment. Again, this question will be answered in terms of two major performance criteria: ability to minimize the mean completion time of projects and ability to meet established due dates.

With regard to mean completion time, there is very little difference in mean completion time attributable to differences in due date rules (see Figures 30-32). However, mean completion time performance is sensitive to the project arrival distribution and scheduling heuristic used.

With regard to due date performance it is obvious that the SFT due date assignment rule does a much better job at setting due dates, regardless of the project arrival distribution, compared to the CPTIME rule (see Figures 33-38). The standard deviation of lateness and mean tardiness is sensitive to the project arrival distribution and scheduling heuristic used when due dates are set according to the CPTIME rule. In general, this sensitivity diminishes when the SFT due date assignment rule is used.

In summary, the answer to this research question is that due date assignment rules do perform differently , in an absolute sense, depending on the arrival distribution of new projects. However, in a relative sense the due date setting rules perform the same: that is, SFT is a much better method of setting due dates when meeting due dates is important. In terms of minimizing mean completion time, the CPTIME and SFT due date assignment rules perform equally well. This finding extends the generalizability of the research cited earlier (5, 6).

Research Question 3. Are any combination of scheduling heuristic and due date setting rule, investigated earlier, impacted by whether new projects arrive according to a uniform, exponential, or triangular distribution?

With regard to mean completion time, there was virtually no difference attributable to a specific combination. Although SASP outperformed the other heuristics on this measure, its performance was identical for the SASP/CPTIME combination and the SASP/SFT combination. Likewise, the other three heuristics when combined with a due date setting rule resulted in virtually the same performance regardless of which due date setting rule was used.

This was not the case with regard to the due date performance criteria, standard deviation of lateness and mean tardiness. As noted in the answer to research question 2, the SFT due date setting rule outperformed the CPTIME due date setting rule. When the SFT rule is used in combination with any heuristic, the combination outperformed, on both due date measures, the CPTIME combination with that same heuristic.

The most interesting observation during this experiment was the outstanding performance of one combination, FIFS/SFT, on the due date criteria. This combination outperformed all other combinations on both due date measures. Additionally, its due date performance remained

the best regardless of the arrival distribution of new projects. It appears reasonably insensitive to the arrival distribution. This result extends the generalizability of the research cited earlier (5, 6).

This chapter provided the detailed results of the experiment and addressed the three research questions posed earlier in Chapter 1. These results will be summarized in Chapter 4 and some insight to the significance of these findings, practical implications of these results, and suggestions for future research will be provided.

IV. Conclusions and Recommendations

This chapter summarizes the results of the simulation experiment. The results indicate that scheduling heuristics, due date rules, and combinations thereof are generally sensitive, in an absolute sense, to whether projects arrive according to uniform, exponential, or triangular distributions. They also confirm that the relative performance of the tested scheduling heuristics, due date assignment rules, and combinations thereof, is the same regardless of the project arrival distribution. Additionally, one particular combination, the FIFS scheduling heuristic and SFT due date assignment rule, proved to be insensitive even in an absolute sense to the different arrival distributions tested. The significance of these findings, a discussion of the practical implications of these findings, and recommendations for future research are addressed below.

Significance of the Findings. Although management can control the method for setting due dates and scheduling resources to activities to meet these due dates, it cannot easily control the arrival distribution of new projects. Performance of several heuristics and due date setting rules was previously determined for projects arriving uniformly. It is important to know if these findings hold for other arrival distributions and, if not, which heuristics and due date rules perform better in different environments.

In almost every case it was found that the absolute performance of scheduling heuristics and/or due date assignment rules are most sensitive to the exponential project arrival distribution. The performance with regard to mean completion time was significantly different for each arrival distribution, and worst in the exponential arrival distribution environment. The performance of the scheduling heuristics and due date setting rules on the due date criteria, standard deviation of lateness and mean tardiness, was found to be significantly different for the exponential arrival distribution.

The differences in relative performance attributable to either the scheduling heuristic factor or the due date assignment rule factor of this experiment were basically the same results observed previously (5). SASP performs well on the criterion of mean completion time but poorly on the due date oriented measures. And, in general, the other three heuristics tested, SASP[DD], MINLFT[DD], and FIFS, perform equally well. The analysis indicated some interaction between the due date rule factor and the arrival distribution factor for the standard deviation of lateness and mean tardiness results. In general, the SFT due date assignment rule performed significantly better than the CPTIME rule even in the difficult exponential arrival distribution environment. The SFT due date rule seems to adjust well to the project arrival distributions.

And, although the CPTIME due date rule is much simpler to implement than the SFT due date rule, it was found to be more sensitive to different project arrival distributions.

The SFT due date rule determines the early activity start times of each new project based on resource availability at that time. If the system is relatively empty, the SFT rule will assign a shorter due date and when the system is full it will assign a longer due date. The SFT due date rule compensates for fluctuations in the project load of the system. The triangular arrival distribution introduced some fluctuations in resource utilization compared to the uniform arrival distribution. The exponential arrival distribution caused significant changes in the system project load and apparently the SFT due date rule compensates for this very well, especially when combined with the FIFS heuristic.

The important discovery of this research was that the FIFS/SFT combination provided outstanding results regardless of the project arrival distribution. It was found that this particular combination is insensitive to whether new projects arrive according to the uniform, exponential, or triangular distribution. The FIFS/SFT combination was found to be the leading performer in previous research and it remains so in this research.

The conclusion is made that the FIFS/SFT combination performs the best for two reasons:

1. The SFT due date rule is scheduling heuristic oriented, meaning it provides very good estimates of the project completion time which tends to be met by the FIFS heuristic (S:193).

2. The FIFS heuristic ignores due dates and therefore is not as "nervous" as the due date oriented heuristics (S:193).

The major significance of these findings is that although there is sensitivity to project arrival distributions, the relative performance of the tested scheduling heuristics, due date assignment rules, and combinations of scheduling heuristic and due date assignment rules is unchanged regardless of the project arrival distribution. Because the three distributions examined (uniform, exponential, and triangular) represent the most likely to occur, this research has ruled out the factor of project arrival distribution in the dynamic, multi-project, constrained resources scheduling problem.

The major contributions of this research were: 1) identifying the specific impact of different project arrival distributions on the performance of scheduling heuristics, due date assignment rules, and combinations thereof; 2) identifying that no significant interactions between the project arrival distribution, scheduling heuristic, or due

date assignment rule were found to drastically change the behavior of scheduling heuristics or due date rules investigated previously; 3) the discovery that the SFT rule decreases the sensitivity to changes in project arrival distribution; and 4) the FIFS/SFT combination performance proved to be insensitive to whether new projects arrived uniformly, exponentially, or approximately normal (triangular distribution).

