This is to certify that the

dissertation entitled

The Effects of Variability and Disruption
On
Project Stability, Duration, and Net Present Value

presented by

Stephen M. Swartz

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Business Administration

Gary Ragatz
Major professor

Date 4/21/99

PRO

THE EFFECTS OF VARIABILITY AND DISRUPTION
ON
PROJECT STABILITY, DURATION, AND NET PRESENT VALUE

VOLUME I

By

Stephen M. Swartz

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Marketing and Supply Chain Management

1999

PROJ

It has been

Resource Constra

alternative project

understanding of t

procedures. The r

scheduling heurist

of stability measur

set of RCPSP case

are compared. The

execution strategy

sensitive to the pre

and evaluated.

ABSTRACT

THE EFFECTS OF VARIABILITY AND DISRUPTION
ON
PROJECT STABILITY, DURATION, AND NET PRESENT VALUE

By

Stephen M. Swartz

It has been demonstrated that the performance of scheduling heuristics for the Resource Constrained Project Scheduling Problem (RCPSP) can be affected by the use of alternative project execution strategies. This current work seeks to expand our understanding of the relationship between planning (scheduling) and execution procedures. The relative performance of a selected group of "high performing" scheduling heuristics on project total duration, Net Present Value (NPV), and a new class of stability measures under four different execution strategies is examined. A benchmark set of RCPSP cases were scheduled and then simulated through execution and the results are compared. The research findings indicate that relative performance is affected by the execution strategy in some cases but not in others; and that these relative standings are sensitive to the presence of variability in task duration. A new heuristic is also proposed and evaluated.

Many peop
recognize their

First, I'd l
Particularly Mark
who got me state
encouragement a
Thanks also to m
incessant whining
misbehave. And
presenters along t
the things that rea

Next, I need
all of the people w
Craig Brandt, my
Brandt also emplo
arrived at my new
have been able to c
pick up the slack fo
obligations. I trust

I certainly ow
shoals and rapids of
Roger Calantone. D
and help me devel
academia. Their me
that I can someday
and hard work of co

ACKNOWLEDGEMENTS

Many people have assisted in this effort, and I would like to take some time to recognize their contributions and extend my sincerest and deepest thanks.

First, I'd like to thank my fellow graduate students at Michigan State University. Particularly Mark Pagell, from whom I stole the idea for measuring Project Stability and who got me stated down this path in the first place. Mark gave me plenty of ideas and encouragement along the way, and I hope to collaborate with him again in the future. Thanks also to my long suffering office partner, Bob Marsh, who put up with my incessant whining whenever I hit the invariable committee snag or had a piece of code misbehave. And I'd certainly like to thank all of the seminar partners and conference co-presenters along the way who tried (sometimes unsuccessfully!) to keep me focused on the things that really mattered in refining my research.

Next, I need to thank my colleagues at the Air Force Institute of Technology, and all of the people who made this endeavor possible in the first place. Special thanks to Dr. Craig Brandt, my department chair, for giving me the opportunity for doctoral study. Dr. Brandt also employed great patience in insulating me from excessive workload when I arrived at my new assignment ABD. Without his efforts on my behalf I would never have been able to complete the dissertation. Thanks also to those colleagues who had to pick up the slack for me when I was unable to dedicate more time to faculty service obligations. I trust that my debt will soon be repaid, with interest!

I certainly owe a debt of gratitude to my committee, who guided me through the shoals and rapids of designing, conducting, and reporting research. Dr. Gary Ragatz, Dr. Roger Calantone, Dr. Paul Rubin, Dr. Rob Handfield, and Dr. Morgan Swink all pitched in to help me develop my skills and attitude to that of a contributing member of academia. Their mentoring and guidance made all the difference in the world, and I hope that I can someday live up to their high expectations. They opened my eyes to the joy and hard work of conducting rational inquiry through the application of the scientific

method, and for [illegible]

my committee [illegible]

seer me from the [illegible]

through the mas[illegible]

punchline goes. [illegible]

Saving the [illegible]

Leslie, and our [illegible]

would never have [illegible]

encouragement. [illegible]

Services, Chief [illegible]

deepest thanks, a[illegible]

did not weigh hea[illegible]

the higher echelon [illegible]

In that regard, my [illegible]

method, and for that I am truly blessed. Special thanks are in order for Dr. Gary Ragatz, my committee chair, who invested time and effort "above and beyond the call of duty" to steer me from the shoals when I needed it. He had the unenviable task of helping me sort through the mass of data I created, and convert the best parts into information. As the punchline goes, " . . . you shoulda seen what went in the other end!"

Saving the best for last, I must extend a special thanks to my family. To my wife, Leslie; and our children Jenniffer, Cassandra, and Mikel I can only say "Dad's back!" I would never have been able to tackle a PhD program without their Herculean support and encouragement. Leslie in particular took up the slack; acting as Social Director, Chief of Services, Chief Financial Officer, and Director of Logistics, she did it all. I offer my deepest thanks, and hope the missed ballgames, recitals, and parent-teacher conferences did not weigh heavily. I hope their surrogate experience of what it's like to struggle at the higher echelons of academia do not sour them from tasting the experience first hand. In that regard, my parting shot to Leslie is "Tag, You're It!"

TABLE OF CONTENTS

VOLUME I

VOLUME II

LIST OF TABLES

LIST OF FIGURES

1.1 Overview

This resea

management o

techniques in re

consists of a ser

order, to achiev

times. Disrupt

When a project

longer, cost mo

important, and th

Coping mec

generally take tw

carefully in order

schedule in such

some scheduling

disruption (more

techniques are m

others. The stab

outcomes, howev

only. These iss

Chapter 1

INTRODUCTION

1.1 Overview

This research investigates the effects of variability and disruption upon the management of projects. The purpose of this effort is to explore the usefulness of various techniques in reducing the negative effects of variability and disruption. A project consists of a series of tasks or activities that must be performed by resources, in a specific order, to achieve a desired result. Variability refers to uncertainty in the project task times. Disruptions to the project consist of the unplanned unavailability of resources. When a project is subject to variability and disruption, the project may begin to take longer, cost more, and achieve less than planned. These negative effects are very important, and the issue has received much study by academics and practitioners alike.

Coping mechanisms to avoid the consequences of variability and disruption can generally take two forms. The first is to schedule or plan the resources and activities carefully in order to make the project less sensitive. The second is to execute the schedule in such a way as to mitigate the damage done as it occurs. It is proposed that some scheduling techniques generate plans that are less sensitive to variability and disruption (more stable) than others. In addition, it is proposed that some execution techniques are more effective at absorbing or dampening the effects of disruption than others. The stability of the project may come at the expense of other desirable project outcomes, however. A more stable project may take longer to complete, or be more costly. These issues have not yet been investigated to any detail. This research will address and begin to resolve some of the fundamental questions and problems surrounding the performance and stability of projects, subject to variability and disruptions, under a variety of conditions.

As will be explained in greater detail in the sections to follow, this paper describes a research effort employing discrete event, dynamic system simulation of a benchmark set of projects. These simulation experiments were designed around the issues just raised. Appropriate statistical techniques were applied to the simulation output in order to explore the relationships between the variables of interest. The following sections will present in further detail **what** this research set out to do, **how** it was done, and **why** the research results are important. First, we will discuss the *Research Problem and Questions* (section 1.2). This chapter will end with a discussion of why the work is important and potentially useful in the *Importance of Research* (section 1.3).

1.2 Research Problem and Questions

Managers calculate and use project schedules to control activities and resources in projects. Schedules are developed using a variety of methods, and the same project or group of projects could be scheduled in many different ways using these different approaches. Each schedule represents a different set of predictions and choices about how best to manage the resources available to complete the project. For a given project, each unique schedule (solution) establishes relationships between activities and resources. These relationships will ultimately determine the performance of the project when managed using that schedule. Overall performance outcomes of particular interest to managers are

measures of

utilization and

have been dev

the other of th

on all criteria.

In theory,

optimize the m

criteria implicit

selecting which

example, some

total project dur

In practice,

anticipated relati

schedule. "Varia

scheduled times.

for a period of tim

example, a resour

piece of equipmen

taken away by an

interfere with the

correct decisions a

managers are total project duration and total project cost (or net present value). Other measures of interest have traditionally included total, peak, and average resource utilization and other measures of resource efficiency. Individual scheduling techniques have been developed which generally provide solutions that perform best against one or the other of these criteria; no single method has been found that provides a "best" answer on all criteria.

In theory, the manager applies the more successful scheduling technique in order to optimize the most important project performance criterion. The trade-offs between criteria implicit in using one scheduling technique over the others are considered when selecting which scheduling method is considered "best" for a particular application. For example, some techniques offer better total cost performance, and others offer shorter total project duration.

In practice, however, the effects of variability and disruptions complicate the anticipated relationship between the scheduling technique and the performance of the schedule. "Variability" occurs when the actual task duration times do not equal scheduled times. "Disruptions" occur when resources (often critical) become unavailable for a period of time, preventing work on some activities from starting as scheduled. For example, a resource disruption may occur as a result of a mechanical breakdown of a piece of equipment. Another type of resource disruption may occur when a resource is taken away by another project, making it unavailable for the current task. These effects interfere with the ability of the project schedule to accurately predict outcomes and guide correct decisions as project activities are completed.

Once var

choices must

schedule repre

project is actu

performs. Bo

project perform

resource requir

the planning an

results of the co

net present valu

Under these

may be how "sta

disruption (stab

under condition

the degree of de

project that is ex

A project that is

be considered to

As will be d

project may ind

encountered as th

desirable outcom

of the same chara

Once variability and/or disruptions cause a deviation from the schedule, additional choices must be made as to how a particular project will be executed. While the original schedule represents a plan (and the scheduling technique is a planning method), once the project is actually begun, the execution method may also determine how well the project performs. Both the planning method and the execution method contribute to overall project performance. Given the nature of the project itself (the technical precedence and resource requirement characteristics which establish the potential performance bounds), the planning and execution methods used to manage the effort will affect the actual results of the completed project against the desired results (e.g., total cost, total duration, net present value).

Under these conditions, an additional concern regarding the performance of a project may be how "stable" it is. The relative "stability" of a project refers to how immune to disruption (stable) or sensitive to disruption (unstable) the activities and resources are under conditions of uncertainty. For the purposes of this research, stability will represent the degree of deviation from schedule for the resources and activities in the project. A project that is executed very closely to the schedule will be considered to be more stable. A project that is executed with numerous (and/or large) deviations from the schedule will be considered to have been (relatively) less stable.

As will be discussed in section 1.3, *Importance of Research*, the loss of stability in a project may indicate an upcoming increase in costs, complexity, and confusion encountered as the project executes. Project stability may therefore be an important, desirable outcome for the project manager. It is anticipated that stability will share some of the same characteristics of other project criteria. To a certain degree, the technical precedence and resource relationships within the projects themselves may impose bounds on the degree of stability a project may exhibit. Also, certain scheduling and execution techniques may contribute to or detract from the stability of the project.

Project stability has not yet been studied explicitly; nor has the role of disruption. This research investigates the performance of both planning and execution techniques in the single project, constrained resource environment, under conditions of uncertainty, when subject to disruptions. Planning techniques include several of the most popular and successful heuristics for project planning and scheduling in the literature today. Similarly, execution techniques include a representative collection of allocation and decision making methods. A known, benchmark set of project scheduling problems representing a broad spectrum of situations have been simulated at multiple levels of variability and disruption. The performance of each combination of planning and execution technique has been measured with respect to time, net present value, and stability. Basic questions surround this issue:

- What is the nature of the tradeoff (if one exists) between schedule stability and schedule performance with respect to the traditional measures in the project?
- How are planning methods affected by variability and disruption?
- How are execution methods affected by variability and disruption?
- Are schedules developed by certain heuristics/scheduling rules more sensitive to variability?
- Are schedules developed by certain heuristics/scheduling rules more sensitive to disruption?
- Do certain execution techniques help minimize the effects of variability?

- Do cer

The proc

greater detail

questions int

variables used

1.3 Importanc

New prod

construction, p

complex endea

management te

that consists of

machines using

organized and c

within this field

and solution of

academic literat

"major" contrib

database search

for the time peri

of interest in the

- Do certain execution techniques help minimize the effects of disruption?

The procedures employed to answer the research questions posed will be covered in greater detail in Chapter 3, *Methodology*. Chapter 3 will include the refinement of these questions into specific research hypotheses, as well as thorough descriptions of the variables used to define the theoretical constructs.

1.3 Importance of Research

New product development, equipment installation, real property acquisition and construction, public works, military campaigns, and shop floor design are all examples of complex endeavors that are managed and controlled through the use of project management techniques. Virtually any large-scale non-sequential human undertaking that consists of the accomplishment of order-dependent tasks or activities by people or machines using resources to achieve a desired result can (and, more properly, should) be organized and controlled using project management/resource scheduling. Problems within this field can have severe cost and performance implications (locally); the study and solution of these problems have broad application (globally). A recent review of academic literature in this research area (Ozdamar & Ulusoy, 1995) identified over 80 "major" contributions since the 1970's; an automated search of the ProQuest/ABI Inform database search on the key phrase "Project Management" turned up over 1,270 references for the time period January 1994 through August 1996 alone! This indicates a high level of interest in the subject. The problems surrounding the proper allocation of resources to tasks in proje

significance.

In order t

large project.

times for the

activities. Sc

satisfying vari

the schedule is

are satisfied.

Once the p

disruptions to t

the schedule. T

events. These

instability in th

synchronization

Loss c

in a degradatio

experience res

fail or weathe

events may de

available for a

perform it may

tasks in projects, and the scheduling of those tasks, are of great practical and academic significance.

In order to synchronize the performance of multiple, interdependent activities in a large project, a schedule is developed. The schedule represents the planned start and stop times for the activities and provides instructions for the resources needed to perform the activities. Schedules are developed in order to achieve some set of objectives, while satisfying various constraints imposed upon the project. On a basic level, performance to the schedule is important in order to ensure that the objectives are met and the constraints are satisfied.

Once the project begins, however, variability in the duration of the activities and disruptions to the resources begin to occur. Variability and disruption cause deviations to the schedule. These deviations, in turn, may cause other deviations to future scheduled events. These deviations in the timing of activities or the allocation of resources indicate instability in the execution of the project. This instability represents a loss in the synchronization of the project.

Loss of synchronization in the activities and resources in the project may result in a degradation of project performance. For example, construction projects often experience resource disruptions and activity variability. A key piece of equipment may fail, or weather conditions may extend the planned duration of an activity. Either of these events may delay the start time of a subsequent activity. Some resources may only be available for a finite period of time. If an activity is delayed, a resource needed to perform it may no longer be available. Additional units of the resource may need to be secured (increasing cost) or substitute resources may need to be used. As a result, the project may fail to meet cost or time performance objectives.

During the development and launch of a new product, the activities of the marketing and design teams may need to be synchronized through adherence to a schedule. The early completion of graphical layout for a visual ad campaign (ahead of final product design work) may result in the need to rework the advertisements or embarrassing misrepresentation of the product. The late completion of customer focus group research may result in the product being designed with (easily avoidable) undesirable characteristics.

In a project like a military campaign, there may be a heavy price to pay for an activity being performed either too early or too late. Supplies delivered to a marshaling point in advance of schedule may expose those supplies unnecessarily to enemy action, resulting in the destruction or capture of the supplies. The destruction of a bridge ahead of schedule may prevent friendly forces from using that bridge to advance into enemy territory. Similarly, the late performance of activities may have undesirable effects on the military project. Resources like aircraft and armored vehicles, if allocated to certain activities either early or late, may be unavailable for higher priority activities or be less effective than if used at the scheduled time.

Both late and early activity starts or stops can degrade project performance. Deviations in the start and finish times of activities or deviations in the allocation of resources represent instability in the project. This instability may result in a loss in the synchronizat

resource distr

It is antic

measures of p

setup cost (in

in order to per

directly affect

premiums may

incurred for ex

Recent art

& Murphy, 19

project cost per

their study of th

unavailability, a

attribute the sou

approaches that

their perspective

excess resource

approach, focus

availability of re

resource unavail

synchronization of the schedule. This loss of synchronization can be triggered by resource disruption or by variability in activity duration.

It is anticipated that the stability of a schedule would be related to the traditional measures of project cost and time performance. On a basic level, if activities incur a setup cost (in time or dollars), or if multiple resources must be simultaneously scheduled in order to perform an activity, then disruptions in the availability of a resource could directly affect cost performance. If resources are rented from outside sources, cost premiums may be incurred as a result of schedule deviations. Extra charges may be incurred for either the early use or late return of rented or leased equipment.

Recent articles in the cost/schedule performance literature (Lee & Gatton, 1994; Just & Murphy, 1994) focus on the "unavailability of resources" as a key determinant in project cost performance. Lee & Gatton approach the issue as a productivity problem. In their study of the construction industry, they identified material unavailability, equipment unavailability, and unreasonable schedules as the main causes of job inefficiency. They attribute the source of these problems to the widespread use of current naive scheduling approaches that assume unlimited or unconstrained resources. An unstated assumption of their perspective is that resource unavailability (disruption) is not a problem as long as excess resource capacity is present (and *vice versa*). Just & Murphy take a similar approach, focusing on the negative effects of building project plans without regard to the availability of resources. In their paper, they demonstrate that a failure to plan for resource unavailability can extend the project length, reduce project efficiency, increase project costs.

profitable pr

Deviatio

project by the

tracked throu

culmination o

deviations fro

et al., 1995).

variance betwe

as of the milest

upon the financ

affect the actua

the costs that s

differences bet

the financial m

alter the financ

managers.

In summa

of a resource (

loss in product

synchronizatio

effectiveness o

project costs, and result in failures to meet contractual obligations– potentially turning a profitable project into an unprofitable one.

Deviations from the project schedule may influence the financial evaluation of the project by the company or its investors. The performance of large projects is often tracked through the accomplishment of milestones. A milestone represents the culmination of a key set of activities. In financial terms, schedule variance refers to deviations from the cash flow schedule associated with the project milestones (Wysocki, et. al., 1995). Financial managers track the progress of the project by comparing the variance between the scheduled cost of the work performed and the actual costs incurred as of the milestone completion date. Instability in the project will have a direct effect upon the financial variance measures. Resource use ahead of or behind schedule will affect the actual costs incurred. Task completion ahead of or behind schedule will affect the costs that should have been incurred according to the schedule. Significant differences between the scheduled and actual costs incurred are a source of concern for the financial managers. Confidence in the project can be shaken, and the investors may alter the financing of the project and demand corrective actions from the project managers.

In summary, instability in a project may lead to many negative effects. First, the loss of a resource (or a delay in its availability) may idle other resources, and result in a direct loss in productivity or efficiency. Second, the project could experience a loss of synchronization of the activities and resources, resulting in a degradation of the effectiveness of the project. Third, disruptions to resources may incur additional costs, degrade pro

result in dev

financial eva

could spread

previously.

grave effects

overall proble

This resea

activity durati

mentioned tha

to the desired

potential achie

resources will

execution meth

noted to have a

have been stud

outcomes, no s

As a first

Next, the stud

factors of proj

projects, the n

disruptions, an

Hopefully, this

degrade project efficiency, or lead to late completion. Finally, project instability can result in deviations in the accomplishment of project milestones, which may affect the financial evaluation of the project or the firm responsible for the project. Disruptions could spread throughout the system, resulting in many of the negative effects described previously. An apparently minor disruption to an apparently minor resource could lead to grave effects on the project as a whole. The degree to which this "ripple effect" creates overall problems is a reflection of the stability of the project as scheduled and executed.

This research seeks to extend the concept of the effects of resource unavailability and activity duration variability into the realm of schedule and resource stability. It has been mentioned that certain factors shape the ultimate performance of the project with respect to the desired outcomes. Technical and resource dependencies serve to limit or bound the potential achievement of the project. Variability in activity durations and disruptions in resources will influence the degree of achievement of project goals. The planning and execution methods used to schedule and perform the project activities have also been noted to have a significant effect on the overall project performance. While these factors have been studied with respect to their effects on the traditional project performance outcomes, no study has investigated these factors as they relate to project stability.

As a first step, this research defines several project management stability measures. Next, the study tries to provide insight into the relationships between the traditional factors of project performance. These traditional factors include the characteristics of the projects, the nature of the project environment (activity variability and resource disruption), and the scheduling and execution methods used to manage the project. Hopefully, insight is provided into the nature of the relationships between these factors and project s

the relations

factors of pr

management

initially will

of performanc

and project stability. Finally, the knowledge gained in studying both project stability and the relationships between project stability, other outcome measures, and the traditional factors of project performance are extended into practical significance for the management of projects. Ultimately, it is hoped that the descriptive theories built initially will be translated into prescriptions to assist managers in achieving higher levels of performance from the projects under their control.

Chapter 2

SIGNIFICANT PRIOR RESEARCH

The importance and complexity of problems in project management have led to a great deal of research activity in this area. Project management/scheduling has been studied and reported upon extensively in the literature for many years. The basic questions have been analyzed in many different ways. However, the intractability of some of the fundamental questions in the field continues to present opportunities. The following review of previous literature will attempt to establish the conceptual structure of the field and the position of this research in it. In addition, specific subsections will establish the state of existing knowledge on (1) Planning Approaches, (2) Execution Approaches, and (3) Stability Measures. Finally, the role of the exogenous or moderating considerations in past research will be described.