Practical Implications of the Results. This research has addressed the issue of what impact differences in project arrival distribution may have on procedures for setting due dates and scheduling project activities to meet those due dates in a dynamic, multi-project, constrained multiple resource, environment. In general it was found that different project arrival distributions do affect the performance of scheduling heuristics and due date setting rules in an absolute sense, but not in a relative sense. Because of this, the project manager does not really need to be concerned about the arrival distribution of new projects because the relative performance of the tested heuristics and due date assignment rules is the same.

The best results are obtained when the Scheduled Finish Time (SFT) due date setting rule is applied. Not only does it provide the most accurate due dates, it provides significantly better results when used with any scheduling heuristic than the other due date setting rules, and it is

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virtually not affected at all by differences in project arrival distribution. Every project manager probably dreams of such a procedure being available, however there is a price to pay for the SFT due date assignment rule. The SFT due date setting rule requires a finite scheduling system, the current status of all projects in the system, and a historical data base to establish the due date compensation factor ("k" value). Not all project managers could implement this procedure due to the computer hardware/software requirements, financial constraints, project duration uncertainty, resource constraints, etc.. If they could use the SFT rule to set the due date of the arriving project, they would be wise to use the very simple First-In-First-Served (FIFS) scheduling heuristic to allocate resources to the project.

An alternative to project managers would be to choose the easier to implement CPTIME due date rule. If this is the case then the manager would want to choose one of the due date oriented heuristics to schedule the activities. The SASP[DD] and MINLFT[DD] produce similar results using the CPTIME due date rule. The CPTIME due date setting rule ignores the current project load when estimating activity completion times and therefore lacks the "self-compensating" feature of the SFT due date assignment rule.

Recall that the goals of the project manager are to first of all determine reasonable due dates for each project

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in order to make a promised completion date to the customer
and then schedule those projects accordingly so that due
dates are met on time. This research has determined that
the relative performance of the tested scheduling heuristics
and due date setting rules is unaffected by the project
arrival distribution. For the project manager, this
confirms that certain scheduling heuristics, due date
assignment rules, and combinations thereof will perform
better than others regardless of the project arrival
distribution. Therefore, the alternatives to management are
1) accept the decrease in performance capability for the
easier to implement CPTIME due date assignment rule used
with the due date oriented heuristics; or 2) make the
necessary commitments and investments to implement at least
one of these heuristics combined with the SFT due date
assignment procedure or better yet; 3) implement the
FIFS/SFT combination for assured performance.

Recommendations for Future Research. Relatively little
research has been devoted to the study of the dynamic,
multi-project, constrained resources scheduling problem
which many project managers face ever day in reality. The
advantage of due date setting rules and scheduling
heuristics is they are good enough procedures for planning
and control purposes in light of the difficulties and
complexities involved with uncertainties in activity
durations, resource constraints, dynamic project arrivals,

and so on. Therefore, this area of project management remains wide open for new research to make the project manager's task of scheduling and meeting due dates much simpler. The author provides these suggestions for possible future research:

1. Evaluate other due date setting rules and scheduling heuristics with the uniform, exponential, and triangular project arrival distributions.

2. Explore other project environmental factors such as different levels of resources, stochastic activity durations, dynamic resource availabilities, etc., and conduct a multi-factor experiment to investigate their impact on setting due dates and using scheduling heuristics to meet those due dates.

These and many other areas of future research could add to the robustness of scheduling heuristics and due date assignment rules already available to today's project managers. The goal of this and any other research in this area should be to provide good tools to project managers so that they can make better estimates of project completion times and deliver the product or service on time, as much as possible, to the customer.

Appendix A: Three Factor ANOVA Results

Appendix A contains the three-factor analysis of variance results and presents the ANOVA table and statistical test procedures used to test for main effects, two-factor interaction effects, and three-factor interaction effects for each of the following performance parameters:

1. Mean completion time.

2. Mean delay time.

3. Standard Deviation of Lateness.

4. Mean Tardiness.

For each parameter listed above a copy of the SAS program is provided and the ANOVA statistical test procedure is shown. The multiple comparison tests are not shown but are readily available by executing the SAS programs included in this Appendix.

Mean Completion Time

The SAS program code developed for the mean completion time performance parameter is shown in Figure 39. The output of this source code is an ANOVA table, main and interaction effects tests, and multiple comparison tests (Tukey, Bonferroni, and Scheffe). Table 32 shows the ANOVA table results for the mean completion time performance parameter.

The seven statistical tests for factor effects and interaction effects are shown below. The nomenclature for these tests follow that used by Neter and Wasserman (14).

```
options linesize=78 pagesize=66;
/*  THIS PROGRAM WILL PROVIDE A THREE FACTOR FULL FACTORIAL
ANALYSIS OF VARIANCE USING PROC ANOVA ON THE PERFORMANCE
PARAMETER.....PROJECT MEAN COMPLETION TIME.
*/
data meancomp;
        do sched=1 to 4;
                do dd=1 to 2;
                        do arriv=1 to 3;
                                do observ=1 to 8;
                                        input y @@;
                                        output;
                                        end;
                                end;
                        end;
                end;
cards;
69.57 64.13 60.47 67.81 64.39 59.73 59.28 68.58
65.68 72.72 68.11 80.26 78.79 67.92 78.39 92.26
64.24 59.66 57.99 63.56 61.14 57.33 58.25 64.09
69.57 64.13 60.47 67.81 64.39 59.73 59.28 68.58
65.68 72.72 68.11 80.26 78.79 67.92 78.39 92.26
64.24 59.66 57.99 63.56 61.14 57.33 58.25 64.09
58.10 56.94 55.26 59.09 56.78 55.73 55.68 58.10
58.03 62.84 58.35 66.68 65.95 61.96 65.38 73.63
56.21 54.08 54.39 56.48 54.98 53.82 54.40 56.63
58.10 56.94 55.26 59.09 56.78 55.73 55.68 58.10
58.03 62.84 58.35 66.68 65.95 61.96 65.38 73.63
56.21 54.08 54.39 56.48 54.88 53.82 54.40 56.63
68.07 61.98 59.01 66.35 62.98 59.96 58.88 65.96
65.57 71.82 66.20 79.15 78.36 69.38 76.54 87.85
61.82 57.97 56.87 61.58 59.50 56.91 58.43 62.01
67.81 62.29 59.68 66.71 64.84 59.68 60.20 66.26
66.54 71.92 66.78 79.74 79.43 70.96 76.48 85.75
61.86 59.22 57.77 63.00 60.85 56.33 58.25 61.52
64.98 61.71 58.42 64.87 61.05 57.98 59.68 63.46
64.99 71.08 66.62 78.82 75.72 68.33 77.03 87.08
60.64 57.35 55.82 61.26 58.82 55.28 57.28 59.80
68.43 63.50 61.32 67.04 63.99 59.38 60.58 66.88
68.07 72.34 69.28 80.77 80.81 69.91 79.84 89.84
62.50 59.16 57.62 64.05 61.30 56.00 59.28 62.12
proc means;
        title "GROUP MEANS FOR PROJECT MEAN COMPLETION TIME (DAYS)";
        var y;
        by sched dd arriv;
proc means;
        title "GRAND MEAN FOR MEAN COMPLETION TIME";
        var y;
proc anova;
        title  "THREE FACTOR ANALYSIS OF VARIANCE ";
        class sched dd arriv;
        model y= sched dd arriv sched*dd sched*arriv dd*arriv
                sched*dd*arriv;
        means sched dd arriv sched*dd sched*arriv dd*arriv
                sched*dd*arriv /alpha=.015 bon scheffe tukey;
```

Figure 39. SAS Program-Mean Completion Time

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Table 32

Three-factor ANOVA Table

Mean Completion Time

Source of Variation	d.f.	Sum of Squares	Mean Square	F	P-value
A	3	2002.03	667.34	29.40	0.0001
B	2	6497.35	3248.68	143.13	0.0001
C	1	23.42	23.42	1.03	0.3112
AB	6	283.34	42.22	1.86	0.0904
AC	3	43.24	14.41	0.64	0.5934
BC	2	0.17	0.09	0.00	0.9963
ABC	6	0.79	0.13	0.01	1.0000
Error	168	3813.05	22.69		
Total	191	12633.38			

The A factor is the scheduling heuristic factor, the B
factor is the arrival distribution factor and the C factor
is the due date rule factor for this experiment.

Test for Three-Factor Interactions. The first test was
conducted for three-factor interaction effects. The
alternatives are:

$$H_o: \text{all } (\alpha\beta\gamma)_{ijk} = 0$$

$$H_a: \text{not all } (\alpha\beta\gamma)_{ijk} = 0$$

The decision rule is:

If $F^* \leq F(.9927, 6, 168) = 3.06$, conclude H_o

If $F^* > F(.9927, 6, 168) = 3.06$, conclude H_a

The F^* test statistic from Table 32 is :

$$F^* = MSABC/MSE = 0.01$$

Since $F^* = 0.01 \leq 3.06$, the researcher concluded that no
ABC interactions are present for the mean completion time

parameter. In other words, no three-factor interactions between scheduling heuristic, due date assignment rule, and project arrival distribution are present for the mean completion time response variable.

Tests for Two-Factor Interactions. The researcher tested next for two-factor interactions. The AB interactions represent the possible interactions between scheduling heuristic and project arrival distribution. The AC interactions represent the possible interactions between scheduling heuristic and due date rule. The BC interactions represent the possible interactions between due date rule and project arrival distribution. The alternatives for the AB interactions are:

$$H_o: \text{all } (\alpha\beta)_{ij} = 0$$

$$H_a: \text{not all } (\alpha\beta)_{ij} = 0$$

The decision rule is:

If $F^* <= F(.9927, 6, 168) = 3.06$, conclude H_o

If $F^* > F(.9927, 6, 168) = 3.06$, conclude H_a

The F^* test statistic from Table 32 is:

$$F^* = MSAB/MSE = 1.86$$

Since $F^* = 1.86 <= 3.06$, the researcher concluded that no AB interactions are present. No interactions are present between the scheduling heuristic and arrival distribution factors.

The alternatives for the AC interactions are:

$$H_o: \text{all } (\alpha\gamma)_{ik} = 0$$

$$H_a: \text{not all } (\alpha\gamma)_{ik} = 0$$

The decision rule is:

If $F^* <= F(.9927, 3, 168) = 4.14$, conclude H_o

If $F^* > F(.9927, 3, 168) = 4.14$, conclude H_a

The F^* test statistic from Table 32 is:

$$F^* = MSAC/MSE = 0.64$$

Since $F^* = 0.64 <= 4.14$, the researcher concludes that no AC interactions are present and therefore no significant interactions are present between the scheduling heuristic and due date rule factors.

The alternatives for the BC interactions are:

$$H_o: \text{all } (\beta\gamma)_{jk} = 0$$

$$H_a: \text{not all } (\beta\gamma)_{jk} = 0$$

The decision rule is:

If $F^* <= F(.9927, 2, 168) = 5.07$, conclude H_o

If $F^* > F(.9927, 2, 168) = 5.07$, conclude H_a

The F^* test statistic from Table 32 is:

$$F^* = MSBC/MSE = 0.00$$

Since $F^* = 0.0 <= 5.07$, the researcher concluded that no BC interactions are present and, therefore, no significant interactions are present between the arrival distribution and due date rule factors.

Tests for Main Effects. The following tests were conducted to detect the presence of the main effects of the

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experiment. The alternatives for the scheduling heuristic factor main effects (A main effects) are:

$$H_o: \text{all} \quad \alpha_i = 0$$

$$H_a: \text{not all} \quad \alpha_i = 0$$

The decision rule is:

If $F^* <= F(.9927, 3, 168) = 4.14$, conclude H_o

If $F^* > F(.9927, 3, 168) = 4.14$, conclude H_a

The F^* test statistic from Table 32 is:

$$F^* = MSA/MSE = 29.40$$

Since $F^* = 29.40 > 4.14$, the researcher concludes that A main effects are present and, therefore, main effects for scheduling heuristic are present for the mean completion time response variable.

The alternatives for the project arrival distribution factor main effects (B main effects) are:

$$H_o: \text{all} \quad \beta_j = 0$$

$$H_a: \text{not all} \quad \beta_j = 0$$

The decision rule is:

If $F^* <= F(.9927, 2, 168) = 5.07$, conclude H_o

If $F^* > F(.9927, 2, 168) = 5.07$, conclude H_a

The F^* test statistic from Table 32 is:

$$F^* = MSB/MSE = 143.13$$

Since $F^* = 143.13 > 5.07$, the researcher concluded that factor B main effects are present and, therefore, arrival distribution factor main effects are present for the mean completion time response variable.