2.1 General Reviews of the Literature

The domain of project management and project scheduling research is incredibly diverse. A large volume of published literature on many different aspects of the problem exists. Many works predate even the formal reports on the initial techniques of the Program Evaluation and Review Technique (U. S. Department of the Navy, 1958) and the Critical Path Method (Kelly and Walker, 1959). Several taxonomic schema have been used over the years to organize this vast body of literature. Major criteria have been developed for the purpose of classifying problem and research types within these schema.

These criteri

approach, h

solved simu

An early

study as crit

fundamental

type and the

problem, the

available at le

amount of tim

infinite resou

outcome and

fundamental

of resource c

constrained c

has become

Researc

Problems ca

precedence c

which are re

available fo

availability

renewable re

These criteria include: the nature of the constraints, the objectives sought, the solution approach, how the resources are utilized, and whether single or multiple projects are solved simultaneously.

An early effort (Davis, 1966) used some primary characteristics of the problem under study as criteria for logically organizing the literature. Davis noted that there existed fundamental differences between research investigating the resource constrained problem type and the resource unconstrained type. In the resource constrained project scheduling problem, the resources required for the performance of tasks are considered finite and available at levels below what would be needed to complete all activities in the minimal amount of time. In the resource unconstrained type, the solution approach assumes that infinite resources are available on demand. As noted by Davis, both the desired solution outcome and method of solution are very different for the two types of problems. The fundamental nature of this split has led to the recognition of the taxonomic characteristic of resource constrainedness by many other researchers in this field. The resource constrained class of problems, perhaps by virtue of having higher practical application, has become the dominant class of problem type in project scheduling research.

Researchers refined the classifications based on the nature of the constraints. Problems can now be classified (Ozdamar & Ulusoy, 1995) as having only technical or precedence constraints (Davis's resource unconstrained); or can have resource constraints which are renewable, nonrenewable, or doubly constrained. Renewable resources are available for a certain amount of time over a given time period (e.g., 8 hours of availability over a 24 hour day for personnel shifts). When a new time period begins, the renewable resources are available once more for the new time period. Non-renewable resources ar

resources su

constrained

renewable re

duration (lik

It must

categorizatio

unconstrained

optimization

minimization

minimization

analysis of tot

used as a class

primary criteri

consistently re

of net present v

There is also a

objectives.

The third m

management sch

work. While ret

unconstrained, a

new axis: the ch

resources are available in a finite amount over the duration of the project. Finite resources such as raw materials or budgeted capital may fall into this category. Doubly constrained resources can be consumed only for a limited time in given time periods (like renewable resources) and have only a finite amount of availability over the total project duration (like nonrenewable resources).

It must be noted that even in 1966 there were several criteria proposed for the categorization of problems within the two broad types of resource constrained and unconstrained. Primary among them was the division of problems based on the desired optimization outcome (Davis, 1966). Outcomes being sought at the time included the minimization of total project duration, the minimization of total project cost, the minimization of resource consumption (resource leveling), and the description and analysis of total time and total cost tradeoff curves. Objective(s) sought continued to be used as a classification criterion by later researchers, and in some cases was used as the primary criterion (Ozdamar & Ulusoy, 1995). While the time minimization outcome has consistently received the bulk of attention, the minimization of cost and the maximization of net present value (NPV) have received considerable attention in the last twenty years. There is also a class of problems that attempt to simultaneously optimize for multiple objectives.

The third major taxonomic criterion for the organization of the project management/scheduling literature was also first noted by Davis in his 1973 follow-up work. While retaining the problem characteristics of resource constrained vs. resource unconstrained, and the desired optimization outcome, he divided the literature along a new axis: the characteristics of the solution method employed. Davis noted that solution methods were either fundamentally exact or heuristic in nature. Exact approaches employ numerical analysis methods to determine best schedules or allocations of resources in order to achieve an optimum result on some desired project performance measure. Heuristic approaches employ inexact rules of thumb or decision rules in order to achieve good (but not necessarily the best) result on some desired project performance measure.

The exact approaches, while promising, have been limited in their application by the size and complexity of problems that are tractable in a realistic sense. The implications of this limitation will be discussed in more detail in a later section of this proposal. The current research applies several previously successful heuristic procedures to a subset of a benchmark set of project scheduling problems (the Patterson Set; Patterson, 1984). These resource constrained project scheduling problems have known, exact solutions for the deterministic case (found by Patterson's modification of an enumerative procedure employed by Talbot in 1976). The known, exact solutions provide project schedules or plans that achieve best results under deterministic conditions.

By the early 1970's, the nature and behavior of the resources and the interaction between the resources and the activities began to be recognized as forming unique problem classes. Davis (1973) began the trend by differentiating between single resource and multiple resource cases. He used three classes of resource utilization types: first, one resource type, common to all jobs; second, multiple resource types, but only one type required for each activity; and third, multiple resource types, that are required in a variety of combinations for the activities in the project. The multiple resource cases were soon expanded to consider flexible situations where the duration of an activity changed based on the amount (and perhaps the type) of resources that were assigned to it. This recognition

based on th

resource em

type) for its

multiple con

A final

is the separat

project cases.

project. The

resources aga

project settin

the successfu

of the single p

in this enviror

results warran

Several ta

of project man

incredibly dive

problem and re

constraints, the

and whether sin

The current

resource constr

recognition of implicit time-resource functions established a classification of problems based on the resource employment mode (Ozdamar & Ulusoy, 1995). Single mode resource employment exists when each activity requires a fixed amount of resources (by type) for its accomplishment. Multi-mode resource employment allows the application of multiple combinations of resources (by type) for the accomplishment of tasks.

A final major taxonomic criterion for the classification of project scheduling research is the separation of single project problems from multiple project problems. In the single project cases, researchers attempt to schedule the activities and resources of a single project. These problems are distinct from the set that attempt to schedule a set of resources against activities in multiple projects. While much more complex, the multi-project setting has great practical application to large firms that must attempt to manage the successful completion of multiple projects (e.g., construction). Due to the simplicity of the single project case, researchers often initially investigate new issues or techniques in this environment and then expand their efforts into the multi-project case if initial results warrant further effort.

Several taxonomic schema have been used over the years to organize the vast body of project management and project scheduling literature. The domain of this research is incredibly diverse. Major criteria have been developed for the purpose of classifying problem and research types within these schema. These criteria include: nature of the constraints, the objectives sought, the solution approach, how the resources are utilized, and whether single or multiple projects are solved simultaneously.

The current research effort studies those problems which can be classified as: **resource constrained**, considering **multiple objectives**, solved **heuristically**, with **single**

mode reso

of this liter

particular f

type will be

problem. In

the planning

employed, n

this study.

2.2 Planning

The fund

(RCPSP) is to

in order to ach

takes the form

next two sectio

applicability o

each class are i

2.2.1 Exact Ap

Exact appr

allocations of r

Project perform

fashion as to co

the project). An

mode resource-activity functions, applied to **single projects** in isolation. The remainder of this literature review will concentrate on those works which have focused on this particular formulation of project scheduling problems. Problem classes outside of this type will be discussed only as they apply to or lend understanding to this narrower type of problem. In the following sections of the literature review, discussions cover (in turn): the planning or scheduling approaches used, the execution approach or decision rules employed, measures of stability, and the environmental or exogenous variables tracked in this study.

2.2 Planning Approaches

The fundamental goal in solving the resource constrained project scheduling problem (RCPSP) is to develop a plan for the allocation of resources to the activities in the project in order to achieve some overall project performance objective(s). This plan generally takes the form of a schedule of which resources perform which activities and when. The next two sections of the literature review discuss the limitations, assumptions, and the applicability of both exact and heuristic approaches. The best specific techniques within each class are identified and discussed.

2.2.1 Exact Approaches

Exact approaches use numerical optimization methods to determine best schedules or allocations of resources. The definition of best is defined by a desired result on some project performance measure. For example, a project may need to be scheduled in such a fashion as to complete all tasks in the shortest time possible (minimize total duration of the project). An exact approach would formulate a mathematical model of the problem (e.g. an integer, linear program) and solve this model for minimum duration. The exact approaches promise (when all of the methodological assumptions are met) to provide a single, best answer to the problem as formulated.

Because of this promise of achieving a best, exact answer, researchers have been attempting to apply exact methods to the RCPSP since the early days (1950s) of research on the problem. These attempts have achieved mixed success for a variety of reasons. Two limitations of the exact approaches to the RCPSP are: first, the assumptions inherent in the exact approaches do not match the realities of the project management problem, leading to a loss of solution fidelity; and second, the size and complexity of realistic RCPSPs put them beyond the capabilities of many of the exact methods.

Patterson (1984) reviewed the state of the art in the use of exact procedures. He noted that the early attempts at finding exact solutions relied on mathematical programming (integer) models. These models required that the problem be formulated in very specific and unrealistic ways, and could only model very simplistic problem characteristics. These attempts were therefore of limited practical use (Davis, 1973). A more recent mathematical programming model (Slowinski, 1981) formulated the RCPSP as a Multiple Objective-Integer Linear Program designed to be attacked using Khachian's algorithm. Such a formulation promised to solve the RCPSP in polynomial time; however, this and subsequent attempts based on Slowinski's formulation have not been borne out.

Due to the failures and limitations of the earlier LP models, specialized formulations were developed, usually relying on an enumerative/search based approach. In the 1984 article Patterson noted that three of these approaches performed best in a wide variety of situations t

Simson's (1

Two additi

1984, the C

(1992).

While t

and activity

realistic than

exact approa

complexity.

(generally) to

complete (Ka

The searc

projects conti

approach on a

advances in co

speed on small

projects tracta

fully develope

problems still

approaches see

(Simpson, 199

significantly lim

situations for the RCPSP: Davis & Heidorn's (1971) Bounded Enumeration procedure, Stinson's (1976) Branch & Bound, and Talbot's (1976) Implicit Enumeration method. Two additional Branch & Bound (depth first) procedures have been developed since 1984; the Christofides et. al. work of 1987 and that of Demeulemeester & Herroelen (1992).

While these exact approaches still require that time be considered in discrete values, and activity times be integer values, the assumptions required by the model are more realistic than the mathematical programming approaches tried initially. However, these exact approaches are still limited in their applicability by the problem size and complexity. Using these enumerative formulations, linear growth in problem size leads (generally) to geometric growth in solution time. The RCPSP is combinatorial and NP complete (Karp, 1972).

The search for efficient analytical exact approaches applicable to practical-sized projects continues. Recently, Simpson & Patterson (1996) used a parallel processing approach on an enumerative search algorithm in order to take advantage of recent advances in computer hardware technology. While representing an improvement in speed on smaller problems, and a potential expansion in the size and complexity of projects tractable within a reasonable amount of time, this technique has not yet been fully developed. Even with the ongoing refinements to the exact approaches, two main problems still persist in trying to use these methods in practice. Currently, exact approaches seem to be generally limited to 50 activities and 3 resources or fewer (Simpson, 1991) in order to produce solutions in a reasonable amount of time. This significantly limits the application of exact approaches to realistic projects. Also, all exact approaches (to date) have relied upon the assumption of deterministic activity times. Real project activities deviate from deterministic estimates to varying degrees. The validity of any exact, deterministic approach is threatened by the stochastic, variable nature of project management in reality. Therefore, this study concentrates on the performance of heuristic methods. However, the performance of the exact, deterministic solutions in the stochastic, variable environment is used as a reference for the performance of the heuristics. The benchmark set of RCPSP's used in this study, the Patterson Set, are solvable using Patterson's (1984) implicit enumeration algorithm and exact time-minimizing solutions for the deterministic cases are known.

2.2.2 Heuristic Approaches

Heuristic approaches use inexact rules of thumb or decision rules in order to achieve a good (but not necessarily the best) result on the desired project performance measure. The technical precedence (network structure) constraints are inviolate; the decisions generated by the heuristic techniques involve only the ordering and prioritizing of activities. The resources, when they become available, are assigned to eligible activities. Activities become eligible when their precedence or technical constraints have been satisfied. The order in which the eligible activities are completed determines the eligibility of additional activites through the technical or precedence constraints. This flow of activities through the eligible list ultimately determines the completion sequence of every activity in the project.

Heuristic techniques are further divided by how the method operates. Generally, the heuristics are either serial or parallel. Serial routines will assign priorities to tasks (for the purpose of dedicating resources to tasks) in a separate step before sequencing the tasks in the schedu

primarily t

quality of s

in use toda

project out

Ulusoy, 19

order to op

minimizati

value, and th

are discusse

2.2.1 Heur

Davis &

Heuristic and

conclusion in

a choice amo

Patterson's eff

which heuristi

constrained pro

using nine sche

enumeration ex

possible due to

schedules were

the schedule. Parallel routines prioritize and sequence the tasks at the same time. Due primarily to the inherent efficiency of the parallel routines, with no loss in applicability or quality of solution, the parallel routines have generally come to dominate the approaches in use today. The parallel heuristics have been further subdivided based on the desired project outcome they have been designed to provide good solutions for (Ozdamar & Ulusoy, 1995). This is analogous to the specific formulation of each exact approach in order to optimize a desired project outcome. The main classes of desired outcome are the minimization of project duration, the minimization of cost/maximization of net present value, and the satisfaction of multiple objectives. Selected best performers in each class are discussed below.

2.2.2.1 Heuristics Seeking Minimum Project Duration

Davis & Patterson (1975) offered a comprehensive review in "A Comparison of Heuristic and Optimum Solutions in Resource-Constrained Scheduling." A general conclusion in the literature at this point was that there was little basis *a priori* for making a choice among the (at that time) literally hundreds of published heuristics. Davis and Patterson's effort was designed to provide a more definitive answer to the question of which heuristics perform better. A problem set of 83 multiple resource, resource constrained projects with 20-27 activities were solved to minimize total project duration using nine scheduling techniques. First, optimal solutions were found using a bounded enumeration exact technique (OPT). The calculation of the optimal schedules was possible due to the small size and limited complexity of the problem set. Second, schedules were generated using a heuristic approach that assigned activities to resources randomly (RND). These two approaches, OPT and RND, provided two important benchmark comparisons for the remaining seven techniques investigated.

The results of this investigation were instructive. First, no single heuristic was found to be consistently best on every problem. Second, four of the popular heuristics consistently performed worse than random assignment. The remaining three outperformed random assignment and performed well enough overall to merit further consideration as a useful technique by the investigators.

The highest performing heuristic was the Minimum Slack (MINSLK) approach. MINSLK assigns the highest priority to those tasks that exhibit the least slack (difference between the earliest possible start time and the latest possible start time on the unconstrained, deterministic CPM formulation of the problem). MINSLK demonstrated only a 5.6% average increase in total project duration over the OPT schedule and found the same solution as the OPT solution in 24 of the 83 total problems.

The second best performing heuristic was the minimum Late Finish Time (LFT) method. The LFT method assigns higher priorities to tasks which have the earliest late finish time in the deterministic CPM formulation of the network. LFT schedules represented a 6.7% average increase over the optimum schedules, and found the OPT solution in 17 cases.

A method that performed closely to LFT was the Resource Scheduling Method or RSM. RSM considers both the current task and any subsequent (dependent) task that relies on its completion in the deterministic CPM network. When evaluating technically feasible activities for the next activity start, the eligibles list is composed of activity pairs. The pairs consist of all currently feasible activities plus each of its follow-on activities.

RSM sche

is calculat

latest start

the amount

next pair w

eligible tas

OPT soluti

The RS

increase in t

evaluated pe

of cases whe

solution was

While n

provided a co

MINSLK tec

comparisons.

In 1982, T

addition of sor

the complexity

applying more

resource proble

formulation and

to the problem a

RSM schedules first those activities that have the smallest delay factor. The delay factor is calculated as the difference between the earliest finish time of the current task and the latest start time of its subsequent task in the pair. In a sense, the delay factor represents the amount of local slack between each task and any task that follows it. The current-next pair with the least slack will receive the highest scheduling priority (for the currently eligible task). RSM achieved a 6.8% mean increase in total task duration, and found the OPT solution for 12 cases.

The RND or random assignment method came in fourth; displaying an 11.4% mean increase in total duration and finding the OPT answer in only 4 cases. All other heuristics evaluated performed worse than RND on at least one of the performance criteria (number of cases where shortest duration solution was found, percentage of times the shortest solution was found, percentage average increase over shortest project duration).

While not contradicting the previous studies, Davis and Patterson's 1975 effort provided a comprehensive comparison of many different and popular methods. The MINSLK technique became established as "the method to beat" for many future comparisons.

In 1982, Talbot performed a comparison similar to that of Patterson but with the addition of some of the more recent heuristics. In his work (Talbot, 1982), he expanded the complexity of the problem set to include multi-mode resource-task activity functions (applying more resources shortens activity durations). A set of 100, 10-activity, 3-resource problems was solved as a benchmark using a 0-1 Integer Linear Programming formulation and the random assignment rule. Eight different heuristics were then applied to the problem and the results were compared.

Whil

percentage

solutions

(34). Min

with the m

equivalent

activity. M

duration ins

methods are

formulation.

In 1990,

procedures fo

and 30 medi

problems, an

problems we

heuristics we

that order. G

outperformed

Bala's 1994 c

MINSLK

test in which

Ulusoy introd

(LCBA). LC

While RSM and MINSLK were not tested, LFT was and ranked first for the highest percentage of best heuristic solutions (84%) and third place for the number of OPT solutions (33). Two heuristics were tied for first rank for the number of OPT solutions (34): Min(L-D) and Min(L-Davg). Min(L-D) assigns the highest priority to activities with the minimum value of late finish time minus the shortest duration. This is equivalent to using the earliest late start time for the fastest resource loading of the activity. Min(L-Davg) is a variation of the formulation that uses the average task duration instead of the shortest (most resources assigned) duration. Both of these methods are specific and peculiar to the multi-mode resource-activity duration problem formulation.

In 1990, Boctor performed another comparison, again using OPT and RND procedures for performance bounding. Boctor's test employed 36 small (5-20 activities) and 30 medium (38-111 activities) problems. OPT solutions were obtained for the small problems, and the deterministic critical path lengths (unconstrained) for the medium problems were used as best achievable benchmarks. Eight parallel and five serial heuristics were applied to the problem set. MINSLK, LFT, and RSM performed best, in that order. Generally, the serial heuristics were poor performers (only two of the five outperformed RND). MINSLK was again found to be the top performer in Oguz & Bala's 1994 comparison.

MINSLK, LFT and RSM have been the top performers in virtually any comparison test in which they have been tried, with one notable exception. In 1994 Ozdamar & Ulusoy introduced a new and promising heuristic, Local Constraint-Based Analysis (LCBA). LCBA is a parallel heuristic that assigns priority to tasks based on an analysis of resource contention amongst the activities on the eligibles list. They tested LCBA against four other heuristics (Ozdamar & Ulusoy, 1995) in both a single-pass mode of operation and a multi-pass mode, using the 110-problem Patterson Set. In the multi-pass mode of operation, the heuristics operate a single, forward pass as they would normally be used. A backward pass is then performed. First, all activity latest finish times are changed to reflect the difference between the (just scheduled) start times and the total project duration. The project completion time is now set to 0 and the scheduling procedure is repeated in reverse, and activities become eligible when their (in the original formulation) successor activities are complete. Forward and backward iterations are repeated until the project duration does not improve.

Ozdamar & Ulusoy reported the results of the heuristics in both the single and multi-pass versions. Generally, the LCBA outperformed both MINSLK and LFT; with a greater difference in the multi-pass approach. Also, the Weighted Resource Utilization and Precedence (WRUP; from an earlier work by Ulusoy & Ozdamar, 1989) technique which formed the earlier LCBA approach also outperformed LFT but not MINSLK.

2.2.2.2 Heuristics Seeking Maximum Net Present Value

While much of the interest in the RCPSP has focused on the minimization of total project duration (by over a 3 to 1 margin according to Ozdamar & Ulusoy's 1995 review of the literature), the maximization of Net Present Value (NPV) has also received some attention. One of the earliest works specifically dedicated to forming and solving the NPV variant is Russell's 1970 "Cash Flows in Networks." Russell notes that "The use of critical path or network techniques in cost control has lagged behind other variations of the basic scheduling technique such as resource allocation for the smoothing or leveling of resourc

importanc

Whil

unconstrai

described

each with

or negativ

attempt to

in large, co

event forw

events and

activity (by

flow" varie

A later

on a set of g

activities (R

minimizing

order to spe

Scheduling (

solution. Th

difference be

essentially pr

unconstraine

of resources, although the cost aspects of project control must be basically of more importance."

While this early work was an attempt at an exact approach to the resource unconstrained case, it is instructive in the way Russell formulated the problem. He described the basic cash flow problem as a network of activities, connected by time arcs, each with an associated pay event or cash flow which could be either positive (a receipt) or negative (a payment). Generally, in order to maximize NPV, the schedule should attempt to bring forward positive pay events and push back negative pay events. Often, in large, complex projects, these two outcomes are in conflict; bringing a positive pay event forward may result in the inability to push back several much larger negative pay events and vice versa. Russell's solution was to calculate the marginal costs of each activity (by duration) and use these costs to formulate a non-linear program (of the "fluid flow" variety) which could be solved iteratively through successive approximation.