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The alternatives for the due date rule factor main effects
(factor C main effects) are:

$$H_o: \text{all} \quad \gamma_k = 0$$

$$H_a: \text{not all} \quad \gamma_k = 0$$

The decision rule is:

If $F^* <= F(.9927, 1, 168) = 7.37$, conclude H_o

If $F^* > F(.9927, 1, 168) = 7.37$, conclude H_a

The F^* test statistic from Table 32 is:

$$F^* = MSC/MSE = 1.03$$

Since $F^* = 1.03 <= 7.37$, the researcher concluded that no
due date rule factor main effects are present for the mean
completion time response variable.

Family of Conclusions. The seven separate F tests for
factor effects led the researcher to conclude for the mean
completion time performance parerameter (with family
level of significance <=0.05):

1. There are no three-factor interactions.

2. There are no two-factor interactions.

3. Main effects for scheduling heuristic (factor A)
and project arrival distribution (factor B) are present.

Mean Delay Time

The SAS program code developed for the mean delay time performance parameter is shown in Figure 40. The output of this source code is an ANOVA table, main and interaction effects tests, and multiple comparison tests (Tukey, Bonferroni, and Scheffe). Table 33 shows the ANOVA table results for the mean delay time performance parameter.

The seven statistical tests for factor effects and interaction effects are shown below. The nomenclature for these tests follow that used by Neter and Wasserman (14). The A factor is the scheduling heuristic factor, the B factor is the arrival distribution factor and the C factor is the due date rule factor for this experiment.

Test for Three-Factor Interactions. The first test was conducted for three-factor interaction effects. The alternatives are:

$$H_o: \text{all } (\alpha\beta\gamma)_{ijk} = 0$$

$$H_a: \text{not all } (\alpha\beta\gamma)_{ijk} = 0$$

The decision rule is:

If $F^* <= F(.9927, 6, 168) = 3.06$, conclude H_o

If $F^* > F(.9927, 6, 168) = 3.06$, conclude H_a

The F^* test statistic from Table 33 is :

$$F^* = MSABC/MSE = 0.12$$

Since $F^* = 0.12 <= 3.06$, the researcher concluded that no ABC interactions are present for the mean delay time

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```
options linesize=78 pagesize=66;
/* THIS PROGRAM WILL PROVIDE A THREE FACTOR FULL FACTORIAL
ANALYSIS OF VARIANCE USING PROC ANOVA ON THE PERFORMANCE
PARAMETER.....PROJECT MEAN DELAY TIME.
*/
data delaybar;
        do sched=1 to 4;
                do dd=1 to 2;
                        do arriv=1 to 3;
                                do observ=1 to 8;
                                        input y @@;
                                        output;
                                        end;
                                end;
                        end;
        cards;
6.01 .86 -2.44 4.43 1.08 -3.45 -3.65 5.26
-9.42 -2.05 -7.32 5.51 4.92 -6.17 3.51 17.42
3.93 -.73 -2.21 3.13 .75 -2.89 -2.06 3.65
.54 .28 .44 .59 .77 .55 .66 .43
.30 .54 .73 .54 .59 .30 .80 .76
.61 .68 .59 .44 .60 .72 .67 .63
1.95 .39 .95 2.45 -.20 -.73 -.56 -1.70
-5.45 -.38 -5.42 3.49 3.17 -1.07 2.06 10.36
1.47 -.73 -.26 1.59 .07 -.85 -.35 1.76
.94 -.90 -2.10 -.34 -1.32 -1.41 -1.98 -.13
-4.04 -.14 -3.52 .71 1.09 -1.82 .94 5.76
.84 -.92 -.65 .57 -.50 -1.16 -1.30 1.21
4.04 -2.17 -4.36 2.50 -.80 -3.69 -4.51 1.79
-8.34 -1.79 -8.06 5.57 5.26 -3.58 2.83 14.19
2.57 -1.14 -2.08 2.40 .37 -2.06 -.62 2.83
1.99 1.40 -.20 1.12 1.33 -.11 -.40 1.49
-1.35 -.83 -2.42 1.97 1.75 1.01 1.31 2.08
1.42 .45 .51 1.25 1.15 -.13 .44 1.13
4.15 .45 -2.47 3.50 -.25 -3.19 -1.08 2.34
-8.02 -1.63 -6.73 6.13 3.51 -3.71 4.22 14.32
2.74 -.62 -1.98 3.23 .84 -2.54 -.62 1.78
1.01 .38 .31 .79 .86 -.26 .23 .51
-.61 -.67 -1.11 -.03 2.50 .11 1.12 -.64
.76 .15 -.07 .82 .62 -.55 .04 .01
proc means;
        title "GROUP MEANS FOR PROJECT MEAN DELAY TIME (DAYS)";
        var y;
        by sched dd arriv;
proc means;
        title "GRAND MEAN FOR MEAN DELAY TIME";
        var y;
proc anova;
        title   "THREE FACTOR ANALYSIS OF VARIANCE ";
        class sched dd arriv;
        model y= sched dd arriv sched*dd sched*arriv dd*arriv
                sched*dd*arriv;
        means sched dd arriv sched*dd sched*arriv dd*arriv
                sched*dd*arriv / alpha=.0073 bon scheffe tukey;
```

Figure 40.   SAS Program-Mean Delay Time

Table 33

Three-factor ANOVA Table

Mean Delay Time

Source of Variation	d.f.	Sum of Squares	Mean Square	F	P-value
A	3	9.35	3.12	0.26	0.8566
B	2	3.26	1.63	0.13	0.8744
C	1	1.87	1.87	0.15	0.6949
AB	6	5.05	0.84	0.07	0.9987
AC	3	14.88	4.96	0.41	0.7472
BC	2	3.89	1.95	0.16	0.8520
ABC	6	8.47	1.41	0.12	0.9944
Error	168	2040.03	12.14		
Total	191	2086.80			

parameter. In other words, no three-factor interactions between scheduling heuristic, due date assignment rule, and project arrival distribution are present for the mean completion time response variable. The A factor is the scheduling heuristic factor, the B factor is the arrival distribution factor and the C factor is the due date rule factor for this experiment.

Tests for Two-Factor Interactions. The researcher tested next for two-factor interactions. The AB interactions represent the possible interactions between scheduling heuristic and project arrival distribution. The AC interactions represent the possible interactions between scheduling heuristic and due date rule. The BC interactions represent the possible interactions between due date rule

and project arrival distribution. The alternatives for the
AB interactions are:

$$H_o: \text{all } (\alpha\beta)_{ij} = 0$$

$$H_a: \text{not all } (\alpha\beta)_{ij} = 0$$

The decision rule is:

If $F^* \leq F(.9927, 6, 168) = 3.06$, conclude H_o

If $F^* > F(.9927, 6, 168) = 3.06$, conclude H_a

The F* test statistic from Table 33 is:

$$F^* = MSAB/MSE = 0.07$$

Since $F^* = 0.07 \leq 3.06$, the researcher concluded that no AB
interactions are present. No interactions are present
between the scheduling heuristic and arrival distribution
factors.

The alternatives for the AC interactions are:

$$H_o: \text{all } (\alpha\gamma)_{ih} = 0$$

$$H_a: \text{not all } (\alpha\gamma)_{ih} = 0$$

The decision rule is:

If $F^* \leq F(.9927, 3, 168) = 4.14$, conclude H_o

If $F^* > F(.9927, 3, 168) = 4.14$, conclude H_a

The F* test statistic from Table 33 is:

$$F^* = MSAC/MSE = 0.41$$

Since $F^* = 0.41 \leq 4.14$, the researcher concludes that no AC
interactions are present and therefore no significant
interactions are present between the scheduling heuristic
and due date rule factors.

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The alternatives for the BC interactions are:

$$H_o: \text{all } (\beta\gamma)_{jk} = 0$$

$$H_a: \text{not all } (\beta\gamma)_{jk} = 0$$

The decision rule is:

If $F^* \leq F(.9927, 2, 168) = 5.07$, conclude H_o

If $F^* > F(.9927, 2, 168) = 5.07$, conclude H_a

The F^* test statistic from Table 33 is:

$$F^* = MSBC/MSE = 0.16$$

Since $F^* = 0.16 \leq 5.07$, the researcher concluded that no BC interactions are present and, therefore, no significant interactions are present between the arrival distribution and due date rule factors.

Tests for Main Effects. The following tests were conducted to detect the presence of the main effects of the experiment. The alternatives for the scheduling heuristic factor main effects (A main effects) are:

$$H_o: \text{all } \alpha_i = 0$$

$$H_a: \text{not all } \alpha_i = 0$$

The decision rule is:

If $F^* \leq F(.9927, 3, 168) = 4.14$, conclude H_o

If $F^* > F(.9927, 3, 168) = 4.14$, conclude H_a

The F^* test statistic from Table 33 is:

$$F^* = MSA/MSE = 0.26$$

Since $F^* = 0.26 \leq 4.14$, the researcher concludes that A main effects are not present and, therefore, main effects for

scheduling heuristic are not present for the mean delay time response variable.

The alternatives for the project arrival distribution factor main effects (B main effects) are:

$$H_o: \text{all } \beta_j = 0$$

$$H_a: \text{not all } \beta_j = 0$$

The decision rule is:

If $F^* \leq F(.9927, 2, 168) = 5.07$, conclude H_o

If $F^* > F(.9927, 2, 168) = 5.07$, conclude H_a

The F^* test statistic from Table 33 is:

$$F^* = MSB/MSE = 0.13$$

Since $F^* = 0.13 \leq 5.07$, the researcher concluded that no factor B main effects are present and, therefore, arrival distribution factor main effects are not present for the mean delay time response variable.

The alternatives for the due date rule factor main effects (factor C main effects) are:

$$H_o: \text{all } \gamma_k = 0$$

$$H_a: \text{not all } \gamma_k = 0$$

The decision rule is:

If $F^* \leq F(.9927, 1, 168) = 7.37$, conclude H_o

If $F^* > F(.9927, 1, 168) = 7.37$, conclude H_a

The F^* test statistic from Table 33 is:

$$F^* = MSC/MSE = 0.15$$

Since F# - 0.15 <= 7.37, the researcher concluded that no due date rule factor main effects are present for the mean delay time response variable.

Family of Conclusions. The seven separate F tests for factor effects led the researcher to conclude for the mean delay time performance parameter (with family level of significance <= 0.05):

1. There are no three-factor interactions.

2. There are no two-factor interactions.

3. Main effects for scheduling heuristic (factor A), project arrival distribution (factor B), and due date rule (factor C) are not present.

Standard Deviation of Lateness

The SAS program code developed for the standard deviation of lateness performance parameter is shown in Figure 41. The output of this source code is an ANOVA table, main and interaction effects tests, and multiple comparison tests (Tukey, Bonferroni, and Scheffe). Table 34 shows the ANOVA table results for the mean delay time performance parameter.

The seven statistical tests for factor effects and interaction effects are shown below. The nomenclature for these tests follow that used by Neter and Wasserman (14). The A factor is the scheduling heuristic factor, the B factor is the arrival distribution factor and the C factor is the due date rule factor for this experiment.

<u>Test for Three-Factor Interactions</u>. The first test was conducted for three-factor interaction effects. The alternatives are:

$$H_o: \text{all } (\alpha\beta\gamma)_{ijk} = 0$$

$$H_a: \text{not all } (\alpha\beta\gamma)_{ijk} = 0$$

The decision rule is:

If $F^* <= F(.9927, 6, 168) = 3.06$, conclude H_o

If $F^* > F(.9927, 6, 168) = 3.06$, conclude H_a

The F^* test statistic from Table 34 is :

$$F^* = MSABC/MSE = 0.90$$

Since $F^* = 0.90 <= 3.06$, the researcher concluded that no ABC interactions are present for the mean delay time