A later work (Russell, 1986) specifically compared the performance of six heuristics on a set of 80 problems. One of the heuristics was based on the random selection of activities (RND), and two were demonstrated to have good track records with respect to minimizing project duration (MINSLK and LFT). Four new heuristics were developed in order to specifically address the characteristics of the NPV RCPSP. The Target Scheduling (TS) rule uses the optimal finish times from the unconstrained NPV optimal solution. This rule assigns the highest priority to those activities with the largest difference between their current earliest finish time and the optimal finish time. TS essentially prioritizes activities based on the degree of their deviation from the unconstrained optimal formulation. In the DUAL heuristic, Russell uses information from the

formulat

unconstr

nodes ch

measures

that node

arc flow v

flow) solu

these tasks

latest earlie

Russell

importance

One interest

resource con

NPV perform

of the heurist

rankings wer

RAN. For p

The relative p

DUAL, TS >

under tightly

random assign

from the solution of a sequence of network flow (transshipment) problems. He formulates the (fundamentally non-linear) NPV problem as a series of simpler resource unconstrained transhipment problems in which only the supply/demand levels at the nodes change (the method used by A. H. Russell, 1970). The arc flow values are measures of the marginal values of delaying the activity associated with the cash flow at that node. The DUAL rule assigns the highest priority to those activities with the highest arc flow value (marginal cost of delay) from the resource unconstrained optimal (cash flow) solution. The Lowest Activity Number (LAN) rule assigns the highest priority to those tasks with the smallest index number when activities are numbered from earliest to latest earliest start time in the unconstrained, deterministic CPM network.

Russell combined these basic decision rules into pairs of primary and tie-breaking importance: TS, LAN; DUAL, TS; TS, DUAL; MINSLK, LAN; LFT, LAN; and RAN. One interesting (and unanticipated) result was noted overall. As the probability of resource contention increased (projects become "more constrained"), the differences in NPV performance became greater. For relatively unconstrained projects, the performance of the heuristics was relatively equivalent. Under these conditions, the performance rankings were: MINSLK, LAN > TS, DUAL > TS, LAN > LFT, LAN > DUAL, TS > RAN. For projects with greater resource tightness, the differences became more acute. The relative performance rankings changed significantly: TS, DUAL > TS, LAN > DUAL, TS > RAN > MINSLK, LAN > LFT, LAN. The duration minimizing heuristics, under tightly constrained resources, were actually worse in maximizing NPV than the random assignment rule.

Shortly after the publication of Russell's heuristics, Smith-Daniels and Aquilano (1987) compared the performance of optimum, early start and late start procedures in achieving higher levels of project NPV. Using five different cash flow profiles for Patterson's 110 problem set, the authors tested the methods on 550 problems. Using the optimal (to minimize time) schedule as a baseline (OPT), the researchers constructed an earliest possible start schedule (ESCR) then used a variety of rules to shift non-critical activities later in time to create a late-start constrained resource schedule (LSCR). This shift (delay) of non-critical activities should have the effect of delaying cash outflows (improving NPV) while not delaying project completion. These right-shifting rules were based on the earlier work of Weist (1964).

The results of this experiment were mixed. Generally, there was no definitive improvement in NPV for all cases for any one the three methods. The NPV for the OPT method was higher in 292 of the cases, the NPV was higher for the LSCR for 248 cases, and in 10 cases the NPVs were equal. The ESCR schedules generally produced inferior NPV results. The researchers noted that the nature of the payment schedule was an important factor in the performance of the heuristic approaches. While the OPT schedule clearly produced the shortest project durations (as expected), the differences in duration between the ESCR and LSCR were slight.

Overall, Smith-Daniels and Aquilano concluded that while right-shifting of non-critical (slack) tasks did result in an improvement in NPV in many cases, the time-minimizing approaches performed well for both time minimization and NPV maximization. A related work (Smith-Daniels & Smith-Daniels, 1987) demonstrated that solutions which maximized NPV were indeed different from solutions that minimize time in many cases. Perhaps more importantly, this work introduced material ordering costs into the NPV-maximizing RCPSP and concluded that these solutions differed significantly from the time minimizing solutions. When viewed together, the results from these two 1987 studies appear contradictory, at least in the claims of how dissimilar the time minimizing and NPV maximizing solutions are. This matter was clarified somewhat in 1990 by Elmaghraby & Herroelen. In this study, the authors included the concept of time dependent payments (bonus schedules). Their general finding was that when project bonus payments (higher cash receipt for earlier completion) were present, a project schedule that first constructed a minimum duration schedule and then right-shifted non critical activities produced the best results. Using a 0-1 Integer Linear Programming method, they demonstrate that their heuristic does indeed find the optimal solution for some small problems. A wider test of the approach was not reported.

Perhaps the most interesting and complete analysis of the NPV maximizing RCPSP is the study performed by Padman and Smith-Daniels in 1993. Based primarily on Russell's (1970) approach, the authors use the dual formulation of the linear approximation to the non-linear NPV maximizing mathematical program to assign earliness costs and tardiness penalties for each activity. While Russell's approach iteratively manipulated target times for activity completion until all marginal costs were equal (implying optimality), Padman used the preliminary marginal costs from Russell's preparation step to guide the performance of selected heuristics. The shadow prices are calculated initially, and scheduling proceeds until resource contention is encountered. Shadow prices are then recalculated, priorities are reassigned, and scheduling continues until the next resource contention occurs and the process repeats.

Eight
resource c
compared
general fir
constraine
differences
or higher).
differences
smaller (50
The two
the Immedia
Release of t
methods. In
highest opp
ICFW-OCC
between the
overall conc
maximizing
a family of
conclusion
of expensiv
create.

Eight new heuristics were applied to 144 projects of varying size, complexity and resource constrainedness. As no optimal solutions were available, the heuristics were compared to each other on the basis of best vs. percent performance below best. Two general findings are noteworthy. First, at low and medium levels of resource constrainedness, there were very small differences among the heuristics. Performance differences only became significant at high levels of contention (2.0 Average Utilization or higher). Second, as the projects became larger and more complex, the performance differences went away. The heuristics seemed to make a big difference only for the smaller (50 or less activities) projects.

The two best performing heuristics in this complex, multiple iteration technique were the Immediate Release of the Opportunity Cost of Scheduling (IOCS) and Immediate Release of the Cash Flow Weight - Opportunity Cost of Cash Flow (ICFW-OCC) methods. In IOCS, highest priority for scheduling is given to those activities with the highest opportunity cost of not being scheduled (based on Russell's dual formulation). In ICFW-OCC, the priority is given to those activities with the highest calculated difference between their cash flow of completion and their opportunity cost of completion. The overall conclusion of this research was that an effective strategy for scheduling the NPV-maximizing RCPSP was to apply a multi-heuristic approach. Schedule the project using a family of heuristics, then select the best schedule for each project. Another overall conclusion was that there was found to be a definite trade-off between the postponement of expensive activities and the possible additional resource contention that this delay may create.

A m

good (in t

by Pinder

optimizati

construct s

was create

resulting s

the criterio

Each c

start times

used as a b

performed

to the relax

procedure c

delaying ea

feasible) lis

rules descri

greatest suc

activities w

activities w

Ten nev

discounted c

on the cash f

A more recent work included several new and promising heuristics for developing good (in terms of NPV) schedules (Pinder and Marucheck, 1996; based on previous work by Pinder and Marucheck, 1989). In their research, Pinder and Marucheck used one optimization-guided heuristic, six established heuristics, and ten new heuristics to construct schedules. A randomly generated set of problems with desired characteristics was created. The scheduling methods were applied to each problem, and the NPV of the resulting schedule was then calculated. The amount of (planned) NPV was then used as the criterion for success for comparing the scheduling methods.

Each of the scheduling methods employed a parallel, multi-pass algorithm to assign start times to activities based on priority rules. The optimization guided heuristic was used as a benchmark for NPV performance for the remaining scheduling techniques. It performed consistently best on all problems. This method formulates and solves the dual to the relaxed (resource unconstrained) NPV maximization LP problem using the procedure of Padman and Smith-Daniels (1993). The marginal costs (NPV reductions) of delaying each activity are then used to prioritize activities on the eligibles (technically feasible) list. The established heuristics used were the MINSLK, EDD, SPT, and GRD rules described earlier. Also used were the greatest number of successors (GNS) and greatest succeeding processing time (GSPT) rules. GNS assigns priority to those activities with the greatest number of following activities. GSPT schedules first those activities with the largest total of processing time for all following activities.

Ten new heuristics (five pairs) were developed, each based on some form of discounted cash flow weights. Each heuristic used a different weighting factor w_i (based on the cash flow, discount rate, and duration) to calculate the scheduling priority of the activities. There are five weighting schemes for calculating w_i as indicated in Table 2.1, Weighting Rules. Each weighting scheme includes two basic variations of w_i, comprising a pair. The first case of the pair simply assigns priority based on min[$1/w_i$]. The second case of the pair assigns priority based on min[d_i/w_i], where d_i is the duration of the activity being considered.

Table 2. 1: Weighting Rules

Acronym	Weight w_i	Prioritization Statistic
DCFD, DCFDW	$CF_i \exp(-\alpha d_i)$	$1/w_i$, d_i/w_i
DCFEF, DCFEFW	$CF_i \exp(-\alpha EF_i)$	$1/w_i$, d_i/w_i
DCFLF, DCFLFW	$CF_i \exp(-\alpha LF_i)$	$1/w_i$, d_i/w_i
ΣDCFEF, ΣDCFEFW	$(\Sigma_{k\in s} CF_k)\exp(-\alpha EF_i)$	$1/w_i$, d_i/w_i
ΣDCFLF, ΣDCFLFW	$(\Sigma_{k\in s} CF_k)\exp(-\alpha LF_i)$	$1/w_i$, d_i/w_i

where CF_i = Cash Flow as a result of activity i
$\propto$ = Discount Rate
LF_i = Late Finish time of activity i
EF_i = Early Finish time of activity i
$k \in s$ = The set of activity i and all of it's successors

The most successful of all methods tested was the optimization guided heuristic. The ΣDCFLF heuristic consistently performed next best. The performance of the remaining new and traditional heuristics was mixed. Generally, the ΣDCFEF (new) and GSRR, GSPT (traditional) prioritization rules performed well also. The SPT, ΣDCFEFW, and ΣDCFLFW rules consistently returned the poorest performance.

In a similar study, Yang, Tay, and Sum (1995; based on the 1989 work by Pinder and Marucheck) added a random prioritization of activities to the set of traditional heuristics, and substituted simulated annealing for the optimization guided approach used by Pinder and Marucheck. The results were similar. The simulated annealing method consistently provided the best performance. Out of the new and traditional rule based heuristics, they found that the ΣDCFLF rule worked almost as well as the simulated annealing method, and better than the remaining heuristics. These results are completely consistent with those found by Pinder and Marucheck in 1989 and 1996.

2.3 Execution Approaches

While extensive research has been performed on the development of schedules or plans for the RCPSP, very little work has been done on the use of decision rules or techniques for the execution of the schedule once the project has actually begun. The schedule represents a series of predictions about the behavior of the resources and activities involved in the project. The degree to which these predictions come true in reality (or don't) may affect the degree to which this schedule remains valid over the lifetime of the project. Variability which is not taken into account, and disruptions to resources which are not planned for, will each contribute to deviations from the schedule during project execution.

An execution approach represents a mechanism for coping with the real-world deviations from the model-world schedule predictions. The effectiveness of the execution approach may determine the outcome of the project to a greater degree than the planning approach used. As the conditions (in reality) depart from what was planned for, the issue of how these departures and uncertainties are handled becomes increasingly important.

An

"Plannin

notes the

practice; i

availabilit

priorities a

utterly use

Burt p

projects ur

baseline a

same man

time an ac

higher lev

beginning

to the lag

beginning

These

results fro

indeed imp

this effect

duration o

projects wi

result of th

An early work recognizing the problems inherent in the execution of schedules is "Planning and Dynamic Control of Projects Under Uncertainty" (Burt, 1977). Burt first notes the absence of network optimization techniques in the management of projects in practice; he attributes this to uncertainty in task durations, the variability in the availability of resources, and the dynamism inherent in managers intervening to reallocate priorities and resources. These factors conspire to make even the best "optimal" schedule utterly useless from a practical standpoint.

Burt proposed four dispatching or execution rules to assist in the management of projects under conditions of dynamic uncertainty. First, the static approach represents a baseline attempt to adhere to the original schedule. Next, dynamic rules behave in the same manner as static, but the project is rescheduled using the original algorithm every time an activity is completed. Third, lag first uses dynamic scheduling, but allocates higher levels of resources at the end of the project (the withholding of resources at the beginning of the project with a sudden increase in the middle). Finally, seq lag is similar to the lag first approach, but smoothly increases resources applied to tasks from the beginning to the end.

These approaches were tested using a discrete event, dynamic simulation. General results from this investigation demonstrated that dynamic updating (of all types) did indeed improve the performance of the projects. Larger projects benefited the most from this effect. Also, the backloading of resources (lag first and seq lag) improved the duration of many of the projects tested. This improvement was most pronounced in projects with a higher degree of variability in individual task durations. This could be the result of the increased resources having a smoothing effect on the negative roll-up of residual

smoothed

A m

Using co

used sim

schedulin

managed

reschedulin

random in

Some

better tha

improved

related res

for others

projects w

key chara

reschedul

occasiona

Also, mo

The

managem

(Yang, 1

schedulin

residual activity delays toward the end of the project (some delays early on would be smoothed by the effect of shorter activities following them).

A more recent work by Partovi and Burton (1993) focused on rescheduling intervals. Using concepts developed in the production scheduling literature, Partovi and Burton used simulation to investigate various monitoring and control techniques for project scheduling. They simulated five different project networks, with 25 to 48 activities, managed using five rescheduling intervals. The frequencies for rescheduling were: no rescheduling, five equal intervals, front-loaded intervals, end-loaded intervals, and random intervals.

Some general conclusions were reached. First, all of the rescheduling schemes were better than the baseline no rescheduling case. Second, while all of the techniques improved the performance of the projects, there was no clear always best method. A related result was that rescheduling seemed to be more helpful for some problems than for others. While shorter projects with fewer activities seemd to benefit more than longer projects with more activities, no specific analysis was performed in order to determine the key characteristics of projects which would benefit the most or least from the different rescheduling methods. More general results indicated that if you can only reschedule occasionally, rescheduling later is better than rescheduling earlier in the project life. Also, more frequent rescheduling is better than less frequent rescheduling.

The application of production scheduling and rescheduling concepts to the project management environment seems to be a promising approach. An interesting recent work (Yang, 1996) uses the concepts of scheduling and dispatching from the production scheduling literature to investigate the effect of variance from predicted activity times (used du

dynamic

dispatchi

environm

Simu

of potenti

dispatchin

activities

were then

executed.

(CRR). M

weighted

Once the

were simu

order to m

Two

FR attemp

eligibles l

unavailab

are reserv

NR rule, c

executed.

available.

(used during scheduling) on project performance during execution. Yang also used a dynamic simulation to evaluate the performance of deterministic scheduling and dispatching rules in the execution of resource constrained projects in stochastic environments.

Simulated annealing was used to build near optimal schedules, by searching the tree of potential scheduling decisions for improvement in the total project time. Three other dispatching rules were used to build schedules. Once the initial schedule was found, activities were assigned priorities based on their scheduled start times. These priorities were then used to order activities on the precedence feasible list as the project was executed. The dispatching heuristics tested were the cumulative resource requirement (CRR), MINSLK, and first come, first served (FCFS). The CRR method is a resource-weighted variation of the cumulative cash flow NPV maximizing rule discussed earlier. Once the schedules were built using the four methods (SA and the heuristics), the projects were simulated and execution rules were applied to the updated priority-eligibles list in order to make the actual resource assignment decisions.

Two execution rules were examined: full reservation (FR) and no reservation (NR). FR attempts to execute activities strictly according to their priority ranking on the eligibles list. If the highest priority activity on the list cannot be executed (due to the unavailability of a needed resource), then those resources which are needed and available are reserved by the high priority activity until all resources needed become available. The NR rule, conversely, does not reserve resources. If the highest priority activity cannot be executed, the next lower priority activity is evaluated and executed if resources are available. While the FR rule tends to ensure that the activities are executed in roughly the same ord

more fu

Som

techniqu

affected

MINSLK

better). U

FCFS, alt

in all but

and timing

the earlier

by resched

rule is help

highly con

projects d

projects b

2.4 Mea

Sche

the ability

represent th

project. A p

same order as the updated priority list, the NR rule tends to ensure that resources are more fully utilized.

Some general conclusions were reached. First, the author noted that the SA technique produced results superior to CRR, MINSLK, and FCFS. Specific results were affected by interaction with the type of execution rule used. When FR was used, MINSLK and CRR produced results only slightly better than FCFS (with SA much better). Under NR execution rules, MINSLK and CRR produced results much better than FCFS, almost as short as SA. Also, the NR rule produced better project results than FR in all but a few cases. In addition, the author explored several rescheduling frequencies and timing schemes using the SA scheduling approach. The results generally matched the earlier conclusions of Partovi and Burton (1993). Project completion times are helped by rescheduling, with more frequent rescheduling producing more improvement. The FR rule is helped by rescheduling more than NR. One interesting general finding was that highly constrained (in resources and precedence relationships) and loosely constrained projects did not seem to benefit much from rescheduling, while moderately constrained projects benefited greatly.

2.4 Measures of Stability

Scheduling stability (the particular concept of stability being studied here) refers to the ability of the schedule to resist or absorb unplanned variance or events. Stability will represent the degree of deviation from schedule for the resources and activities in the project. A project that is executed very closely to the schedule will be considered to be more sta

schedule

Stab

carefully

available

the projec

undesirab

schedule

unplanned

be put to t

down or lo

brought in

Learning a

resources a

validity, lo

the global

misdirected

(Steele, 19

While

in the litera

performed.

literature; p

Steele (197

more stable. A project that is executed with numerous (and/or large) deviations from the schedule will be considered to have been (relatively) less stable.

Stability is an important issue in scheduling when resources are limited and must be carefully managed. The schedule represents a plan for how to best use the resources available in order to achieve some set of objectives within the constraints imposed upon the project. When the schedule or plan cannot be met, several direct and indirect undesirable consequences may result. First, the desired objectives toward which the schedule is optimized may not be achieved. If the schedule is unable to resist an unplanned variation, or loses validity when a disturbance occurs, the resources may not be put to their best use from that point forward. In addition, when the schedule breaks down or loses validity, resources that must be secured from outside the system may be brought in (and paid for) too early or too late, resulting in idle time and additional costs. Learning and unlearning, as well as other tangible set up costs, may take place when resources are set up and broken down as priorities change. When the schedule loses validity, local decisions (based on the invalid schedule) may no longer integrate well with the global objectives. As the plan breaks down the activities and resources may be misdirected and misused, resulting in both a loss of effectiveness and an increase in costs (Steele, 1975; Mather, 1977; Kropp, Carlson, and Jucker, 1979).

While no direct study of the stability issue for project scheduling has been provided in the literature (a gap the current research hopes to fill), some related work has been performed. The issue of stability has been addressed in the production scheduling literature; particularly with respect to the generation of schedules in MRP systems. Steele (1975) defines "A 'nervous MRP' system is one that generates excessive changes to low-lev

negative

"Nothin

change f

believe."

Math

causes ar

changes i

errors in

sources o

recomme

of the un

However

sensitivity

negative s

for the de

system w

The v

studied in

Udayabha

a non-res

strategy is

priori, e g

low-level requirements when there are no major changes in the master schedule." The negative effects of this instability in the schedule are further described by the author: "Nothing is more disconcerting to the new MRP owner than to have his system priorities change faster than he can respond to them, or worse, to a degree more than he can believe."

Mather (1977) also examined the instability problem in MRP schedules, focusing on causes and outcomes of frequent rescheduling. He identified six causes of rescheduling: changes in lot size, lead time, or safety stock; changes in product design or configuration; errors in records; and unplanned transactions. These are correctly considered to be sources of variability or disruptions unaccounted for by the scheduling logic. His recommendations to address the causes mention variance reduction (attacking the source of the unpredictability) as the best way to reduce the instability of the MRP schedules. However, the majority of his comments focused on dampening mechanisms to reduce the sensitivity of the schedule and make it less responsive to change. This, he noted, has the negative side effect of reducing the effectiveness of the schedule in achieving best results for the desired system outcomes- potentially negating the very reason why the MRP system was installed in the first place!

The variation source reduction approach to reducing MRP nervousness has been studied in detail at the level of addressing specific sources of variation (Sridharan, Berry, Udayabhanu, 1988; Federgruen and Tzur, 1994; Metters, 1993). These studies advocate a non-response strategy to cope with variability and disruption. An example of this strategy is the freezing of input variables to the schedule; refusing to accept changes *a priori*, e.g., not accepting demand inputs within a certain time window. A second example

manager

changes

(without

to preven

As s

effects of

nervousn

number o

and Mille

captures t

Exten

current ef

developed

absolute v

measure a

weighted.

(logistics

In pro

while ma

a stable sc

(1995) ref

stability m

example involves the dampening of changes. By refusing to respond to changes *post hoc*, managers can attempt to limit the damage. For example, if the lead time for an item changes due to a delay in processing, simply accept the delay in that one end item (without examining the affect on other items or rescheduling around that change) in order to prevent the disruption from spreading through rescheduling.

As study progressed on MRP nervousness (schedule instability) and the negative effects of it, more formal definitions and measures were developed. Two measures of nervousness were the number of unplanned orders in the present time period and the number of times the planned orders in the present period were altered (Blackburn, Cropp, and Millen, 1986). The first measure captures the level of disruption, and the second captures the response of the system to these disruptions.

Extending this work, Sridharan et al. noted that those measures only dealt with the current effects of past changes, providing a static snapshot at a single point in time. They developed a measure of nervousness that was based on a weighted moving average of the absolute values of the schedule deviations (Sridharan, Berry, Udayabhanu, 1987). This measure allows the capture of the longitudinal effects of nervousness, appropriately weighted. The concept of instability (nervousness) has been expanded into DRP (logistics) systems as well (Ho, 1992).