```
options linesize=78 pagesize=66;
/*   THIS PROGRAM WILL PROVIDE A THREE FACTOR FULL FACTORIAL
ANALYSIS OF VARIANCE USING PROC ANOVA ON THE PERFORMANCE
PARAMETER.....PROJECT STANDARD DEVIATION OF LATENESS TIME.
*/
data stdlate;
        do sched=1 to 4;
                do dd=1 to 2;
                        do arriv=1 to 3;
                                do observ=1 to 8;
                                        input y @@;
                                        output;
                                        end;
                                end;
                        end;
                end;
        cards;
36.80 29.69 28.57 36.41 29.38 29.38 26.31 42.48
44.09 44.79 41.14 47.89 39.32 37.83 49.08 71.70
28.42 24.83 24.43 29.41 25.71 24.47 24.78 34.62
2.57 2.46 2.44 2.78 2.47 2.61 2.68 2.68
3.17 2.80 2.63 3.10 3.41 2.87 3.51 4.15
2.47 2.67 2.21 2.40 2.47 2.51 2.62 2.74
62.82 49.71 41.18 55.24 49.86 42.34 38.01 60.87
42.24 63.11 51.46 64.13 66.31 47.66 66.93 94.25
49.61 41.61 39.77 47.55 45.02 36.66 35.80 57.65
53.66 42.30 38.36 44.11 40.80 35.41 33.03 50.97
36.43 51.37 44.11 48.37 58.05 41.89 58.93 74.62
43.00 36.41 38.26 36.94 38.00 32.14 30.46 49.58
29.07 21.78 21.20 29.20 20.95 22.05 18.75 34.95
30.02 38.77 31.22 38.63 29.15 25.81 39.44 61.94
21.73 17.78 17.14 22.84 18.77 17.79 18.92 27.63
11.49 9.36 9.13 10.44 9.07 9.34 8.01 13.14
14.91 13.27 12.78 14.36 12.01 13.29 16.39 19.61
8.89 7.74 8.10 8.87 7.62 7.61 7.57 9.78
24.93 19.97 19.41 25.27 18.11 19.12 16.46 31.00
27.92 33.50 30.09 34.63 24.69 24.47 36.69 57.78
17.97 15.74 15.12 19.46 15.33 14.63 15.99 24.29
9.62 9.41 8.39 9.36 8.77 8.79 7.82 10.54
14.52 12.07 12.50 14.36 11.53 12.22 15.73 16.45
8.26 7.97 7.57 8.45 8.13 7.51 7.43 9.33
proc means;
        title "GROUP MEANS FOR STANDARD DEVIATION OF LATENESS (DAYS)";
        var y;
        by sched dd arriv;
proc means;
        title "GRAND MEAN FOR STANDARD DEVIATION OF LATENESS";
        var y;
proc anova;
        title  "THREE FACTOR ANALYSIS OF VARIANCE ";
        class sched dd arriv;
        model y= sched dd arriv sched*dd sched*arriv dd*arriv
                sched*dd*arriv;
        means sched dd arriv sched*dd sched*arriv dd*arriv
                sched*dd*arriv / alpha=.0073 bon scheffe tukey;
```

Figure 41.   SAS Program—Standard
Deviation of Lateness

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Table 34

Three-factor ANOVA Table

Standard Deviation of Lateness

Source of Variation	d.f.	Sum of Squares	Mean Square	F	P-value
A	3	31538.82	10512.94	223.47	0.0000
B	2	15205.29	7602.65	323.22	0.0000
C	1	4996.70	4996.70	53.11	0.0001
AB	6	158.63	26.44	0.56	0.7601
AC	3	3929.35	1309.78	27.84	0.0001
BC	2	1037.23	518.62	11.02	0.0001
ABC	6	253.43	42.24	0.90	0.5000
Error	168	7903.31	47.04		
Total	191	65022.77			

parameter. In other words, no three-factor interactions between scheduling heuristic, due date assignment rule, and project arrival distribution are present for the standard deviation of lateness response variable. The A factor is the scheduling heuristic factor, the B factor is the arrival distribution factor and the C factor is the due date rule factor for this experiment.

Tests for Two-Factor Interactions. The researcher tested next for two-factor interactions. The AB interactions represent the possible interactions between scheduling heuristic and project arrival distribution. The AC interactions represent the possible interactions between scheduling heuristic and due date rule. The BC interactions represent the possible interactions between due date rule

and project arrival distribution. The alternatives for the
AB interactions are:

$$H_o: \text{all } (\alpha\beta)_{ij} = 0$$

$$H_a: \text{not all } (\alpha\beta)_{ij} = 0$$

The decision rule is:

If $F^* <= F(.9927, 6, 168) = 3.06$, conclude H_o

If $F^* > F(.9927, 6, 168) = 3.06$, conclude H_a

The F^* test statistic from Table 34 is:

$$F^* = MSAB/MSE = 0.56$$

Since $F^* = 0.56 <= 3.06$, the researcher concluded that no AB
interactions are present. No interactions are present
between the scheduling heuristic and arrival distribution
factors.

The alternatives for the AC interactions are:

$$H_o: \text{all } (\alpha\gamma)_{ik} = 0$$

$$H_a: \text{not all } (\alpha\gamma)_{ik} = 0$$

The decision rule is:

If $F^* <= F(.9927, 3, 168) = 4.14$, conclude H_o

If $F^* > F(.9927, 3, 168) = 4.14$, conclude H_a

The F^* test statistic from Table 34 is:

$$F^* = MSAC/MSE = 27.84$$

Since $F^* = 27.84 > 4.14$, the researcher concludes that AC
interactions are present and therefore significant
interactions are present between the scheduling heuristic
and due date rule factors.

The alternatives for the BC interactions are:

$$H_o: \text{all } (\beta\gamma)_{jk} = 0$$

$$H_a: \text{not all } (\beta\gamma)_{jk} = 0$$

The decision rule is:

If $F* <= F(.9927, 2, 168) = 5.07$, conclude H_o

If $F* > F(.9927, 2, 168) = 5.07$, conclude H_a

The F* test statistic from Table 34 is:

$$F* = MSBC/MSE = 11.02$$

Since $F* = 11.02 > 5.07$, the researcher concluded that BC interactions are present and, therefore, significant interactions are present between the arrival distribution and due date rule factors.

Tests for Main Effects. The following tests were conducted to detect the presence of the main effects of the experiment. The alternatives for the scheduling heuristic factor main effects (A main effects) are:

$$H_o: \text{all } \alpha_i = 0$$

$$H_a: \text{not all } \alpha_i = 0$$

The decision rule is:

If $F* <= F(.9927, 3, 168) = 4.14$, conclude H_o

If $F* > F(.9927, 3, 168) = 4.14$, conclude H_a

The F* test statistic from Table 34 is:

$$F* = MSA/MSE = 223.47$$

Since $F* = 223.47 > 4.14$, the researcher concludes that A main effects are present and, therefore, main effects for

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scheduling heuristic are present for the standard deviation
of lateness response variable.

The alternatives for the project arrival distribution factor
main effects (B main effects) are:

$$H_o: \text{all } \beta_j = 0$$

$$H_a: \text{not all } \beta_j = 0$$

The decision rule is:

If F* <= F(.9927, 2, 168) = 5.07, conclude H_o

If F* > F(.9927, 2, 168) = 5.07, conclude H_a

The F* test statistic from Table 34 is:

$$F* = MSB/MSE = 53.11$$

Since F* = 53.11 > 5.07, the researcher concluded that
factor B main effects are present and, therefore, arrival
distribution factor main effects are present for the mean
delay time response variable.

The alternatives for the due date rule factor main effects
(factor C main effects) are:

$$H_o: \text{all } \gamma_k = 0$$

$$H_a: \text{not all } \gamma_k = 0$$

The decision rule is:

If F* <= F(.9927, 1, 168) = 7.37, conclude H_o

If F* > F(.9927, 1, 168) = 7.37, conclude H_a

The F* test statistic from Table 34 is:

$$F* = MSC/MSE = 323.22$$

Since F* = 323.22 > 7.37, the researcher concluded that

due date rule factor main effects are present for the standard deviation of lateness response variable.

Family of Conclusions. The seven separate F tests for factor effects led the researcher to conclude for the standard deviation of lateness performance pararameter (with family level of significance <= 0.05):

1. There are no three-factor interactions.

2. No two-factor interactions between scheduling heuristic and arrival distributions (AB). Interactions do exist between scheduling heuristic and due date rule (AC) and also between due date rule and arrival distribution (BC).

3. Main effects for scheduling heuristic (factor A), project arrival distribution (factor B), and due date rule (factor C) are all present.

Mean Tardiness

The SAS program code developed for the mean tardiness performance parameter is shown in Figure 42. The output of this source code is an ANOVA table, main and interaction effects tests, and multiple comparison tests (Tukey, Bonferroni, and Scheffe). Table 35 shows the ANOVA table results for the mean delay time performance parameter.

The seven statistical tests for factor effects and interaction effects are shown below. The nomenclature for these tests follow that used by Neter and Wasserman (14). The A factor is the scheduling heuristic factor, the B factor is the arrival distribution factor and the C factor is the due date rule factor for this experiment.

Test for Three-Factor Interactions. The first test was conducted for three-factor interaction effects. The alternatives are:

$$H_o: \text{all } (\alpha\beta\gamma)_{ijk} = 0$$

$$H_o: \text{not all } (\alpha\beta\gamma)_{ijk} = 0$$

The decision rule is:

If $F^* \leq F(.9927, 6, 168) = 3.06$, conclude H_o

If $F^* > F(.9927, 6, 168) = 3.06$, conclude H_o

The F* test statistic from Table 35 is :

$$F^* = MSABC/MSE = 0.63$$

Since $F^* = 0.63 \leq 3.06$, the researcher concluded that no ABC interactions are present for the mean tardiness

```
options linesize=78 pagesize=66;
/*   THIS PROGRAM WILL PROVIDE A THREE FACTOR FULL FACTORIAL
ANALYSIS OF VARIANCE USING PROC ANOVA ON THE PERFORMANCE
PARAMETER.....PROJECT MEAN TARDINESS TIME.
*/
data stdlate;
        do sched=1 to 4;
                do dd=1 to 2;
                        do arriv=1 to 3;
                                do observ=1 to 8;
                                        input y @@;
                                        output;
                                        end;
                                end;
                        end;
                end;
        cards;
16.81 12.27 9.77 15.46 12.24 9.15 8.50 17.86
11.84 16.22 12.84 21.23 18.12 11.48 20.12 34.15
13.09 9.43 8.35 12.70 10.68 7.67 8.55 14.30
1.12 .93 1.06 1.22 1.23 1.13 1.22 1.11
1.10 1.15 1.23 1.26 1.36 1.03 1.52 1.51
1.13 1.24 1.05 1.06 1.16 1.18 1.22 1.20
13.60 11.33 10.09 13.96 11.68 10.65 10.02 13.76
9.74 15.15 10.58 18.12 16.59 12.39 16.25 25.03
11.70 9.70 9.97 12.27 10.57 9.62 9.27 12.80
11.61 9.33 8.33 10.66 9.55 9.04 8.10 10.64
8.29 11.92 8.73 13.10 13.41 10.25 13.15 18.63
10.23 8.57 8.69 9.69 8.90 8.58 7.79 10.72
13.67 8.22 6.60 12.19 8.37 6.93 5.27 13.87
8.40 12.91 9.27 17.29 14.66 8.47 16.40 26.85
9.93 6.95 5.90 10.04 7.96 6.00 7.09 11.73
5.69 4.20 3.80 4.76 4.56 3.86 3.21 5.55
5.22 5.35 4.11 6.67 5.97 5.96 6.68 8.12
4.42 3.63 3.68 4.30 3.81 3.15 3.38 4.40
11.80 8.59 6.35 11.08 7.16 5.77 5.98 12.47
7.50 11.66 8.96 16.08 12.05 7.64 15.88 27.39
8.22 6.35 5.02 9.04 6.69 4.42 5.77 9.80
4.54 4.20 3.71 4.35 4.16 3.40 3.38 4.48
5.21 4.59 4.59 5.92 6.20 4.95 6.57 6.07
3.91 3.38 3.15 4.04 3.75 2.84 3.22 3.86
proc means;
        title "GROUP MEANS FOR MEAN TARDINESS (DAYS)";
        var y;
        by sched dd arriv;
proc means;
        title "GRAND MEAN FOR MEAN TARDINESS";
        var y;
proc anova;
        title   "THREE FACTOR ANALYSIS OF VARIANCE ";
        class sched dd arriv;
        model y= sched dd arriv sched*dd sched*arriv dd*arriv
                sched*dd*arriv;
        means sched dd arriv sched*dd sched*arriv dd*arriv
                sched*dd*arriv /alpha=.015 bon scheffe tukey;
```

Figure 42.   SAS Program-Mean Tardiness

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Table 35

Three-factor ANOVA Table

Mean Tardiness

Source of Variation	d.f.	Sum of Squares	Mean Square	F	P-value
A	3	616.82	205.61	20.97	0.0001
B	2	576.66	288.33	29.41	0.0001
C	1	2073.43	1036.72	211.46	0.0001
AB	6	1.82	0.30	0.03	0.9999
AC	3	685.22	228.41	23.29	0.0001
BC	2	173.56	86.78	8.85	0.0002
ABC	6	37.16	6.19	0.63	0.7047
Error	168	1647.25	9.81		
Total	191	5811.94			

parameter. In other words, no three-factor interactions between scheduling heuristic, due date assignment rule, and project arrival distribution are present for the standard deviation of lateness response variable. The A factor is the scheduling heuristic factor, the B factor is the arrival distribution factor and the C factor is the due date rule factor for this experiment.

Tests for Two-Factor Interactions. The researcher tested next for two-factor interactions. The AB interactions represent the possible interactions between scheduling heuristic and project arrival distribution. The AC interactions represent the possible interactions between scheduling heuristic and due date rule. The BC interactions represent the possible interactions between due date rule

and project arrival distribution. The alternatives for the
AB interactions are:

$$H_o: \text{all } (\alpha\beta)_{ij} = 0$$

$$H_a: \text{not all } (\alpha\beta)_{ij} = 0$$

The decision rule is:

If $F^* <= F(.9927, 6, 168) = 3.06$, conclude H_o

If $F^* > F(.9927, 6, 168) = 3.06$, conclude H_a

The F^* test statistic from Table 36 is:

$$F^* = MSAB/MSE = 0.03$$

Since $F^* = 0.03 <= 3.06$, the researcher concluded that no AB
interactions are present. No interactions are present
between the scheduling heuristic and arrival distribution
factors.

The alternatives for the AC interactions are:

$$H_o: \text{all } (\alpha\gamma)_{ik} = 0$$

$$H_a: \text{not all } (\alpha\gamma)_{ik} = 0$$

The decision rule is:

If $F^* <= F(.9927, 3, 168) = 4.14$, conclude H_o

If $F^* > F(.9927, 3, 168) = 4.14$, conclude H_a

The F^* test statistic from Table 36 is:

$$F^* = MSAC/MSE = 23.29$$

Since $F^* = 23.29 > 4.14$, the researcher concludes that AC
interactions are present and therefore significant
interactions are present between the scheduling heuristic
and due date rule factors.

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The alternatives for the BC interactions are:

$$H_o: \text{all } (\beta\gamma)_{jk} = 0$$

$$H_a: \text{not all } (\beta\gamma)_{jk} = 0$$

The decision rule is:

If $F^* \leq F(.9927, 2, 168) = 5.07$, conclude H_o

If $F^* > F(.9927, 2, 168) = 5.07$, conclude H_a