In project scheduling, the concept of stability is not as well studied. Willis (1985), while mainly concerned about activity float (critical and non-critical), as an aside defined a stable schedule as one that does not drastically alter activity start and stop times. Pagell (1995) refined the concept of stability to include a more formal definition, proposing a stability metric:

where

Stabi

time devi

shock act

captures t

than 1 inc

total proj

the sprea

value of

than on th

Whil

size" (in a

Pagell me

because i

be undefi

occurring

$$S = \frac{\sum_{i=x}^{n} |OSD_i - ASD_i|}{(n-x) \cdot DL}$$

where n = number of activities in project
x = sequence number of first delayed activity
DL = total project Delay Length
OSD_i = Original Start Date of activity i
ASD_i = Adjusted (actual) Start Date of activity i

Stability (Pagell's formula) calculates the average absolute value of the activity start time deviations for all activities after the first deviation. This average deviation of post-shock activities is then divided by the total project delay length. In this respect, stability captures the "effect size" of the disruptions upon the total project length. A value greater than 1 indicates that the average deviation of all post-shock activities was greater than the total project delay length. This could represent the tapering off of an initial disruption, or the spread of the disruption to non-critical (as opposed to critical) activities. Similarly, a value of less than 1 indicates that the disruption had a greater effect on the total project than on the average post-shock activity.

While the measure is intuitively appealing in that it attempts to capture the "effect size" (in a sense) of disruptions, and generally appealing because it is filling a void, the Pagell measure has some shortcomings. In a practical sense, the measure is problematic because it is unbounded. If a schedule were to execute with no delay, the measure would be undefined (division by zero). Small overall delays, in conjunction with disruptions occurring first toward the end of the project, cause the measure to become large (potent

and ear

differen

The

schedul

metrics

relevanc

2.5 Envi

Seve

problem

upon the

that the r

He prop

various H

characte

has char

Problem

Patt

the heuri

themselv

performa

(indirect

(potentially very large). In addition, the measure does not differentiate between late starts and early starts. Depending upon the circumstances, late or early starts may have very different practical consequences for the project manager.

There is no commonly accepted definition of nor metric for stability in project scheduling. A number of approaches might therefore be considered. Some alternative metrics are presented and discussed in Chapter 3, *Methodology*. The usefulness and relevance of these metrics are explored in this research.

2.5 Environmental Variables

Several characteristics of the problem itself and the environment in which the problem is scheduled and executed have been investigated for their moderating effects upon the performance of the planning and execution methods. Patterson (1976) found that the nature of the problem itself can affect the performance of scheduling heuristics. He proposed that 12 key characteristics of the problem influenced the performance of various heuristics in achieving schedules of shorter duration. This list of problem characteristics that "matter" has been altered by other researchers, and Patterson's own list has changed. The problem characteristics are listed and categorized in Table 2.2, Problem Characteristics, at the end of this section.

Patterson (Patterson et al., 1990) found in a recent study that the performance of both the heuristics and exact approaches can be affected by the characteristics of the problems themselves. His recognition of the influence of problem characteristics upon the performance of the scheduling method indicated the need to identify and control for the (indirect) effects of these variables when studying the (direct) affects of the methods themselves. His more recent list was updated to refine some definitions and included cash flow measures reflecting NPV concerns. Overall size and complexity characteristics include the number of activities, network complexity ratio (ratio of arcs/nodes), and mean number of activity modes (for projects which allow multiple modes for activity duration). Project length characteristics were measured using minimum, mean and maximum activity durations; standard deviation of activity durations, and critical path length (based on deterministic minimum activity durations). Project resource utilization was captured using the average fraction of resources used by activity mode. Finally, cash flow characteristics were represented by mean per-period cash out, number of positive cash payments, and mean magnitude of positive cash payments. His 1990 study noted that the performance of many heuristics and exact approaches alike can be influenced by these problem characteristics.

Russell (1986) sought to identify the individual contributions to performance of eighteen problem characteristics as a subsection of his exploration of the performance of scheduling rules. He characterized the problems in his problem set using Patterson's original (1976) twelve and six additional cash flow measures. Russell formulated the problem using simple linear regression. The dependent variable was calculated as an NPV performance score derived by taking the difference between the best and worst performing heuristics for each problem (the TS-DUAL and MINSLK-LAN procedures, respectively). The independent variables were the respective problem characteristics. Russell was measuring the performance degradation between the two scheduling heuristics as predicted by problem characteristics. Measures of resource constrainedness were found to be particularly powerful, accounting for over 74% of all variation. These measures included the average percent of demand for resources, maximum resource utilization, maximum resource constrainedness, and maximum resource constrainedness over time. Another significant measure was the average utilization factor (R^2 = .75). This is unsurprising, as the average utilization factor is another form of the concept of resource constrainedness. Average resource constrainedness was also found to be a valuable (although less so) resource measure (R^2 =.15). While not an intrinsic project characteristic *per se*, the makespan delay factor was also strongly related to NPV performance (R^2 = .78). The makespan delay factor is calculated as the ratio of the constrained critical path length over the unconstrained critical path length; this represents the growth in project completion time due to the unavailability of resources. The measure therefore reflects both the nature of the problem itself (based on interactions between the technical and resource constraints) and the efficiency of the scheduling method. Because of this, it can be inferred that the makespan delay factor is not particularly useful *a priori* in a practical sense with respect to the selection of a scheduling method. However, once the schedule has been developed, or after alternate schedules have been developed, the makespan delay factor information may be useful in predicting the performance of execution methods or the anticipated performance of the schedule itself. In summary, the key point of Russell is the identification of resource utilization and constrainedness as key factors affecting the NPV performance of scheduling heuristics.

Another comprehensive analysis of the effects of problem characteristics on the performance of scheduling heuristics was performed by Smith-Daniels and Aquilano in 1987 ("Using a Late-Start Resource-Constrained Project Schedule to Improve Project Net

Present

case, t

The fir

constra

and tota

consiste

resource

resource

unconstr

flow mea

difference

coefficien

the fourth

in the act

As ch

contribute

present va

problem co

been contr

utilization,

(over time

version of n

number of a

Present Value"). In addition to regression analyses of characteristics (eighteen in this case), the authors performed a principle components, varimax-rotated factor analysis. The first factor to be strongly related to NPV performance consists of resource constrainedness and utilization measures. Average and maximum resource utilization, and total and average resource obstruction were included in this factor. The second factor consisted of maximum and average resource constrainedness, and average and maximum resource constrainedness over time. Resource constrainedness is represented by the resource loading (requirement) divided by the resource availability over the unconstrained CPM formulation of the problem. Total project duration and three cash flow measures (total cash outflow, present value of cash outflows, and the present value difference between early start and late start schedules) made up the third factor. The coefficient of network complexity and the coefficient of network density stood alone as the fourth and fifth factors. Network complexity was defined as the ratio of arcs to nodes in the activity on arc representation of the problem.

As characteristics of the project, the following five factors have been demonstrated to contribute significantly to the performance of heuristics attempting to maximize net present value: resource utilization, resource constrainedness, cash flow structure, problem complexity, and problem density. Three additional project characteristics have been contributed by Yang (1996). First, Yang uses a modified version of resource utilization, calculating resource availability as the ratio of the total resources required (over time) divided by the total resources available (over time). Yang also includes a version of network density termed order strength. Order strength is calculated as the total number of actual precedence relationships divided by the total number of possible preced

a prob

times th

of these

Category
Size Scop
Length
Constrai
Utilizatio
Cash Flo

Key 1.

precedence relationships, including redundant arcs. Finally, he studies error estimation as a problem characteristic. Error estimation is a measure of the variation in actual activity times from the estimated activity times used for building the schedule. Yang found each of these characteristics to be significantly related to the total duration of the projects.

Table 2. 2: Problem Characteristics

Category	Metric	Duration	NPV
Size/Scope	Number of Activities	3	1
	Network Density Ratio	3	1, 2
	Network Complexity Ratio		2
	Order Strength	4	
	Error Estimation	4	
	Mean Number of Activity Modes	3	1
Length	Minimum Activity Duration	3	1
	Mean Activity Duration	3	1
	Maximum Activity Duration	3	1
	Standard Deviation of Activity Durations	3	1
	Critical Path Length	3	1, 2
Constrainedness	Average Resource Constrainedness		1, 2
	Maximum Resource Constrainedness		1, 2
	Maximum Resource Constrainedness Over Time		1, 2
	Total Resource Obstruction		2
	Average Resource Obstruction		2
	Makespan Delay Factor		1
Utilization	Average Fraction of Resources Used by Activity Mode	3	1
	Average Percent Resource Demand		1
	Average Resource Utilization		2
	Maximum Resource Utilization		1, 2
	Average Utilization Factor	3	1
	Resource Availability	4	
Cash Flows	Mean Per-Period Cash Out		3
	Number of Positive Cash Payments		3
	Mean Magnitude of Positive Cash Payments		3
	Total Cash Outflow		2
	Present Value of Cash Flows		2

Key: 1. Russell, 1986 2. Smith-Daniels & Aquilano, 1987 3. Patterson, 1990 4. Yang, 1996

2.6 Su

Se

have d

used m

Second

variab

the mea

environ

perform

current

Chapter

Two

finding th

known op

performi

LSCR an

a right sh

latest sta

expected

measures.

Two p

release (w

2.6 Summary

Several key areas in the study of project scheduling emerge from the literature which have direct relevance to the current research. First, the nature of the planning approaches used must be considered carefully, as the performance of the different methods can vary. Second, the execution approaches must also be considered. Under the conditions of variability, with resource disruptions, it may not be possible to follow the schedule and the means of execution begins to influence performance outcomes. Finally, several environmental variables must be considered as possible moderating influences upon performance. These considerations will each be discussed in turn as they relate to the current research. They are mentioned briefly here and described in greater detail in Chapter 3, *Methodology*.

Two planning heuristics have been used to represent methods that perform well in finding the shortest project duration: MINSLK and LFT. These are compared to the known optimal (shortest time) solution referred to as OPT. Also, two of the better performing NPV maximizing methods were used to construct schedules. These are the LSCR and ΣDCFLF heuristics. The NPV performance of these methods are compared to a right shifted version of the optimum (RSOPT) solution. The RSOPT schedule uses the latest start times from the known optimal shortest duration schedule. While it was expected that the solution methods would perform well on their target performance measures, their performance with respect to the stability measures was unknown.

Two primary execution methods were tested: the reservation (full and no) and the release (waiting and no waiting) types. This resulted in four combinations: full reserv

reserv

(1996

activit

feasible

consider

proced

Sev

constrai

measure

Problem

complexi

resource

experime

character

reservation, waiting; full reservation, no waiting; no reservation, waiting; and no reservation, no waiting. The full and no reservation rules were as described by Yang (1996). The waiting and no waiting rules refer to the release of technically eligible activities with respect to their scheduled start times. The activities, while technically feasible, were either forced to wait until their scheduled start times before being considered eligible, or released immediately upon becoming technically feasible. These procedures are discussed in greater detail in Chapter 3, *Methodology*.

Several problem characteristics related to problem size, duration, complexity, constrainedness, and utilization were tracked. The number of activities was used to measure problem size, and the minimum-duration critical path length measured duration. Problem complexity was represented by the network density ratio and network complexity ratio. The level of constrainedness was represented by average and maximum resource constrainedness, as well as the overall makespan delay factor. Problems for the experiment were selected to represent a broad and balanced spectrum of these characteristics.

Chapter 3

METHODOLOGY

3.1 Introduction

As previously mentioned (refer to section 1.2, *Research Problem and Questions*,) the purpose of this research was to investigate the performance of both planning and execution techniques in the single project, constrained resource environment, under conditions of uncertainty, when subject to disruptions.

3.1.1 Theoretical Model

The theoretical model proposes that the choice of both a planning and execution method has an effect upon the performance of the project. Further, the model posits that the effects of the planning and execution methods on performance are moderated by the characteristics of the project and environment in which the project is performed (see Figure 3.1, Theoretical Model). The selection of a planning and execution method represent policy decisions that would be actively taken by the manager of a project. These choices would be made against the backdrop of the situation; the characteristics of both the project and the environment in which the project exists. Decisions taken by managers under these conditions would benefit from an understanding of how these factors interact.

The planning and execution methods represent the two primary constructs of interest in this study. Previous research has already established that the planning method can play a role in determining project outcomes. The influence of the execution method, while not

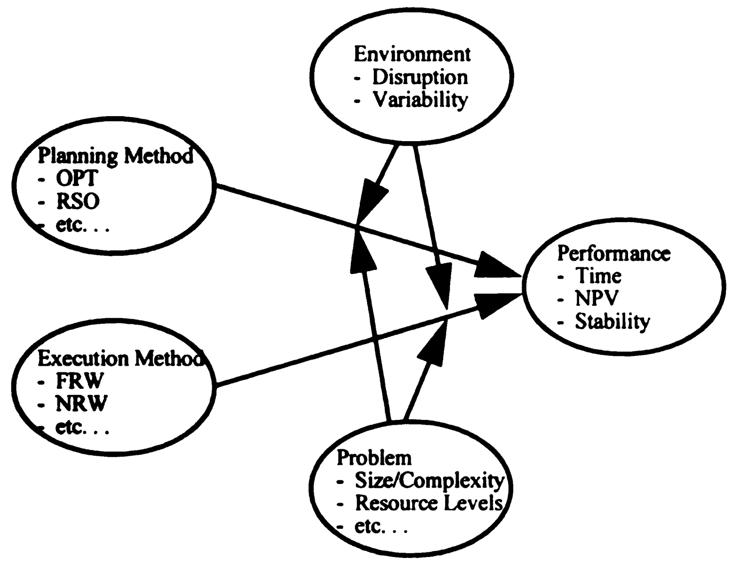


Figure 3. 1: Theoretical Model

studied as extensively, has also been established. The relationships between these constructs and the project performance construct has a solid theoretical basis in the literature (as described in Chapter 2, *Significant Prior Research*, sections 2.2 and 2.3). The current research seeks to extend these relationships to include stability as a new class of performance measure affected by planning and execution method.

Two moderating constructs were included in this study. The environmental moderator construct includes the factors of task duration variability and resource disruption. This construct was manipulated as part of the experiment. The problem moderator construct includes factors that are characteristics of the problem itself. While not manipulated explicitly during the experiment, an appropriate range of values were employed through the selection of representative problems. Characteristics selected for inclusion in this study were those which either have already demonstrated or are suspected to demonstrate significant effects on the performance of the planning and execution methods. The moderating effects of the problem characteristics are also well-grounded in the literature (Chapter 2, *Significant Prior Research*, section 2.5).

3.1.2

In

choice

determ

are mo

environ

NPV, a

include

H1: Sta
me

H2: Pr

H3: Pro

H4: Rel
env

H4a

H4b

H4c

H4d

The r

hypothese

through 3.

3.1.2 Hypotheses

In the theoretical model (see Figure 3.1: Theoretical Model), it is proposed that the choices of which planning and execution methods are used to manage the project will determine, to a large degree, the overall performance of the project. These relationships are moderated by several key characteristics of both the project problem itself and the environment in which the project is managed. Project performance includes the duration, NPV, and stability of the projects measured upon completion. Specific hypotheses include:

H1: Stability measures are positively correlated with traditional project performance measures.

H2: Project performance is significantly affected by the planning method used.

H3: Project performance is significantly affected by the execution method used.

H4: Relative planning & execution method performance is significantly affected by environmental characteristics.

- **H4a:** Relative planning performance is significantly affected by the presence of activity duration variability.
- **H4b:** Relative planning performance is significantly affected by the nature of the resource disruptions (longer, less frequent vs. shorter, more frequent disruptions).
- **H4c:** Relative execution performance is significantly affected by the presence of activity duration variability.
- **H4d:** Relative execution performance is significantly affected by the nature of the resource disruptions (longer, less frequent vs. shorter, more frequent disruptions).

The remainder of this chapter describes the methodology used to test these hypotheses. The discussion includes descriptions of the variables used (sections 3.2 through 3.4), the experimental design (section 3.5), how the data analysis was performed (section 3.6), and finally a discussion of the limitations and key assumptions inherent in the research.

3.2 Dependent Variables

Three main performance variables of interest were investigated in this study: project length, project NPV, and stability. Project length is quite simply measured as the total duration of the project, from the start of the first activity to the completion of the last activity. This has traditionally been considered the most important overall measure of performance. In project scheduling, financial aspects of project performance are also considered (especially by practitioners) to be important. Primary among these is project Net Present Value (NPV).

3.2.1 Net Present Value

The NPV was calculated for each project at the termination of the simulation as the sum of all cash flows, discounted for when they were realized following the definition (Russell, 1970):

$$NPV = \sum_{i=1}^{n} CF_i \cdot e^{-\alpha T_i}$$

where CF_i = Cash Flow realized as a result of completing activity i
α = Discount Rate
T_i = Time at which activity i is complete
n = Number of activities

Each activity in the project, from the initial ($i = 1$) to the terminal ($i = n$), has a cash outflow ($CF_i < 0$), cash inflow ($CF_i > 0$), or cash neutral ($CF_i = 0$) event associated with it and a specific time T_i at which it is realized. The sum of all negative and positive cash flows for each activity, discounted for when they occurred, represents the value of the project as a whole.

The projects in this study were modeled as being composed entirely of negative cash flow events for each activity, with a single large positive cash flow upon completion. The specific negative flow (cost) for each activity was calculated as the total resource time used by the activity times an arbitrary cost constant (in this case, \$25). The T_i realization time of the cost was established as the completion time of the activity. All times are incremented in units of days. The discount rate α (internal rate of return; hurdle rate) was selected to be .15, corresponding to a typical investment rate of return expected from a Standard & Poors 500 corporation (Laderman, 1996).

The terminal positive cash flow was calculated to be representative of a completion payment as formulated by a firm bidding for the project as a contract. This value includes all costs and a profit. The payment was based on anticipated costs and timing as projected by the schedule. First, the present value of all costs (scheduled) was calculated. This was multiplied by the arbitrary factor of 1.5 to allow for profit and cost overruns. The cost plus profit value was then time adjusted using the NPV formula. The calculated payment would therefore cover all costs and result in a positive total NPV for the project as long as the project was completed according to schedule.

The project duration and NPV were calculated as an actual value, expected value, and an actual/expected ratio. The actual value calculations were based upon the activity start and stop times as simulated during the experiment. The expected value calculations were based upon the activity start and stop times as programmed by the scheduling method used.

3.2.2 Stability

The final dependent variable, stability, was measured in several different ways. Some basic precepts were followed when designing and selecting the stability measures used. One precept was that the measures should capture some level of deviation from the schedule. This can represent a deviation in activity timing (start and stop times) or a deviation in resource use, or a combination of the two. Each of the following measures was designed to capture activity deviation, resource deviation, or a combination of the two.

3.2.2.1 Weighted Activity Deviation

$$WADE = \frac{w_E \cdot \sum_{i=1}^{n} \max\begin{bmatrix} SS_i - AS_i \\ 0 \end{bmatrix}}{n \cdot ASAD} \qquad WADL = \frac{w_L \cdot \sum_{i=1}^{n} \max\begin{bmatrix} AS_i - SS_i \\ 0 \end{bmatrix}}{n \cdot ASAD}$$

where i = index number of activity
n = index number of last activity
AS_i = Actual Start time of activity i
SS_i = Scheduled Start time of activity i
w_L = weight for late activities
w_E = weight for early activities
ASAD = Average Scheduled Activity Duration

W

from

and s

(WA

sched

latene

weigh

vs. lat

the siz

sched

Fo

A comp

as the s

the indi

stability

3.2.2.2

POIR

where

Weighted Activity Deviation (WAD) calculates the mean magnitude of deviation from scheduled start time for all activities, weighted according to earliness or lateness, and scaled for scheduled project size. In Weighted Activity Deviation, Earliness (WADE) the numerator captures the total earliness of all activities that started before their scheduled times. Weighted Activity Deviation, Lateness (WADL) captures the total lateness of all activities that started after their scheduled times. The distribution of weight between w_L and w_E assigns a penalty based on the relative importance of earliness vs. lateness for the management of the project. The denominator scales the deviations by the size of the project as represented by the number of activities times the average scheduled activity deviation. This is equivalent to the total scheduled activity time.

For this initial study, the earliness and lateness penalties were set equal $w_L = w_E = 1$. A composite measure WADC (Weighted Activity Deviation, Composite) was calculated as the sum of the earliness and lateness numerators divided by the denominator used for the individual measures. In each of the three measures, a larger value represents less stability.

3.2.2.2 Resource Profile Offset

$$POIR = \frac{\sum_{t=0}^{t_n} (t_i - t_{i-1}) \cdot \max\begin{bmatrix} SR_t - AR_t \\ 0 \end{bmatrix}}{\sum_{t=0}^{t_n} (t_i - t_{i-1}) \cdot SR_t} \qquad POOR = \frac{\sum_{t=0}^{t_n} (t_i - t_{i-1}) \cdot \max\begin{bmatrix} AR_t - SR_t \\ 0 \end{bmatrix}}{\sum_{t=0}^{t_n} (t_i - t_{i-1}) \cdot SR_t}$$

where t_i = time at which a level of resource use changes; scheduled or actual
t_n = time at which terminal activity ends
SR_t = scheduled resource use over the interval $[t_{i-1}, t_i)$
AR_t = actual resource use over the interval $[t_{i-1}, t_i)$

T

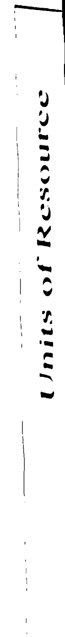
actua

regar

with

'wron

Th



Figur

actua

The f

funct

by th

graph

the pr

These two measures compare the profile of scheduled resource use to the profile of actual resource use over time. These measures capture resource use deviations without regard for activities. In other words, these variables measure resource use deviations without considering whether the resources are being used for the "right" (scheduled) or "wrong" activities.

The POIR (Profile Offset, Idleness Ratio) measure sums the amount of resource use over time when the actual resource use is less than the scheduled resource use. This is unscheduled idleness. The POOR (Profile Offset, Overuse Ratio) measure captures the amount of resource use over time when the actual resource use is greater than scheduled resource use. This is unscheduled overuse.

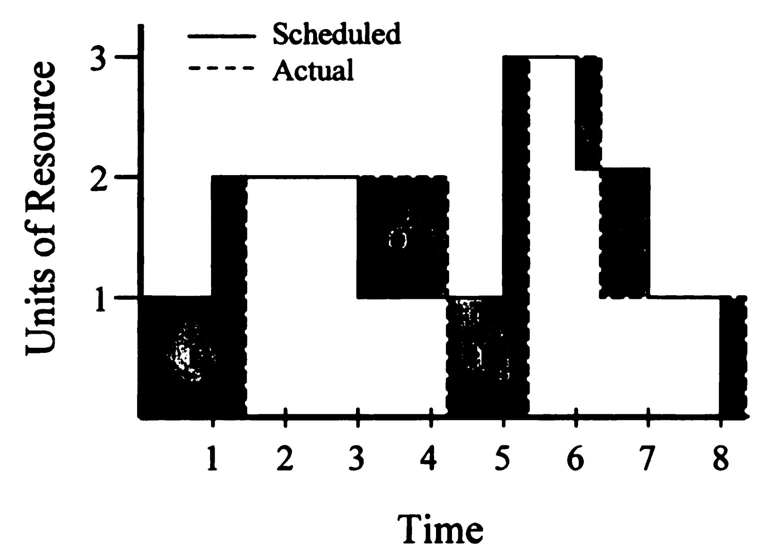


Figure 3. 2: Resource Profile Offset

The formula represents the discrete integral (since the resource profile functions are step functions) of the area between the two profiles with respect to time. This is then divided by the total area under the scheduled resource profile (these relationships are depicted graphically in Figure 3.2: Resource Profile Offset). Note that each resource type used by the project will have its own profile. The measure in use for this research will sum the areas across the resources equally. Weighted formulations could be constructed, assigning different weighting "penalties" to various resource types.

A composite measure was not constructed. In each of the two measures, a larger value represents less stability. POIR is bounded by [0, 1]. A value of 0 implies no unplanned idleness. A value of 1 implies that all resources were idle during the scheduled length of the project. POOR is bounded by $[0, \infty)$. A value of 0 implies that no resource was used outside of the scheduled usage profile. Larger values imply that unscheduled resource usage occurred. As a practical matter, it is anticipated that values would not greatly exceed 1.0 (virtually all resource usage is over use and project duration not much greater than twice scheduled). "Raw" measures were calculated by assigning variables POIC and POOC to the values of the numerators.

3.3 Independent Variables: Treatments

Two main treatments, the methods for planning and execution, were applied in the study. The planning method generated the project schedule. The execution method was the set of rules used to assign resources to activities as the project was simulated. Most of the planning and execution methods have been discussed in detail in Chapter 2, ***Significant Prior Research***. Exceptions are discussed in detail as required.

3.3.1 Planning Methods

Planning methods were used to construct the original schedule for each project. First, two benchmark planning methods were chosen to provide a basis for comparing the performance of the remaining methods. The OPT method generates the known optimal (time) solution for the deterministic case. The "right-shifted" version of the OPT (the RSO) was used as a benchmark approach oriented toward improved NPV. RSO constructs a schedule by right-shifting all activities in the OPT schedule to zero slack. Other planning heuristics used were Minimum Slack (SLK), Late Finish Time (LFT), Late-Start Constrained Resource (LSC), and the Sum of Discounted Cash Flow of Future Activities at Late-Finish Times (DCF) (previously discussed in Chapter 2). The SLK and LFT methods are representative of good time-minimizing procedures, and the LSC and DCF methods represent good NPV-maximizing methods.

Finally, an experimental method (a new heuristic) was used. This heuristic was based on a combination of Greatest Resource Demand and Bowers' resource-constrained MINSLK (Bowers, 1995). It schedules first the activity which has the least slack along a resource-constrained critical path, with virtual ties being settled by assigning priority to the activity that uses the most heavily tasked resource.

Stage 1 of the algorithm uses the Bowers definition of criticality (Bowers, 1995) to establish the initial MINSLK priority. The problem starts with a typical unconstrained CPM formulation, then considers resource constraints on a second set of passes as follows:

Step 1: Forward pass, yielding earliest start and finish times (technical precedence).

Step 2: Backward pass, yielding latest start and finish times (technical precedence).

Step 3: Forward pass, resolving resource contention by assigning resources to CPM priority activities (minimum CPM slack), yielding earliest start and finish times (technical and resource precedence).

Step 4: Backward pass, applying resource precedence links from previous step to update the latest start and finish times (technical and resource precedence).

Step 5: Calculate Resource Critical float (slack) as the difference between earliest and latest start times for each activity.

Slack (latest start - earliest start) is now based on the contention-free start and finish times. The critical path (zero slack path) flows along both technical and resource dependency arcs. These slacks are used in the classical MINSLK method in order to construct the schedule. The second stage of the algorithm adjusts this schedule by considering the resource loading in the project. "Virtual Ties" are determined and solved in the following manner:

Step 1: Establish the sensitivity constant, δ (arbitrarily use $\delta = 1.0$ times average activity duration).

Step 2: Identify the currently unscheduled activities with the highest priority (based on Bowers-MINSLK resource critical float value above) and determine virtual ties: a virtual tie is defined as a situation where two activities have amounts of resource critical float that are within δ of each other.

Step 3: Assign priority (break the virtual tie) by scheduling first the activity that uses more of the most heavily utilized resource (over the remainder of the project); if each activity uses the same amount, break tie using the next-most heavily utilized resource until the tie is broken. If the tie can't be broken on the basis of resource utilization, break the tie using the original resource-critical float priority.

Step 4: If, in the previous steps, the schedule has changed, reschedule the remaining activities using the Bowers-MINSLK method.

Step 5: Continue to loop through Steps 2-5 of this stage until the terminal activity has been scheduled.

It was anticipated that this heuristic would develop schedules that while not necessarily "optimal" in a deterministic sense will nevertheless be robust to disruption and stable during the simulation. This heuristic is designed to trade project duration and

NPV away for an increase in stability. The sensitivity constant δ has been set to an arbitrary value (equal to the average activity duration). This constant represents the degree of "separation" between slack values that will be allowed before rescheduling based on resource utilization is forced. Higher values of δ will result in more frequent virtual tie conditions; and smaller values of δ will result in less frequent virtual tie conditions. Obviously, any future research considering the use of this new heuristic must consider alternative rationales for the assignment of values for δ. This heuristic will be referred to as the Bowers-Critical Path method (B-CPM).

3.3.2 Execution Methods

The execution methods are the decision rules used to assign resources to activities as the simulation progresses. Two primary dimensions of execution method were tested: the Reservation (Full and No) and the Release (Waiting and No Waiting) types. This resulted in four combinations: Full Reservation, Waiting (FR-W); Full Reservation, No Waiting (FR-N); No Reservation, Waiting (NR-W); and No Reservation, No Waiting (NR-N).

The Full and No Reservation rules were as described by Yang (1996). Under Full Reservation, an activity reserves the resources it needs as soon as the activity is technically feasible. Reserved resources can not be used by any other activity. Resources are reserved on a FCFS basis in order of priority each time a completing activity releases the resources it was using. This execution method sacrifices resource utilization in order to achieve stricter activity completion by priority order. The No Reservation rule does not allow activities to tie up any resources until all resources needed are available and the acti

techr

whic

lowe

I

activ

feasi

fully

vying

3.4 In

Tw

Charac

charact

While

problem

characte

3.4.1 C

The

each pro

(see Tab

activity begins. Under No Reservation, a lower priority activity (which is otherwise technically feasible) that uses fewer resources can start before a higher priority activity which uses more resources. The higher priority activity may now have to wait until the lower priority activity is complete.

The Waiting and No Waiting rules refer to the release of technically eligible activities with respect to their scheduled start times. Under Waiting, a technically feasible activity is forced to wait until its scheduled start time before being considered fully eligible (to seize resources). Under No Waiting conditions, an activity may begin vying for resources immediately upon becoming technically feasible.

3.4 Independent Variables: Moderating

Two main classes or types of moderating variables were investigated: the Characteristics of the Problem and the Characteristics of the Environment. Most of these characteristics have been previously discussed in Chapter 2, *Significant Prior Research.* While these characteristics were not explicitly manipulated in the experiment, a set of problems was used which represent an appropriate range of values for these characteristics.

3.4.1 Characteristics of the Problem

The characteristics of the problem are those relevant descriptive aspects unique to each problem in the problem set. Several specific problem characteristics were tracked (see Table 3.1: Problem Characteristics).

Table 3. 1: Problem Characteristics Studied

Problem Characteristic	Measure
Size	Number of Activities
	Critical Path Length (scheduled)
Complexity	Network Complexity Ratio
	Network Density Ratio
Constrainedness	Makespan Delay Factor
	Average Resource Constrainedness
	Maximum Resource Constrainedness
Utilization	Average Resource Utilization (scheduled)
	Maximum Resource Utilization (scheduled)
	Average Resource Utilization (actual)
	Maximum Resource Utilization (actual)

First, problem size was measured using the Number of Activities and the Critical Path Length (duration of critical path). The complexity of the problem was assessed using two separate measures: the Network Complexity and Density Ratios. The Network Complexity Ratio is the ratio of arcs (dependencies) over the nodes (activities). The Network Density Ratio is defined here as the ratio of actual precedence arcs over the total possible arcs. The measure used here includes redundant arcs. The number of total possible arcs is determined by finding the sum of the series 1 + 2 + 3 + . . . + (n-1) where n is the total number of activities (or by using the formula [n(n-1)]/2 which is equivalent). This definition is consistent with the "Order Strength" measure of Yang (Yang, 1996) and differs from the classical definition of density used in network analysis which does not count the redundant or duplicate arcs.

The degree to which the project is "resource constrained" was tracked using three separate numbers. First, constrainedness was measured fairly directly by the Average and Maximum Resource Constrainedness, based on the simultaneous or overlapping demand for a resource by project activities. Constrainedness was calculated as the ratio of total planned resource requirements (number and duration for all activities) divided by the resource availability over the unconstrained CPM critical path length (unconstrained duration). The Makespan Delay Factor is a similar measure of constrainedness. It reflects the growth in project schedule length to account for resource dependencies. The Makespan Delay Factor was calculated as the ratio between the constrained duration (provided by the specific scheduling technique) to the unconstrained CPM duration.

The final group of problem characteristics measured were those relating to the utilization of the resources. The Average Resource Utilization and Maximum Resource Utilization were measured for the problem; for both scheduled and actual use. These measures were calculated as the requirement for or use of the resources (load) over the availability (capacity) of the resources over the duration of the project. Utilization was calculated for both planned and actual project execution. The utilization measures should, of course, show a close and direct relationship to the constrainedness measures (higher constrainedness should generally result in higher utilization).

3.4.2 Characteristics of the Environment

Key characteristics of the project execution environment were also accounted for. Two of these were explicit to the design of the experiment. First, the variability (uncertainty in duration of activity/task times) was set at two levels: None (deterministic activity times), and Some (distribution range 30% of activity time). The "actual" activity durations were selected randomly from a Beta(1.5, 3) distribution with a mean equal to the "planned" duration and a spread as described above. The distribution was thus offset such that the endpoints reside approximately 1/3 of the spread below and 2/3 of the spread above the mean.

The second environmental characteristic was the Disruption Level (disruptions in resource availability). Each project has between 1 and 3 total types of resources used, and each resource type has between 1 and 15 units available. The types and numbers of resources required are a fixed part of the problem. A disruption will be modeled as the unplanned shutdown or loss of availability of a resource during idle time. While shut down, the resource is unavailable for use by any project activity. The frequency and duration of the disruptions were established at reasonable (but arbitrary) levels. Disruptions were set at three levels: None (no interruptions in resource availability), Frequent-Short (F-S), and Infrequent-Long (I-L). The F-S and I-L disruptions occurred randomly, according to sampling from an exponential distribution. Disruptions to each resource occur independently. The length of the shutdown was also sampled from an exponential distribution. The parameters for the distributions were selected to result in approximately the same total amount of disruption over the same length of time. F-S generated shutdowns of each resource expected once every 5 days, expected to last 1 day. The I-L schedule generated exponential shutdowns expected every 15 days, each expected to last 3 days. Over the same length of simulated time, the total disrupted time wou

duri

3.5 I

I

resea

hypot

analy

descri

proble

3.5.1

T

(4 leve

includ

proble

"natura

Fi

variabl

experin

problen

depend

would be about the same for each resource type. This expectation was investigated during the pilot runs of the model and was found to be reasonable.

3.5 Experimental Design

The experimental design used in this research was selected in order to address the research questions (section 1.2, *Research Problem and Questions*) by testing the hypotheses (section 3.1, *Introduction and Hypotheses*) using data provided through an analysis of the behavior of the variables just described. The remainder of this section will describe the research design by presenting the theoretical model, experimental factors, problem set, and generation of the data.

3.5.1 Experimental Factors

The main experimental factors are the methods of planning (7 levels) and execution (4 levels). In addition, there are the moderating factors related to the environment. These include the variability (2 levels) and disruption (3 levels). The characteristics of the problem (11 variables plus the problem name as a categorical variable) are experienced as "naturally occurring" over the 18 problems in the benchmark set.

Figure 3.3: Experimental Design, shows a simplified diagram of the treatment variables and the environmental moderators. Each cell of the diagram represents an experimental combination of the variables. Each of the 18 problems in the reduced problem set were simulated for multiple replications in each cell. Output values of the dependent variables were recorded along with the values of all dependent variables.

Moderating Environment

Fig

prob

(of t

prod

Stab

3.5.2

sche

repre

on th

of 11

detern

differ

proble

to 18

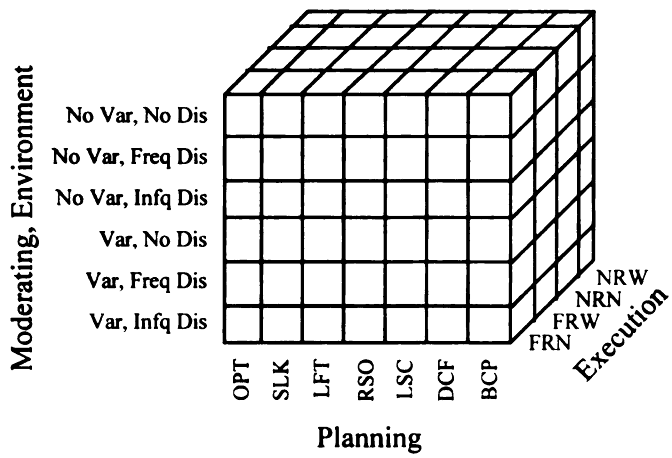


Figure 3. 3: Experimental Design

There are, then, 168 combinations of factors (7x4x2x3) that will establish the cells in the full-factorial design of the experiment. Each of these 168 combinations were simulated for each of the 18 problems in the set, yielding a total of 3,240 experiments conducted. Each experiment (of the 168 combinations of the 18 problems) was conducted multiple times in order to produce estimates of the 11 outcome variables (two Duration, two NPV, and the seven Stability variables).

3.5.2 Problem Set

A subset of problems from a known, benchmark set of resource constrained project scheduling problems (the "Patterson Set") were used. This subset has been selected to represent a broad spectrum of problem types to provide an appropriate level of variation on the problem characteristics identified. The Patterson Set is an accepted benchmark set of 110 basic project scheduling problems for which optimal solutions (in the deterministic case) have already been derived. This set of 110 problems includes three different levels of resource constrainedness (comprising 330 total problems), and problems of various sizes (7 to 51 activities), complexity, resource type, and duration (6 to 189 time units duration).

ther
ben
real
prev
work
beha
was
will

T
Table
comp
the re
unlik
the na
probl
up in
Projec
sched
proble
cases.

Generalizability of the benchmark set comes from the variation of the problems themselves. Over time, problems with unique characteristics have been added to this benchmark set in order to provide a wide range of variation in problem types. In a very real sense, this approach increases the validity of the research in terms of comparability to previous theoretical work, but makes the results un-generalizable to any specific real-world, practical project scheduling environment. For this exploratory study into the behaviors of projects with respect to stability, this loss of specificity in external validity was considered to be appropriate. It is anticipated that more practical, follow-on research will increase the extensibility of any general concepts or theories developed here.

The characteristics of the reduced problem set is compared to the full Patterson set in Table 3.2, Problem Set Characteristics. The first grouping of characteristics to be compared relates to problem size. Along the characteristic Number of Activities (NAct), the reduced set differs from the full set by not including the smallest problems. It seemed unlikely that problems with fewer than 22 activities would offer any useful insights into the nature of stability. Many of the statistical differences between the full and reduced problem sets are a result of this decision to not include the smaller problems. This shows up in the characteristic Critical Path Length (CPL), which refers to the duration of the project as scheduled. The full set CPL is based on the optimum (minimum duration) schedules as provided in the Patterson set of problems. The exclusion of the smaller problems from the reduced set has resulted in a loss of the shorter duration (smaller CPL) cases.

The next grouping of characteristics to be compared relate to problem complexity. Along the characteristics Network Complexity Ratio (NCR) and Network Density Ratio (NDR), the reduced set offers acceptable comparability. Most of the statistics are either identical or similar. The notable exception is the difference in range (at the high end) for NDR. The reduced set does not offer the same level of density as the full set, with a reduction of about 30%. While the impact of this loss in range is unclear, it is considered to be acceptable for the purposes of this study.

The next set of characteristics to be discussed are those related to constrainedness. The characteristics Makespan Delay Factor (MDF), Average Resource Constrainedness (ARC), and Maximum Resource Constrainedness (MRC) all seem to be comparable between the full and reduced problem sets. The ranges are all either identical or very close. The means and medians do not show any disparate central tendencies.

The final grouping of characteristics describe the utilization of the problems. Both Average Resource Utilization (ARU) and Maximum Resource Utilization (MRU) show a slightly restricted range at both the high and low ends in the reduced set. The means and medians are comparable. It was decided that in an overall sense, the reduced set of 18 problems could be considered to be a fairly representative sample of the full set of 330 problems as compiled by Patterson. The restriction in range as a result of the exclusion of very small problems was not considered to be troublesome for the purposes of this study. The restriction in range along the utilization and density characteristics was considered small enough to be acceptable.

Table 3. 2: Problem Set Characteristics

Full	**NAct**	**CPL**	**MDF**	**NCR**	**NDR**	**ARC**	**MRC**	**ARU**	**MRU**
Low	7	6	1.00	1.09	0.05	0.40	0.42	0.38	0.39
Mean	26	59	1.99	1.55	0.14	1.43	1.54	0.70	0.77
SD	9	32	0.66	0.31	0.06	0.54	0.56	0.08	0.09
Median	25	60	2.13	1.52	0.12	1.49	1.64	0.70	0.76
High	51	189	3.77	3.09	0.39	2.75	2.85	0.96	1.00
Reduced									
Low	22	20	1.00	1.09	0.05	0.44	0.44	0.43	0.43
Mean	36	75	1.87	1.69	0.11	1.28	1.39	0.67	0.72
SD	12	44	0.77	0.53	0.07	0.63	0.67	0.09	0.11
Median	35	67	1.92	1.57	0.10	1.25	1.30	0.67	0.73
High	51	189	3.85	3.09	0.29	2.75	2.85	0.84	0.90

3.5.3 Data Generation

Dynamic, discrete-event system simulation was used to generate the data for the experiment in order to address the research questions. The experiment was conducted as a full-factorial simulation of project scheduling and execution over the appropriate levels of experimentally manipulated variables and the "naturally occurring" variation in the problems themselves. Each run of the simulation model represented an independent, terminating execution of the planned schedule with "actual" events (task variability and disruptions) occurring randomly. Four versions of the model were used, each representing the individual execution methods required by the experimental design. The schedule generated by the planning method was read into the model during model initialization.

env
par
the
per
wit
diff
writ
com
cons
and

routin
platfo
intere
enviro

P
model
conduc
individ
problem
selected

Through the management of simulation parameters, a range of values for key environmental characteristics (levels of variability and disruption) was provided. Each parameter requiring random sampling used an independent random number stream, and the random number streams were synchronized between the four model versions. The performance of each combination of planning and execution technique was measured with respect to time, NPV, and stability under a range of variability and disruption for the different types of projects as described under the experimental design. Programs were written and run under the GPSS/H modeling language on a variety of IBM-PC compatible desktop computers using the 386 and 486 chipsets. The simulation output consisted of matrices of the start and stop times ("actual") for all activities in the project, and a listing of the values of all experimental parameters used in the simulation.

The simulation output matrices were converted into lines of data using conversion routines written in Turbo Pascal 6.0 and executed on the same 386 and 486 desktop platforms. The conversion routines calculated and tabulated the primary statistics of interest for the study, including all independent and dependent variables as well as the environmental and problem characteristics referenced in the experimental design.