The F^* test statistic from Table 35 is:

$$F^* = MSBC/MSE = 8.85$$

Since $F^* = 8.85 > 5.07$, the researcher concluded that BC interactions are present and, therefore, significant interactions are present between the arrival distribution and due date rule factors.

Tests for Main Effects. The following tests were conducted to detect the presence of the main effects of the experiment. The alternatives for the scheduling heuristic factor main effects (A main effects) are:

$$H_o: \text{all } \alpha_i = 0$$

$$H_a: \text{not all } \alpha_i = 0$$

The decision rule is:

If $F^* \leq F(.9927, 3, 168) = 4.14$, conclude H_o

If $F^* > F(.9927, 3, 168) = 4.14$, conclude H_a

The F^* test statistic from Table 35 is:

$$F^* = MSA/MSE = 20.97$$

Since $F^* = 20.97 > 4.14$, the researcher concludes that A main effects are present and, therefore, main effects for

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scheduling heuristic are present for the mean tardiness

response variable.

The alternatives for the project arrival distribution factor

main effects (B main effects) are:

$$H_o: \text{all } \beta_j = 0$$

$$H_a: \text{not all } \beta_j = 0$$

The decision rule is:

If $F^* <= F(.9927, 2, 168) = 5.07$, conclude H_o

If $F^* > F(.9927, 2, 168) = 5.07$, conclude H_a

The F^* test statistic from Table 35 is:

$$F^* = MSB/MSE = 29.41$$

Since $F^* = 29.41 > 5.07$, the researcher concluded that

factor B main effects are present and, therefore, arrival

distribution factor main effects are present for the mean

tardiness response variable.

The alternatives for the due date rule factor main effects

(factor C main effects) are:

$$H_o: \text{all } \gamma_k = 0$$

$$H_a: \text{not all } \gamma_k = 0$$

The decision rule is:

If $F^* <= F(.9927, 1, 168) = 7.37$, conclude H_o

If $F^* > F(.9927, 1, 168) = 7.37$, conclude H_a

The F^* test statistic from Table 35 is:

$$F^* = MSC/MSE = 211.46$$

Since $F^* = 211.46 > 7.37$, the researcher concluded that

due date rule factor main effects are present for the standard deviation of lateness response variable.

Family of Conclusions. The seven separate F tests for factor effects led the researcher to conclude for the standard deviation of lateness performance parareometer (with family level of significance <= 0.05):

1. There are no three-factor interactions.

2. No two-factor interactions between scheduling heuristic and arrival distributions (AB). Interactions do exist between scheduling heuristic and due date rule (AC) and also between due date rule and arrival distribution (BC).

3. Main effects for scheduling heuristic (factor A), project arrival distribution (factor B), and due date rule (factor C) are all present.

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Block 19. Abstract

This research found, in general, that different project arrival distributions do affect the performance of scheduling heuristics and due date setting rules in an absolute sense, but not in a relative sense. Because of this, the project manager does not really need to be concerned about the arrival distribution of new projects.

The best results are obtained when the Scheduled Finish Time (SFT) due date setting rule is applied. Not all project managers could implement this procedure due to the computer hardware/software requirements, financial constraints, project duration uncertainty, resource constraints, etc.. If they could use the SFT rule to set the due date of the arriving project, they would be wise to use the very simple First-In-First-Served (FIFS) scheduling heuristic to allocate resources to the project.

An alternative to project managers would be to choose the easier to implement CPTIME due date rule. If this is the case then the manager would want to choose either the SASP[DD] or the MINLFT[DD] rule which produce similar results using the CPTIME due date rule.

This research has determined that the relative performance of the tested scheduling heuristics and due date setting rules is unaffected by the project arrival distribution. For the project manager, this confirms that certain scheduling heuristics, due date assignment rules, and combinations thereof will perform better than others regardless of the project arrival distribution. Therefore, the alternatives to management are 1) accept the decrease in performance capability for the easier to implement CPTIME due date assignment rule used with the due date oriented heuristics; or 2) make the necessary commitments and investments to implement at least one of these heuristics combined with the SFT due date assignment procedure or better yet; 3) implement the FIFS/SFT combination for assured performance.

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