Pilot runs of the models and conversion routines were conducted for the purposes of model validation and run size estimation. Debugging and *prima facie* validation was conducted with small runs (n=5) for each cell of the experimental design and each individual problem (scheduling method x execution method x variability x disruption x problem). Based on a cursory examination of the initial data, sequential sampling was selected as the simulation management procedure. Successive batches of runs were con

size

wer

was

T

suffic

duratio

be sep

Disn-p

Precisi

of the e

conducted and analyzed until the desired level of precision was achieved. The initial run size was selected to be n=40 per cell. Parameter estimates and their confidence intervals were then analyzed for sufficiency of n (see Table 3.3, Pilot Run Data). This analysis was performed on the parameter Duration.

Table 3. 3: Pilot Run Data

Factor	Level	Mean	CI (99%)	SD	N
SKED	lft	118.8596	3.73	178.1763	17280
	rso	119.7431	3.81	181.6762	17280
	opt	119.8072	3.81	181.6928	17280
	slk	121.4167	3.78	180.3401	17280
	bcp	124.8155	4.10	195.7626	17280
	dcf	129.2070	4.09	195.1381	17280
	lsc	129.2070	4.09	195.1381	17280
EXEC	frn	76.4474	0.69	43.5456	30240
	frw	79.0979	0.71	44.6163	30240
	nrw	164.4700	3.81	240.3958	30240
	nrn	173.1596	4.19	264.4338	30240
DIS	none	76.7464	0.60	43.7062	40320
	long-infreq	113.0239	1.60	116.4872	40320
	short-freq	180.1109	3.97	289.7730	40320
SPD	none	122.9814	2.10	187.6725	60480
	beta	123.6061	2.09	186.3968	60480

The confidence interval half widths indicate that overall, the initial run size should be sufficient to provide discriminating precision between the dependent variables. For the durations, the data indicate that means within the factor Scheduling method (SKED) can be separated into groups. Means within the factors Execution method (EXEC) and Disruption level (DIS) can be separated. It appears as though there was inadequate precision to separate means within the factor Variability (SPD). Based on an examination of the existing sample size and estimates of standard deviation (N and SD), it would seem that the sample size would have to become very large- to the point of impracticality- before any differences could be established with confidence.

3.6 Data Analysis Issues

The methods used to analyze the data were appropriate for the experimental design and selected in order to address the research issues, problem, questions, and hypotheses. As a designed, full factorial experiment, the selection of Analysis of Variance (ANOVA) as a primary analytical technique was indicated. However, nonparametric comparison techniques were also used where warranted. These will be discussed as needed in Chapter 4, *Results and Analysis*. The ANOVA and other subsequent statistical tests were conducted using SPSS 8.0 for Windows running on IBM-PC compatible desktop computers employing Pentium II type chipsets.

3.7 Limitations and Key Assumptions

Several limitations were imposed upon the scope and nature of this research effort. The primary limitations included: single projects, single mode resource use, no preemption of activities, and small (51 activities or less) projects. Due to the exploratory nature of this investigation into the unexplored topical area of project schedule stability, a subset of well understood examples from a benchmark problem set and a restricted number of behaviors was studied.

While there is a great deal of interest and research into the scheduling of multiple projects simultaneously, many new concepts have been tested in the single project environment first. The reasons for this are several; primarily, when multiple RCPSP projects are studied simultaneously, the subtle or secondary behaviors of the planning methods may become "lost" in the complexity of the problem. Interactions between "problem characteristics" and "execution methods," for example, may be overwhelmed by delays induced into smaller projects by the presence of the larger problems in the same scheduling mix. In order to avoid this potential source of behavior masking, this research effort considered only single, independent projects for the time being. It is anticipated that the more interesting findings of this study will be extended into the multiple-project case in the future.

Second, while "multi-mode resource use" cases are of some interest (due to higher fidelity to certain real world situations), only single mode behaviors will be studied here. The assumption underlying the use of the single mode is that each activity requires a fixed number and type of resources for its completion, and that the completion generally takes a certain amount of time. This characterization has been used more often in the literature than the multi-mode scenario. The Patterson Set is formulated following this assumption. Currently, for the purposes of comparing the results of this study to other studies and aligning the assumptions with the benchmark set of problems, only the single mode operationalization will be used. Once more, it is anticipated that future extensions of this work will include the study of multi-mode behaviors.

While it may be noted that the preemption of activities and the accrual of "set-up costs" are *prima facie* of great interest in any study formulated around the issues of variability, disruption, and stability, preemption will not be studied here. This is also planned for inclusion into future research. The additional complexity of including various preemption rules and set-up cost structures into the experimental design (above and beyond the more basic variables and levels currently proposed) is deemed beyond the scope of this initial study on the current items of interest.

Fourth, only relatively "small" projects (as contained in the benchmark set of problems) will be studied. It is important for an initial study of this type to be able to perform some reasonable comparisons to known phenomena that have been previously studied. This can be achieved in two ways: first, by using any standards or benchmarks that have been used before (like the problem set itself); and second, by manipulating the relevant variables in similar ways and at similar levels. The use of small problems also allows us to use known, optimal solutions (for the deterministic case, minimizing duration). The known, optimal solutions provide a "best case" schedule to compare the performance of the other heuristics.

Chapter 4

RESULTS AND ANALYSIS

4.1 Introduction

This chapter presents the results of statistical tests and analysis of the data created by the procedures outlined in Chapter 3, *Methodology*. This presentation is performed in five sections.

First, the schedules created by the different scheduling methods are compared. The next three sections compare the performance of the schedules when executed under the simulated environmental conditions. The first of these presents exploratory analyses of the key variables. The second presents analyses of covariation. The final section of the three compares treatment means.

The fifth section of this chapter draws inferences from the statistical results with respect to the hypotheses and theoretical model under study. The chapter closes with a brief summary of the data analyses.

4.2 Planning Method Performance under Deterministic Assumptions

This section compares the schedules created prior to simulation. Each of the 7 scheduling methods was applied to each of the 18 problems in the problem set. "Scheduled Duration" and "Scheduled NPV" performance measures were then calculated for each schedule. These measures were calculated assuming no schedule variation. The values correspond to relative levels of performance that represent optimistic bounds on potential actual performance. Often, this potential performance is used by managers to select a schedule, and is also used as a basis for predictions of actual performance.

4.2.1 Comparison Tables

The scheduling results are presented in Table 4.1, Schedules by Problem (SDUR) and Table 4.2, Schedules by Problem (SNPV). For each problem in the problem set, the performance level (duration or NPV) is listed. Each scheduling method that achieved that level of performance is listed on the same row. Identical schedules are those with the same start and stop times for every activity. Identical schedules are separated by commas. Schedules that achieve the same level of overall duration or NPV performance, but are not identical, are separated by semicolons. In instances where many schedules achieve the same level of overall performance, the row is continued on the next line with no entry in the performance column. The percent range between the highest and lowest values for each problem (range/midpoint) is given under the problem identifier.

The scheduling methods create schedules that differed by duration in the majority of cases. Three of the problems were solved with 6 different durations, 4 were solved with 5, 2 were each solved with 4, 3, and 2 different durations, and only 5 of the 18 problems were solved with the same overall duration. Among those problems that were solved with the same overall duration, schedule activity timing differed. Each of these problems were solved with at least 5 unique activity timing schedules. It is interesting to note that

Pr
H1 3(
H1 2
H4 36
H4
H5 4°
H5
H1- 9°
H1- 21
H1- 16

in a

RSC

notec

high

versi

Table 4. 1: Schedules by Problem (SDUR)

Prob	Dur	Schedule
H13A	20	OPT, RSO
30%	21	SLK; LSC
	22	LFT
	26	DCF
	27	BCP
H13C	49	OPT; RSO; BCP
2%	50	SLK, LSC; LFT, DCF
H48A	23	OPT; RSO
36%	24	LFT; LSC
	25	SLK
	29	BCP
	33	DCF
H48C	55	OPT, RSO; SLK, LSC; LFT; DCF; BCP
-		
H56A	27	OPT, BCP; SLK, LFT; RSO; LSC
4%	28	DCF
H56C	55	OPT, RSO; SLK, LSC; LFT; DCF; BCP
-		
H14A	43	OPT; RSO; LSC
9%	44	SLK; LFT
	45	BCP
	47	DCF
H14B	74	OPT; RSO
21%	77	SLK; LSC
	78	BCP
	80	LFT
	91	DCF
H14C	90	OPT; RSO
16%	95	LFT
	98	BCP
	100	LSC
	101	SLK
	106	DCF

Prob	Dur	Schedule
H15A	43	OPT; RSO; LSC
17%	44	SLK, LFT; BCP
	51	DCF
H15B	75	OPT; RSO
18%	77	LFT
	81	BCP
	83	SLK; LSC
	90	DCF
H15C	95	OPT; LFT; RSO
8%	96	SLK; LSC
	102	BCP
	103	DCF
H105A	76	RSO
16%	77	OPT; LSC
	78	LFT
	79	SLK
	84	BCP
	89	DCF
H105C	158	OPT, RSO; SLK, LSC; LFT; DCF; BCP
-		
H107A	78	OPT; SLK, BCP; RSO; LSC
7%	80	LFT
	84	DCF
H107C	189	OPT, RSO; SLK, LSC; LFT; DCF; BCP
-		
H110A	50	OPT; RSO
18%	51	LSC
	52	SLK
	53	LFT
	54	BCP
	60	DCF
H110C	119	OPT, RSO; SLK, LSC; LFT; DCF; BCP
-		

in all of these cases, the scheduling methods grouped together the same way: OPT and RSO, SLK and LSC, then LFT, DCF, and BCP. This is not unexpected, however. It is noted that in cases where the problem network has diminishing non-critical slack, the “right shifting” methods (RSO and LSC) will converge on their respective non-shifted versions (OPT and SLK). Inspection of the 5 problem networks involved will indicate th

co

to

we

sa

(da

mi

we

sho

of t

eigh

over

rang

case

5 wi

all s

perf

dura

(inst

perf

that this is indeed the case. It would be a surprising result if the methods involved did not come up with identical schedules.

While the duration differences between the schedules exist, the question remains as to how great the differences were. Of course, in five cases the differences in duration were 0; corresponding to the problems where the scheduling methods came up with the same duration. In two cases the greatest difference between the durations was 1 time unit (day). In percentage terms, these one day differences amounted to 2% and 4% of the midrange duration. For these problems, the differences between scheduled durations were practically negligible. The remaining 11 problems all had differences between the shortest and longest scheduled duration of 4 days or more. Percent differences for three of these were less than 10% (4 days/9%, 8 days/8%, and 6 days/7%). The remaining eight problems all had differences that could be considered significant, spanning either over 15 days or 30% or both. This is to be considered in light of the total durations which range from 20 days to 189 days.

The scheduling methods created schedules that differed by NPV in the majority of cases. Five of the problems were solved with 5 different NPVs, 6 with 4 different NPVs, 5 with 3, and 2 problems were solved with 2 different NPVs. No problem existed where all scheduling methods came up with the same NPV. General patterns in the grouping of performance by method can be noted here as well, although not as sharply defined as for duration. OPT and RSO again came up with the same NPV in 12 cases. SLK and LFT (instead of LSC) came up with the same result in 7 cases. Scheduling method performance on NPV were mixed for the remainder of the problems.

Table 4. 2: Schedules by Problem (SNPV)

Prob	NPV	Schedule
H13A	5,910	OPT, RSO
-	5,909	SLK,LFT
	5,908	BCP
	5,906	LSC, DCF
H13C	13,288	BCP
-	13,285	OPT, RSO
	13,280	LFT, LSC, DCF
	13,279	SLK
H48A	6,664	OPT, RSO
-	6,661	SLK, LFT
	6,659	BCP
	6,657	LSC, DCF
H48C	16,624	OPT, RSO, LFT,
-	16,623	SLK
	16,620	LSC, DCF
H56A	6,660	OPT, SLK, LFT, BCP
-	6,659	LSC, DCF
	6,657	RSO
H56C	19,677	OPT, RSO, LSC,
-	19,676	LFT, BCP
	19,675	SLK
H14A	3,910	OPT, SLK, LFT, BCP
-	3,907	RSO, LSC, DCF
H14B	7,746	OPT, RSO
-	7,741	BCP
	7,738	SLK
	7,732	LFT
	7,720	LSC, DCF
H14C	9,978	OPT, RSO
-	9,963	LFT
	9,960	BCP
	9,952	SLK
	9,938	DCF, LSC
H15A	6,650	OPT, SLK, LFT, BCP
-	6,445	RSO, LSC, DCF
H15B	12,721	OPT, RSO
-	12,715	LFT
	12,705	BCP
	12,697	SLK
	12,686	LSC, DCF
H15C	16,499	OPT, RSO, LFT
-	16,493	SLK
	16,474	BCP, DCF, LSC
H105A	19,591	OPT
-	19,585	LFT, RSO
	19,583	SLK
	19,556	BCP
	19,548	LSC, DCF
H105C	48,028	LFT
-	48,027	BCP, SLK, LSC,
	48,026	OPT, RSO
H107A	20,190	OPT, SLK, BCP
-	20,184	LFT
	20,181	RSO
	20,161	LSC, DCF
H107C	51,635	OPT, RSO
-	51,629	LSC, DCF
	51,619	LFT
	51,614	SLK
	51,609	BCP
H110A	12,645	OPT, RSO
-	12,642	SLK, LFT
	12,636	BCP
	12,632	LSC, DCF
H110C	32,625	SLK, LFT
-	32,619	OPT, RSO
	32,617	BCP
	32,616	LSC, DCF

While NPV differences existed for all problems, the size of the differences was slight. Seventeen of the problems reflected an NPV difference of $43 or less. The remaining problem showed a scheduled NPV difference of $205. These differences must be considered slight when compared to the NPV totals; which range from a low of $5,906 to a high of $48,028. None of the NPV differences reached a level equal to 1% of the mi

dif

the

du

Th

thi

4.2

dif

per

sit

mu

val

Sc

Me

and

per

(pe

aga

met

wer

midrange NPV for that problem (indicated by a – in Table 4.2). The nature of these differences is a function of the total durations and discounting rate as programmed into the model under study. It is unlikely, with the discounting rates used (15%) and the durations expected (20 to 189 days), that any great differences in NPV would be seen. The sensitivity of NPV to time and discounting rates will be discussed in a later section in this chapter.

4.2.2 Formal Test Results

A nonparametric multiple comparison method (Conover, 1980) was used to test for differences between the scheduling methods on the scheduled duration and NPV performance measures. This method extends the Friedman's Rank Sum test to the situation where multiple comparisons need to be made. The comparison is analogous to a multiple differences of means test, but uses the rank sums instead of the actual mean values. The comparisons are shown in Table 4.3, Nonparametric Comparison of Scheduling Methods (SDUR) and Table 4.4, Nonparametric Comparison of Scheduling Methods (SNPV). The overall significance (that at least one rank sum score differs from another) of the test is indicated in the heading of the table. Individual comparisons were performed at the 0.05 level of significance in all cases. The actual mean values (performance of the scheduling method on all 18 problems) are provided for comparison against the rank sums.

Overall, it can be seen that the relative duration performance between the scheduling methods against all 18 problems can be statistically separated into groups. RSO and OPT were generally the best performers, and DCF was the worst. OPT, LSC, LFT, and SLK could be considered part of the "top middle" group of performers, and LFT, SLK, and BCP fell into the "bottom middle" group. The OPT, SLK, and LFT methods were selected to represent the "high performers" on duration. Putting aside the performance of the two benchmarks (OPT and RSO), the SLK and LFT methods comprise the highest performing group, along with LSC. The hybrid heuristic BCP came in near the bottom of the rankings against scheduled project duration. Only DCF performed worse.

Table 4. 3: Nonparametric Comparison of Scheduling Methods (SDUR)

SDUR	(0.0000)					
Mean	Method	Rank Sum				
73.3	RSO	44.5	A			
73.3	OPT	46.0	A	B		
74.8	LSC	67.0		B		
74.7	LFT	76.0		B	C	
75.2	SLK	78.5		B	C	
76.2	BCP	83.5			C	
79.7	DCF	108.5				D

Table 4. 4: Nonparametric Comparison of Scheduling Methods (SNPV)

SNPV	(0.0000)				
Mean	Method	Rank Sum			
17279.44	OPT	103.5	A		
17266.89	RSO	87.5	A	B	
17275.67	LFT	86.0		B	
17271.67	BCP	73.0		B	
17273.78	SLK	72.0		B	
17254.56	DCF	41.0			C
17254.56	LSC	41.0			C

It is also apparent that the relative NPV performance between the scheduling methods against the 18 problems can be statistically separated into groups. Again, OPT and RSO form the top performing group. LSC and DCF (the two methods selected because of their strong track record on NPV) formed the poor performing group. RSO, LFT, BCP, and SLK were all grouped in the middle range. The RSO, LSC, and DCF methods were selected to represent the "high performers" on NPV. Ignoring the two benchmark methods (OPT and RSO), the LSC and DCF methods comprise the lowest performing group. All of the other heuristics performed better. Even the hybrid heuristic BCP out-performed LSC and DCF.

4.2.3 Expectations of Performance under Stochastic Conditions

Central to this current research is the theory that the predicted performance of various scheduling methods can be changed significantly by the presence of environmental variability (disruptions and task time deviations) and execution procedures. A key issue to be investigated in the current study is to what degree the scheduling methods come up with robust or stable plans that continue to achieve high levels of performance in spite of the environmental factors and execution methods.

It is expected that both the relative and absolute performance of the various schedules will change as a result of adding environmental uncertainty and differing execution policies. It is also presumed that the highest-performing schedules under the deterministic assumptions may suffer the most under stochastic conditions; certainly in an absolute sense, but perhaps also in a relative sense. The better schedules (deterministically) are generally "tighter," with less non-critical slack. Less slack should make the schedule less able to absorb variability without causing some type of performance degradation. More slack in a schedule should allow the schedule to experience variability and still perform reasonably close to what was predicted. It is thus surmised that the "looser" (less efficient under deterministic assumptions) schedules may actually outperform the "tighter" schedules when variability and disruptions are added. Whether or not the ability of a particular schedule to use slack in absorbing variability (a

an

4.

sc

di

wi

fr

di

M

the

tin

pro

cas

the

con

or d

com

NPV

NPV

(and remain on schedule) in the absolute sense is enough to counteract the superiority of another schedule in a relative sense remains to be seen.

4.2.4 A Note About the Sensitivity of NPV to rt

It was previously noted that the magnitude of the differences in NPV between scheduling methods for each problem were a function of (in large part) the duration and discount rate used by the model. Either a small discount rate or a short duration (or both) will result in small values of the product rt (r is the discount rate, as a fraction; t is the fraction of time in years). The basic discounting procedure used in calculating NPV discounts the value of a cash flow by e raised to the rt power (as described in Chapter 3, *Methodology*). The model in use here assumes a negative cash flow for each activity, then a single positive cash flow upon completion.

Schedules can achieve different NPVs for each problem in two ways. First, the timing of activities can change the timing of the negative cash flows. This effect would probably be slight. Second, the total duration will affect the timing of the single positive cash flow. This effect would probably be a greater differentiator between schedules than the effect of different negative cash flows. In addition, if all activities and the project completion are generally all "early" or all "late," the effects on NPV of either accelerating or delaying negative flows and accelerating or delaying the positive flow have complementary effects that may further reduce the impact of schedule deviations on NPV. If cash outflows are early (late), and the cash inflow is late (early), the effect on NPV would be enhanced. These situations would seem to be unlikely.

d.

2.

n

th

tw

th

th

sc

ca

slo

slo

val

of Y

App

rela

ma

no

fou

Op

met

A simple investigation was conducted into the sensitivity of NPV to changes in the discount rate r and total duration t. NPV was calculated for four different levels of rt (1, 2, 3, and 4 times the scheduled rt), for each schedule and problem in the problem set. An rt value of 1 corresponds to an r of 0.15 (as used in the study) and a total duration equal to the scheduled duration. Values of 2, 3, and 4 correspond (respectively) to an rt factor of two, three, or four times the baseline value. In this sense, 2 would correspond to either the same r but double the duration, or the same duration and double the discount rate. As the rt factor increases, the project value would decrease. Representative data for scheduling method OPT is given in Table 4.5, NPV vs. rt (OPT). This table includes a calculation of the slope and percent slope of the NPV-rt curve for each problem. The slope is calculated as the dollar change in NPV for each factor increase in rt. The percent slope is calculated as the slope as a percentage of the average NPV over the range of rt values from one to four. These results are depicted graphically in Figure 4.1, Sensitivity of NPV to rt (OPT). Full tables and figures for all scheduling methods are provided in Appendix L, NPV vs. rt.

From Table 4.5 and Figure 4.1, no great differences in NPV were seen even for relatively large increases in rt. As expected, the shorter (smaller) project problems were much less sensitive to changes in rt than the larger (longer) projects. As a percentage rt, no problem exhibits greater than a 4% decrease in NPV for an increase in rt from one to four times greater than that used in the study (a 3.73% decrease for Heur107C under OPT). The greatest sensitivity (3.78%) was exhibited by Heur107C under the scheduling method BCP. A summary table of all percent slopes, with the average percent slopes and

Fi

st

st

st

ex

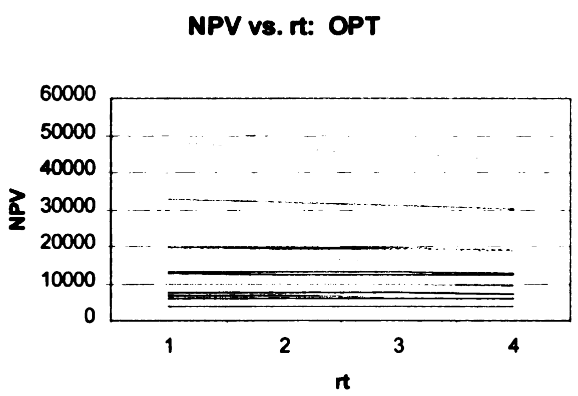


Figure 4. 1: Sensitivity of NPV to rt (OPT)

ranges for all scheduling methods and problems is provided in Table 4.6, Percent Slopes, NPV vs. rt.

It is expected that differences in NPV in the data would be very small. Any detectable differences, if statistically significant, would be surprising. It would be even more surprising if any practically significant differences were to be found. If a pattern of statistically significant differences in NPV were present, this would indicate an effect strength powerful enough to overcome the slight nature of differences in NPV explainable by small changes in rt alone.

Table 4.5: NPV vs. rt (OPT)

	Rt Factor 1	2	3	4	Slope	%slope
HEUR013A	5910	5882	5854	5827	-28	-0.47
HEUR013C	13285	13147	13011	12877	-136	-1.04
HEUR048A	6664	6628	6592	6557	-36	-0.54
HEUR048C	16624	16426	16232	16040	-195	-1.19
HEUR056A	6660	6620	6580	6541	-40	-0.60
HEUR056C	19677	19445	19217	18992	-228	-1.18
HEUR014A	3910	3870	3831	3793	-39	-1.02
HEUR014B	7746	7619	7496	7374	-124	-1.64
HEUR014C	9978	9786	9599	9417	-187	-1.93
HEUR015A	6450	6387	6326	6265	-61	-0.97
HEUR015B	12721	12521	12325	12133	-196	-1.58
HEUR015C	16499	16170	15848	15535	-321	-2.01
HEUR105A	19591	19288	18991	18699	-297	-1.55
HEUR105C	48027	46473	44985	43561	-1489	-3.25
HEUR107A	20190	19862	19540	19226	-321	-1.63
HEUR107C	51635	49719	47899	46168	-1822	-3.73
HEUR110A	12646	12518	12393	12268	-126	-1.01
HEUR110C	32619	31862	31129	30419	-733	-2.33

4.

na

du

as

as

tre

4.

in

son

Table 4.6: Percent Slopes, NPV vs. rt

	OPT	SLK	LFT	RSO	LSC	DCF	BCP	avg	range
HEUR013A	-0.47	-0.48	-0.49	-0.47	-0.50	-0.36	-0.50	-0.47	0.14
HEUR013C	-1.04	-1.09	-1.08	-1.04	-1.09	-0.72	-1.02	-1.01	0.37
HEUR048A	-0.54	-0.59	-0.58	-0.55	-0.58	-0.43	-0.61	-0.55	0.18
HEUR048C	-1.19	-1.20	-1.19	-1.19	-1.20	-0.81	-1.19	-1.14	0.39
HEUR056A	-0.60	-0.60	-0.60	-0.64	-0.65	-0.41	-0.60	-0.59	0.24
HEUR056C	-1.18	-1.19	-1.18	-1.18	-1.19	-0.79	-1.18	-1.13	0.40
HEUR014A	-1.02	-1.02	-1.02	-1.10	-1.07	-0.73	-1.02	-1.00	0.37
HEUR014B	-1.64	-1.74	-1.82	-1.65	-1.77	-1.31	-1.70	-1.66	0.51
HEUR014C	-1.93	-2.18	-2.08	-1.93	-2.18	-1.56	-2.11	-1.99	0.63
HEUR015A	-0.97	-0.96	-0.96	-1.03	-1.04	-0.69	-0.96	-0.95	0.35
HEUR015B	-1.58	-1.76	-1.62	-1.59	-1.77	-1.24	-1.70	-1.61	0.54
HEUR015C	-2.01	-2.04	-2.01	-2.01	-2.05	-1.44	-2.15	-1.96	0.71
HEUR105A	-1.55	-1.59	-1.58	-1.58	-1.61	-1.18	-1.72	-1.54	0.54
HEUR105C	-3.25	-3.25	-3.25	-3.25	-3.25	-2.19	-3.25	-3.10	1.06
HEUR107A	-1.63	-1.63	-1.66	-1.67	-1.67	-1.18	-1.63	-1.58	0.49
HEUR107C	-3.73	-3.77	-3.76	-3.73	-3.77	-2.52	-3.78	-3.58	1.26
HEUR110A	-1.01	-1.04	-1.04	-1.02	-1.04	-0.75	-1.09	-1.00	0.34
HEUR110C	-2.33	-2.31	-2.31	-2.33	-2.31	-1.57	-2.33	-2.21	0.76

4.3 Exploratory Analysis

The first set of analyses performed on the simulation output were exploratory in nature. This section is concerned with an initial analysis of the output variables of duration, NPV, and stability. Specifically, the next three subsections will report aggregate statistics, a presentation of mean values in the treatment cells, and an assessment of the likelihood of normality and homoscedasticity within and between treatment cells.

4.3.1 Summary Statistics of Key Variables

A standard set of statistics were calculated for each output variable and are presented in Table 4.7, Summary Statistics of Key Variables. While the results are unsurprising, some items of interest can be noted.

Table 4.7: Summary Statistics of Key Variables

	Min	Max	Mean	Std. Dev.	Skew	Kurtosis
ADUR	19.4400	226.8400	78.1106	45.5356	1.115	0.697
RDUR	0.8323	1.14865	1.0371	0.0467	1.400	3.490
ANPV	3268.4400	56462.6400	17130.1934	13289.3512	1.486	1.229
RNPV	0.7820	1.1944	0.9934	0.0398	-0.630	3.421
WADE	0.0000	2.3401	0.0821	0.1959	3.335	13.816
WADL	0.0000	8.0607	0.5286	0.7475	2.831	11.305
WADC	0.0000	8.0607	0.6107	0.7710	2.551	9.336
POIC	0.0000	1152.1000	117.5245	148.5411	2.324	6.236
POIR	0.0000	0.4648	0.0797	0.0651	1.002	1.524
POOC	0.0000	1251.8100	120.5200	154.5222	2.327	6.372
POOR	0.0000	0.4944	0.0819	0.0694	0.979	1.171

Actual durations (ADUR) range from a low of 19.44 days to a high of 226.84 days. This is reasonable, given the scheduled durations (SDUR) from 20 days to 189 days. In addition, the durations appear to be clustering in the "short, medium, and long" categories as designed in to the problem set (see Figure 4.2, Histogram of Aggregate Statistics (ADUR) and histograms for the remaining variables in Appendix A). The mean ADUR of 78.1106 is larger than the average SDUR of 75.3143. Combined with the mean RDUR of 1.0371, and an ADUR skewness of 1.115, this indicates that there is more "lateness" than "earliness" being experienced in the problem set. The NPV statistics indicate a

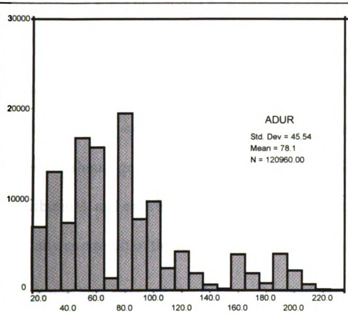


Figure 4. 2: Histogram of Aggregate Statistics (ADUR)

corresponding reduction from what was scheduled. The actual NPV (ANPV) mean of $17,130.00 is lower than the scheduled mean of $17,268.08, and the average ratio of actual to scheduled NPV (RNPV) is less than unity (0.9934). The minimum and maximum values are reasonably close to the minimum and maximum scheduled values. The ratio variables RDUR and RNPV appear relatively symmetrical around 1.0 which is also expected.

A footnote to the NPV statistics must be made. The large variance (30% of the mean) of the aggregate measure reinforces the expectation that differences in NPV between treatments for the same problem will be undetectable. Once more it is noted that any underlying effect on NPV as a result of differing treatment would have to be very consistent and powerful if it is to be detected. However, these differences are still expected to be practically insignificant even if statistically significant. Conversely, an examination of the NPV histograms indicates that some clustering is occurring and this may indicate some underlying relationships between NPV and the treatments.

Each of the stability measures should be bounded by zero, and this is reflected in the actual minimum values. The measures are unique in this. When the disruption and variability levels are set to "none," the stability measures will respond as 0. The stability measures should generally appear left-peaked and right tailed (similar to an exponential distribution), and each histogram shows a spike at 0 and a long tail to the right at least partially as a result of the left-bounded characteristic.

It was also expected that the ratio forms of resource profile offset (POIR and POOR) would be less than unity, and the maximum values reflect this. Another interesting thing

to note is that the resource profile offset measures are quite similar. The resource profile offset "idleness" (POIC) and "overuse" (POOC) statistics, as well as the ratio statistics, are quite similar. This was somewhat expected, as a shortening or lengthening of the project duration would most probably be associated with accelerated or delayed activity start and stop times. This, in turn, will compress or expand the resource profile evenly, and for every unit of overuse (accelerated start) we would expect a unit of idleness (accelerated stop) and vice versa.

The weighted activity deviation stability measures appear to be behaving as expected. Earliness (WADE) happens less than lateness. The contribution of earliness to the composite measure (WADC) is small. Each measure displays a long tail to the right (mean much closer to the minimum than the maximum level, and the skewness statistics indicate long tails in the positive direction. The histograms also display this characteristic.

4.3.2 Treatment Cell Means

Table 4.8, Means: ADUR by Scheduling and Execution Method, by Disruption and Variability contains the mean values of ADUR within each treatment combination. The complete set of tables for all performance measures is included in Appendix B. The columns in the table separate the treatments by variability (top header) and disruption type (bottom header). The rows in the table separate the treatments by scheduling method (left header) and execution method (right header).

This information is presented graphically in Figure 4.3, ADUR Treatment Means. The complete set of figures for all performance variables is included in Appendix C,

Table 4.8: Means: ADUR by Scheduling, Execution, Disruption, Variability

ADUR		some			none		
Sched	Exec	none	freq	Infq	None	freq	infq
OPT	FRN	74.53	76.03	79.79	73.33	74.91	78.84
	FRW	75.45	76.51	79.64	73.33	74.93	78.29
	NRN	75.40	77.21	78.70	74.44	76.39	78.49
	NRW	75.35	77.02	79.37	73.33	75.39	78.31
SLK	FRN	76.22	77.74	81.57	75.17	76.82	80.67
	FRW	77.23	78.32	81.46	75.17	76.78	80.00
	NRN	76.12	77.77	79.53	75.22	77.13	78.87
	NRW	76.94	78.49	81.00	75.17	77.26	79.80
LFT	FRN	75.75	77.23	80.89	74.72	76.38	80.12
	FRW	76.74	77.83	81.10	74.72	76.39	79.58
	NRN	75.47	77.45	78.69	74.83	76.83	78.31
	NRW	76.58	78.13	80.23	74.72	76.81	79.19
RSO	FRN	74.55	75.99	79.70	73.28	74.84	78.73
	FRW	75.58	76.61	79.78	73.28	74.90	78.26
	NRN	75.34	77.00	78.76	74.56	76.30	78.13
	NRW	75.40	76.96	79.48	73.28	75.38	78.00
LSC	FRN	75.78	77.31	81.03	74.78	76.40	80.20
	FRW	76.99	78.08	81.24	74.78	76.48	79.83
	NRN	75.94	77.58	79.11	75.22	76.61	78.40
	NRW	76.73	78.31	80.99	74.78	76.92	79.66
DCF	FRN	80.45	81.86	85.49	79.67	81.14	84.91
	FRW	81.62	82.57	85.74	79.67	81.20	84.47
	NRN	79.57	81.07	83.65	79.00	80.64	83.25
	NRW	81.13	82.62	84.99	79.67	81.64	84.35
BCP	FRN	77.26	78.56	82.22	76.22	77.70	81.41
	FRW	78.28	79.25	82.32	76.22	77.79	80.90
	NRN	76.69	77.99	79.76	76.28	77.53	79.57
	NRW	77.95	79.64	82.03	76.22	78.30	80.82

Graphical Treatment Means. The graphs present the mean values within a treatment combination for each variable. Each variable is represented by four graphs, one for each execution method. On any individual graph, separate series are used for each scheduling method. The x axis captures the 6 different combinations of spread (variability; none and some) and disruption (none, frequent-short, and infrequent-long). Values 1-3 indicate no variability and none, frequent, and infrequent disruption (in that order). Values 3-6 indicate the same disruption pattern but with variability. The y axis captures the value of the performance variable.

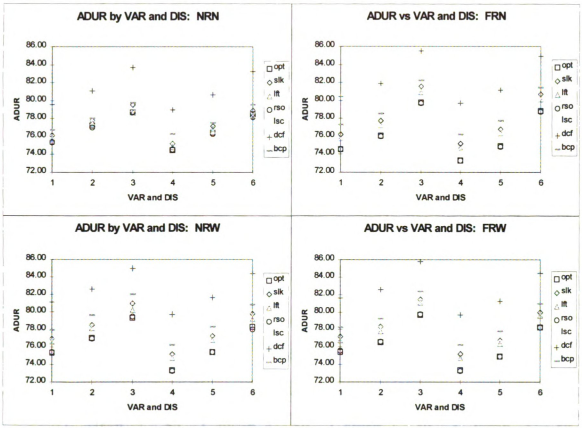


Figure 4. 3 : ADUR Treatment Means

4.3.3 Treatment Cell Normality and Homoscedasticity

The next step in the exploratory analysis was to assess the data for suitability for more formal statistical testing. Each of the 3,024 treatment cells (168 factor combinations and 18 problems in the problem set) was tested for normality, and the skew, kurtosis, and standard deviation values were calculated. These metrics were deemed essential to establishing normality and equality of variance within the treatment cells; assumptions that must be met in order to claim strong inference for a wide variety of parametric tests (Cohen and Cohen, 1983; Neter et. al., 1996).

The SAS procedure UNIVARIATE was used with the NORMAL option to generate summary statistics within each treatment cell, to include measures of kurtosis, skewness, and standard deviation. A statistic (the Shapiro-Wilk statistic, W) was generated to conduct a formal test for normality. Small values of W lead to a rejection of the hypothesis that the data are sampled from a normal distribution (SAS Institute, 1985). These results are all summarized in Table 4.9, Treatment Statistics: Assessment of Normality and Homoscedasticity. The normality and standard deviation data are summarized graphically for ADUR in Figure 4.4 and for the rest of the variables in Appendix D.

Table 4.9: Treatment Statistics: Assessment of Normality and Homoscedasticity

	Kurtosis		Skew		Pr<W		Std. Deviation	
	Mean	Sd	mean	Sd	mean	sd	mean	sd
ADUR	0.6517	2.7814	0.6011	0.7136	0.2352	0.2830	5.1740	8.5434
RDUR	0.6509	2.7753	0.6010	0.7132	0.2352	0.2830	0.0009	0.0011
ANPV	0.5642	2.1052	-0.4586	0.6351	0.3782	0.3424	541172	1181700
RNPV	0.6167	2.6086	-0.4511	0.6620	0.3757	0.3427	0.0016	0.0018
POIC	0.2169	1.6595	0.3972	0.6306	0.2576	0.2829	2189	3910
POIR	0.2170	1.6600	0.3972	0.6306	0.2576	0.2829	0.0010	0.0011
POOC	0.2767	1.6938	0.4630	0.6447	0.2265	0.2746	3368	5972
POOR	0.2769	1.6942	0.4631	0.6447	0.2265	0.2745	0.0014	0.0015
WADE	4.4572	8.6369	1.5623	1.4780	0.0595	0.1653	0.0103	0.0272
WADL	1.1099	2.5033	0.9450	0.6447	0.0968	0.1855	0.1593	0.3033
WADC	1.1296	2.3776	0.9237	0.6466	0.1031	0.1977	0.1586	0.3022

Table 4.9 generally indicates significant levels of skewness and kurtosis in many treatment cells. This is unsurprising; many of the variables are bounded on one side and have the potential to exhibit extreme values on the other. The wide spread in levels of skew and kurtosis (noted by the high standard deviations relative to mean values) also suggest that the shapes of the distributions between treatment cells for the same variable differ significantly. These characteristics may present problems in meeting the assumptions of parametric statistical tests.

Meeting the assumption of normality is also unsupported. The mean probabilities (of values less than W) are less than .4 for all variables, and less than .3 for all but two of them. The standard deviations of the probabilities indicate that a wide range of values is present for each variable. A closer examination of the values for ADUR (presented graphically in Figure 4.4) explains both the low means and wide ranges. It is known *a priori* that the treatment cells corresponding to the No Variability and No Disruption combinations will have no variance; the values will all be identical. These treatment

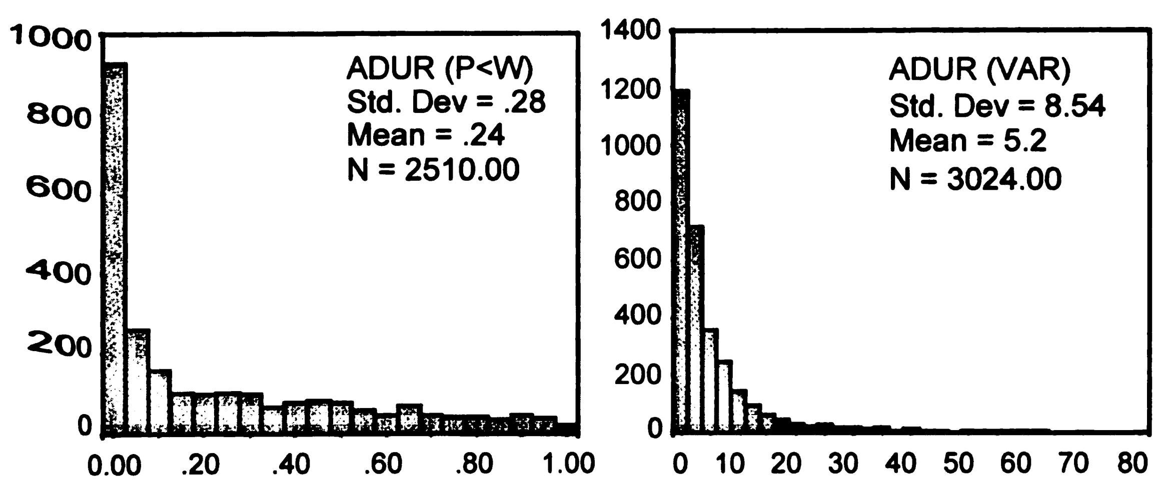


Figure 4. 4: Distributions, P Normality and Variance (ADUR)

combinations represent 504 out of the 3024 possible combinations. In addition, some of the variables may be relatively immune to task time variability or resource disruption. No Disruption and Some Variability represent an additional 504 combinations; No Variability and either Frequent-Short and Infrequent-Long represent another 504 combinations each. It would be anticipated (and this is borne out by the charts) that the distribution of probabilities less than W would be heavily weighted on the left. This is the case for ADUR as shown, and is also present to a similar degree for RDUR, ANPV, RNPV, POIC, POIR, POOC, and POOR. WADE, WADL, and WADC exhibit a much greater left-shifting than the rest. At this point, normality of the data is in question. A reduced data set (excluding all of the no variability/no disruption cases) was examined. Even after excluding these cases, it was unreasonable to assume normality.

A similar problem exists with the assumption of equal variance. The amount of "spread" of the standard deviation values is indicated in Table 4.9. For every variable, the standard deviation (of the standard deviations) is greater than the mean. Graphically, we see (on Figure 4.4) that the values again are left-shifted around zero. This is due to the previously mentioned deterministic treatment cells. The spread of values imply that the assumption of equal variances would not be met by the data. This effect is present for all of the performance variables. Unequal variances were prevalent in the reduced data set as well.

Parametric statistical testing requires data to be relatively normal (or at least mound shaped) and the variances of comparison sets to be approximately equal in order to draw the strongest inferences from sampled data (Cohen and Cohen, 1983; Neter et. Al., 1996).

Summary statistics relating to normality and homoscedasticity were generated, and indicate that the data may have trouble meeting these assumptions. Therefore, while parametric data analysis methods may be employed, caution must be exercised in drawing inferences from the results. The following analyses will take this into account.

4.4 Covariation

In order to assess the behaviors of and relationships between the variables in the study, two analyses of covariation were performed. First, relationships between and among the outcome variables were assessed using biserial correlations. This information should help determine how unique or similar the individual measures are; and whether or not the proposed stability measures offer information that is significantly different from the existing, traditional measures. Also, a classical Analysis of Variance (ANOVA) was performed assessing the degree of covariation between levels of the factors (independent variables) and the outcome variables. This information should help determine which factors are more or less important to the outcomes, and whether or not a selection of combinations of factors would result in better performance levels.

4.4.1 Biserial Correlation

Two biserial correlations were performed in order to assess the degree to which the outcome variables responded in concert with one another. Table 4.10 (Biserial Correlations: Parametric) and Table 4.11 (Biserial Correlations: Nonparametric) present

Table 4.10: Biserial Correlations: Parametric (Pearson's)

	ADUR	RDUR	ANPV	RNPV	WADE	WADL	WADC	POIC	POIR	POOC	POOR
ADUR	-										
RDUR	.077 (.000)	-									
ANPV	.897 (.000)	.051 (.000)	-								
RNPV	-.064 (.000)	-.452 (.000)	.009 (.002)	-							
WADE	.005 (.108)	-.123 (.000)	.001 (.851)	.146 (.000)	-						
WADL	.456 (.000)	.723 (.000)	.402 (.000)	-.295 (.000)	-.009 (.002)	-					
WADC	.443 (.000)	.670 (.000)	.390 (.000)	-.249 (.000)	.245 (.000)	.967 (.000)	-				
POIC	.649 (.000)	.494 (.000)	.655 (.000)	-.111 (.000)	.092 (.000)	.845 (.000)	.842 (.000)	-			
POIR	.099 (.000)	.621 (.000)	.061 (.000)	-.130 (.000)	.305 (.000)	.640 (.000)	.698 (.000)	.623 (.000)	-		
POOC	.643 (.000)	.543 (.000)	.635 (.000)	-.255 (.000)	.062 (.000)	.865 (.000)	.854 (.000)	.982 (.000)	.613 (.000)	-	
POOR	.100 (.000)	.693 (.000)	.045 (.000)	-.400 (.000)	.246 (.000)	.663 (.000)	.705 (.000)	.597 (.000)	.961 (.000)	.627 (.000)	-

Table 4.11: Biserial Correlations: Nonparametric (Spearman's)

	ADUR	RDUR	ANPV	RNPV	WADE	WADL	WADC	POIC	POIR	POOC	POOR
ADUR	-										
RDUR	.121 (.000)	-									
ANPV	.773 (.000)	.043 (.000)	-								
RNPV	-.165 (.000)	-.596 (.000)	-.009 (.001)	-							
WADE	-.010 (.001)	-.044 (.000)	-.029 (.000)	.011 (.000)	-						
WADL	.388 (.000)	.832 (.000)	.299 (.000)	-.524 (.000)	.063 (.000)	-					
WADC	.373 (.000)	.716 (.000)	.289 (.000)	-.459 (.000)	.332 (.000)	.917 (.000)	-				
POIC	.487 (.000)	.607 (.000)	.513 (.000)	-.336 (.000)	.246 (.000)	.837 (.000)	.898 (.000)	-			
POIR	.152 (.000)	.698 (.000)	.080 (.000)	-.330 (.000)	.309 (.000)	.782 (.000)	.877 (.000)	.833 (.000)	-		
POOC	.477 (.000)	.669 (.000)	.473 (.000)	-.483 (.000)	.230 (.000)	.872 (.000)	.917 (.000)	.979 (.000)	.823 (.000)	-	
POOR	.157 (.000)	.769 (.000)	.051 (.000)	-.542 (.000)	.278 (.000)	.821 (.000)	.891 (.000)	.806 (.000)	.957 (.000)	.849 (.000)	-

the correlation coefficients and significance levels for the combinations of variables. A graphical presentation of the data is included in Appendix E, Biserial Scatterplots.

In general, the results found on the parametric and non-parametric tables are similar. The following discussion will refer to the non-parametric correlation matrix. First, the significance levels (values above the diagonal) were all 0.001 or less; indicating a high degree of statistical confidence in the correlations. Three main categories of correlations will be discussed: within the traditional measures, within the stability measures, and between the traditional and stability measures.

Traditional Measures. Within the traditional measures, the correlation between ADUR and ANPV (0.773) was strong, indicating that long durations are associated with high levels of NPV. This is unsurprising, as the model calculated the cash flows based on a "cost plus" method, which would generally make the larger (longer) projects more profitable. Between ADUR and RDUR, the low correlation (0.121) indicates that longer projects did not necessarily experience longer delays (as a percentage of scheduled duration) than shorter projects, but that this effect was mildly present. An even lower and negative (-0.009) correlation between ANPV and RNPV indicates no relationship between actual NPV and changes in NPV from scheduled. Similarly, no relationship (0.043) was detected between RDUR and ANPV. A mild and negative (-0.165) correlation was observed between ADUR and RNPV. This suggests that for projects with longer actual durations, the actual NPV decreased compared to the scheduled NPV. This relationship may come from two distinct sources. "Higher" values of ADUR may result from either longer schedules, or delays in any schedule. On the other hand, "smaller" values of RNPV can result only from reductions in anticipated NPV on a project of any size. The relationship may be the result of longer projects being more susceptible to reductions in NPV (vice planned values), or may be the result of delays in a project of any size resulting in reductions in NPV. A strong and negative relationship (-0.596) was found between RDUR and RNPV. This indicates that when a project is delayed beyond schedule, the NPV is reduced below schedule. This phenomenon would lend credence to the idea (just discussed) that the source of the negative relationship between ADUR and RNPV could be the result of delayed projects.

Stability Measures. The next set of correlations to be discussed are those among the stability measures. In general, strong, positive correlations were found between the stability measures. The lowest relationships were found between WADE and anything else (0.063 with WADL to 0.332 with WADC). As anticipated, the relationship between WADE and WADL was slight (0.063). Therefore, activity lateness was not found to coexist with activity earliness. WADE was correlated more strongly with WADC (0.332); since WADC is a measure consisting of the sum of WADE and WADL this is not surprising. The vast majority of the WADC variable came from WADL. WADC and WADL share a 0.917 correlation coefficient. WADE was correlated mildly with the resource overuse and idleness measures (POOC, POOR, POIC, and POIR); slightly more with the ratio variables than the raw amounts. WADL and WADC exhibit strong relationships with the resource measures, with WADC consistently showing higher correlations. These values range from 0.877 (POIR) to 0.917 (POOC). Also, strong correlations were present between the resource measures themselves. As expected, the relationships were stronger within the idleness and overuse forms themselves. The coefficient values were all above 0.806, with a 0.979 between POIC and POOC and a 0.957 between POIR and POOR. These findings indicate that while simple activity earliness was not related to the other measures, activity lateness, lateness and earliness, and the resource idleness and overuse measures were all closely related.

Traditional Measures vs. Stability Measures. The final set of correlations to be discussed are those between the traditional measures and the stability measures. The first striking result is that WADE and RNPV are negatively correlated with all of the other measures, and are positively related only to each other. Higher amounts of simple activity earliness is associated with lower ADUR, RDUR, and ANPV (-0.010, -0.044, -0.029). Higher amounts of lateness, lateness and earliness combined, resource idleness and idleness vs. schedule, and resource overuse and overuse vs. schedule are all associated with lower NPV vs. scheduled (-0.524, -0.459, -0.336, -0.330, -0.483, -0.542).

It is unsurprising that lateness measures would be associated with lower RNPV, as previously discussed. However, there is no *a priori* reason to suspect that high levels of resource offset would necessarily be strongly (negatively) correlated with RNPV. Indeed, high amounts of resource offset (either idleness or overuse) would be present in either high (project early) or low (project late) RNPV situations. In this case, it has already been established that the high levels of resource offset are associated with lateness (high WADL; ~0.8 correlation). The range restriction on duration (and NPV) "built-in" to the experiment may be more responsible for this relationship than any underlying effect, however. For any given project, the amount of "earliness" that can be experienced is bounded by the dependencies (resource and task) in the network. The amount of "lateness," on the other hand, is virtually unbounded. In general, the amount of resource offset and earliness would be relatively small, and the amount of offset and lateness would be relatively large, across all problems in the problem set and across all levels of factors and treatments. Perhaps, therefore, the apparent association between resource offset and RNPV is more artifactual than actual. Additional evidence for this can be found in analysis of the next correlations to be discussed, between the duration and offset measures.

Raw idleness (POIC) and overuse (POOC) show a strong correlation with raw duration (ADUR; 0.487 and 0.477 respectively). The correlations drop below 0.2 for the idleness and overuse ratios. All correlations are strong between the raw and ratio offset measures and the duration ratio measure; each above 0.6 (and POOR-RDUR at 0.769). High levels of offset are associated with project lateness. The associations between the offset measures and RDUR indicate that even when the scheduled durations of the projects are set aside, offset (instability) and delays are closely related. This, in turn, leads to reductions in NPV (vice scheduled).

It should also be noted that the correlations between offset and ANPV are similar to those between offset and ADUR; with higher values for the raw measures and lower values for the ratio measures. It is proposed that the same phenomenon is at work in both instances. The longer projects have higher NPVs (as previously discussed) and more activities by design. A longer project, with more activities, would show higher raw values for offset than a shorter project with fewer activities even if the "rate" of offset were the same for both. The ratio measures were included in the study specifically to account for this. When the ratio variables are used, a truer picture of the relationship (without the confound of project size) is possible.

The final set of relationships to be discussed in this section are those between WADL/WADC and the traditional duration and raw NPV measures. The behaviors of WADL and WADC are very similar; of course, WADL comprises the vast majority of the composite WADC measure. The term "lateness" will be used to refer to both WADL and WADC. Lateness is strongly correlated positively with duration; both raw (ADUR, 0.373) and ratio (RDUR, 0.716). This is to be expected. Lateness is also mildly correlated with ANPV (0.289). This seems surprising, as it appears to suggest that higher amounts of lateness correspond to higher levels of NPV. Once more this appears to be an artifactual result of the design of the problems in the problem set. Larger, longer projects will necessarily accumulate more lateness over time, as well as having higher scheduled NPV amounts.

Summary. Some general conclusions can be drawn from an analysis of the biserial correlations (Appendix E, Biserial Scatterplots and Table 4.10, Biserial Correlations: Nonparametric). First, the traditional measures clearly measure two distinct concepts: duration and value. This finding is consistent with previous research into duration and NPV. The raw values ADUR-ANPV and the ratio variables RDUR-RNPV show strong correlations. When adjusted to take into account the project size (through the use of the ratio variables), this correlation is negative. While not explicitly recognized in the literature, this result is consistent with previous general findings. The stability measures divide into two distinct groups, the offset measures and the deviation measures. Idleness and overuse appear to behave similarly; they covary both in raw and ratio form. The activity deviation measures seem to consist of a trivial earliness component, and a much more prevalent lateness component. Between and among the traditional and stability measures, two phenomena seem to suggest that the two types of measures indeed constitute different classes of project performance characteristics. First, while the traditional and stability measures exhibit strong covariation in some areas, in others the relationships are weak. Second, the overall correlations between the types of measures are lower than those within each type of measure, indicating that perhaps there are differing degrees of commonality or overlap between and among the types of measures. Overall, it can be said that duration, stability, and value are distinct aspects of project performance; and that these aspects are related to each other. The characteristics of and relationships between the project performance measures must be considered when analyzing the remainder of the research results.

4.4.2 ANOVA Results

The next step in the analysis of the data was to perform Analysis of Variance (ANOVA) procedures in accordance with the experimental design. The factors (project identifier, disruption level, and variability level) and treatments (scheduling and execution method) were used in a model to predict project performance along each of the measures. Table 4.12, ANOVA Results, indicate the degree of success (adjusted R^2) and significance of each model. These will be discussed in a later section. First, a discussion of ANOVA model assumptions and how well the data fit the assumptions is in order.

Table 4.12: ANOVA Results

	ADUR	RDUR	ANPV	RNPV	WADE	WADL	WADC	POIC	POIR	POOC	POOR
Levene	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Adj. R^2	.994	.355	.997	.022	.435	.465	.482	.648	.469	.625	.434
Model	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Intcpt	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
N	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
S	.000	.000	.898	.417	.000	.000	.000	.000	.000	.000	.000
E	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
D	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
V	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
SE	.000	.000	1.000	.999	.000	.000	.000	.000	.000	.000	.000
SD	.007	.000	1.000	1.000	.000	.000	.000	.000	.000	.000	.000
SV	.000	.000	1.000	.999	.000	.029	.000	.000	.000	.000	.000
ED	.000	.000	.000	.320	.000	.000	.000	.000	.000	.000	.000
EV	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
DV	.000	.000	.000	.750	.000	.000	.000	.000	.000	.000	.000
SED	.003	.000	1.000	1.000	.000	.000	.000	.002	.000	.015	.000
SDV	.946	.789	1.000	1.000	.118	.793	.704	.075	.000	.151	.000
SEV	.778	.011	1.000	1.000	.000	.980	.131	.000	.000	.000	.000
EDV	.000	.000	.060	.997	.000	.730	.000	.206	.032	.691	.089
SEDV	1.000	1.000	1.000	1.000	.140	1.000	1.000	.999	.224	1.000	.529

Model Assumptions. In order to draw strong inferences from ANOVA results, the data must satisfy several assumptions (Neter, et. al., 1996; Cohen and Cohen, 1983; and others). As the data increasingly violates these assumptions, the ANOVA model departs from its intended purpose and the validity of the model falls apart. Moderate levels of departure may be acceptable for the interpretation of strong results, but cast doubt upon subtle results. High levels of departure tend to jeopardize even strong results. Before placing trust in the ANOVA results, or drawing inferences from these results, the departures of the model from the assumptions must be checked.

Five departures have been identified as critical to the interpretation and acceptance of ANOVA results (Neter, et. al., 1996):

1. Nonconstancy of error variance: the ANOVA model requires that the error terms (model estimate minus actual value) have constant variance for all treatment levels. Two types of tests were used to check this assumption, formal tests and an informal test. The formal test used on the error terms was the Levene test, reported as a probability or likelihood that the variances of the error terms are equal. These results are shown as the top row in Table 4.12, ANOVA Results. Also, the raw data was tested formally as already discussed in section 4.3.3, Treatment Cell Normality and Homoscedasticity. It is noted at this time that all ANOVA models and the raw data failed the formal tests. The informal test was a visual examination of scatterplots of the error variance (standardized residuals) versus the predicted values. Most of the models failed the informal test as well. The informal tests generally indicated that variance increased in direct proportion to the predicted values. Scatterplots for models are provided in Appendix F. Most models also failed this informal test, with two exceptions. The models RDUR and RNPV did not appear to depart radically from the assumption of equivariance. All other models displayed a troubling level of departure.

2. Nonindependence of error terms: time series data are susceptible to autocorrelation between elements in the time series. This departure is not applicable to the current study or models. Statistical independence is built in to

the experimental design and the conduct of the simulation experiments themselves.

3. Outliers: the presence of extreme values can bias and complicate appropriate analysis of results. An informal test was used here; a visual inspection of the scatterplots of error terms vs. predicted values (refer to previous figure). It should be noted that the nature of the distributions of the variables (left-bounded, and right-tailed distributions with high levels of skew) would lend themselves to the creation of extreme values as a matter of course. No unusual or significant presence of outliers was observed.

4. Omission of important explanatory variables: unaccounted for sources of variance, which exist primarily in empirical studies. The departure of a model in a designed laboratory experiment is dependent upon the completeness and validity of the experimental design itself. As long as the theoretical model is valid, and accounts for the relevant variables to be studied, the design and conduct of a full factorial experimental simulation mitigates against this departure. From a purely statistical and analytical sense, within the current experiment, all relevant explanatory variables have been identified and carefully managed.

5. Nonnormality of error terms: the ANOVA models used are essentially parametric tests; they rely on an assumption of normality. Normality of the data itself was tested formally, and the surrogate normality of the error terms was tested informally. The results of the formal tests have already been discussed in

section 4.3.3, Treatment Cell Normality and Homoscedasticity. The informal test on the error terms consisted of a visual inspection of scatterplots of the standardized residuals vs. expected normal values (see Appendix F, ANOVA Residual Plots). Departures from normality were observed for all models.

Departures from the ANOVA model assumptions were observed both in the formal and informal tests. The departures from normality and equivariance are particularly troubling, as these assumptions are considered vital to having confidence in ANOVA results and the validity of their interpretation. Remedial efforts were considered and attempted. Transformations of the variables did moderate the departures somewhat, but additional problems in interpreting the ANOVA results caused the remediation efforts to be abandoned.

Results. Based on the departures of the ANOVA models from the assumptions, the results must be viewed with some caution. While in some cases these departures were moderate, in others they were quite large. This realization must be balanced against the apparent statistical significance of the results presented in Table 4.12, ANOVA Results.

For each project performance variable, the ANOVA model used the project problem identifier ("Name," N) as a blocking factor. The main effects of this blocking factor was accounted for by the model first, and this blocking factor was not used in any of the interactions tests. The remaining factors and treatments were each considered for both main and interaction effects according to the full factorial experimental design. The Scheduling Method (S, 7 levels), Execution Method (E, 4 levels), Disruption Type (D, 3 levels) and Variability (V, 2 levels) were all entered into the model.

The explanatory power of the ANOVA models on the traditional performance measures was high in the case of ADUR and ANPV (adjusted R^2 of 0.994 and 0.997, respectively). While the overall model significance appears to be better than 0.000 in each case, the model departed quite significantly from the assumptions. Ironically, in the case of the ratio versions of these variables (RDUR and RNPV), the explanatory power was much lower (0.355 and 0.022) but the departures were much less. Interpretation of these results is further confounded by the significance levels of many higher-order interactions. ADUR, RDUR, and ANPV each have significant two- and three-way interactions. ADUR and RDUR show all factors and interactions to be significant down to the two-way level, and at least two of the three-way interactions to be significant. ANPV shows about half of the two-way and one of the three-way interactions to be significant. This seriously complicates any interpretation of the results, above and beyond the departures of the data from the model assumptions. For RNPV, the assumptions aren't violated as much as the others, and the interactions are less of a problem as well, but the explanatory power is quite low (model adjusted R^2 of 0.022).

Results for the stability measures were similar. Adjusted R^2 values range from 0.434 to 0.648, indicating that the models provide a fairly high degree of explanatory power. However, interpretation of these results are complicated by the departures of the models from the assumptions, and the presence of interactions between factors. With one exception, all variables showed interactions significant at 0.000 or better for all two-level interactions, and at least two three-way interactions significant at 0.05 or better.

Overall, the ANOVA results are uninformative with respect to either the traditional or stability variables. However, the ANOVA did detect interactions between factors. Even with the departures from the assumptions, the presence of interactions would complicate additional testing. A weak inference could be drawn that the significance of the interactions supports the idea that each of the factors is important, and selection or "fitting" of scheduling and execution method to the appropriate environmental condition is indicated. While the assumptions of the ANOVA analysis were violated, there is evidence that significant interactions exist between the factors in the study. The focus of analysis needs to include an assessment of the nature and importance of these interactions. Multiple comparisons are indicated in order to evaluate interactions.

4.5 Differences of Means

Due to the insurmountable problems with the ANOVA analyses, nonparametric differences of means tests were performed. A multiple comparison version of the Friedman nonparametric rank sum test (Conover, 1980) was used to detect differences in ranked performance between the scheduling and execution methods for each factor level combination. For each treatment of interest (either the scheduling or execution method), performance was ranked using the problem identifier as the blocking factor. This comparison is performed independently for each combination of the remaining treatment (execution or scheduling method, respectively) and environmental factors. The results of these multiple comparisons are included in Appendix G, Nonparametric Comparisons. A sample is presented in Table 4.13, Scheduling Method Performance by Execution Method

(ADUR). These results correspond to the graphical information previously seen in Appendix C, Graphical Treatment Means.

Before presenting the multiple comparison results, a brief description of the tables is in order. Referring to the sample table (Table 4.13), the performance variable is indicated in the upper left hand corner (ADUR in this case). In the second column of the header row, the factor of interest used for the comparison is given next. Since this table reports the rankings of the scheduling methods within each execution method, the headers are FRN, FRW, NRN, and NRW. At the next level of headings, the disruption type (none, freq, infq) is given. This header is not repeated for each execution method type, but all entries in the respective column belong to that disruption type category. Finally, the variability level (some or none) is indicated, along with the overall significance of the multiple comparison test. For every comparison, a significance level of 0.05 was used to differentiate between groups within each comparison set. Finally, the critical treatment members (scheduling, in this case) are listed according to their rank scores, and significant differences in ranks are indicated by grouping similar scores alphabetically. For example, under FRN-NONE-none for ADUR, there was no significant difference between scheduling methods RSO and OPT (group A), but they both differed significantly from LSC (group B). In turn, LSC was ranked differently from SLK (group D) and so on. This format was used for all multiple comparisons.

The following sections present comparisons between scheduling methods for each execution method, and then comparisons between execution methods within scheduling method. In each case, a discussion of results for the traditional measures is presented first, followed by a discussion of the results for the stability measures.

Table 4.13: Scheduling Method Performance by Execution Method (ADUR)

ADUR		**FRN**									
NONE				**FREQ**				**INFQ**			
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
RSO	A	OPT	A	RSO	A	RSO	A	RSO	A	RSO	A
OPT	A	RSO	A	OPT	A	OPT	A	OPT	A	OPT	A
LSC	B	LSC	B	LSC	B	LSC	B	LSC	B	LSC	B
LFT	C	LFT	C	LFT	C	LFT	B	LFT	C	LFT	B
SLK	D	SLK	C	SLK	D	SLK	C	SLK	D	SLK	C
BCP	E	BCP	D	BCP	E	BCP	D	BCP	E	BCP	D
DCF	F	DCF	E	DCF	F	DCF	E	DCF	F	DCF	E
		FRW									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
RSO	A	OPT	A	OPT	A	OPT	A	OPT	A	OPT	A
OPT	A	RSO	A	RSO	A	RSO	A	RSO	A	RSO	A
LSC	B	LSC	B	LSC	B	LSC	B	LSC	B	LSC	B
LFT	C	LFT	BC	LFT	C	LFT	BC	LFT	B	LFT	B
SLK	D	SLK	C	SLK	C	SLK	C	SLK	B	SLK	B
BCP	E	BCP	D	BCP	D	BCP	D	BCP	C	BCP	C
DCF	F	DCF	E	DCF	E	DCF	E	DCF	D	DCF	D
		NRN									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
OPT	A	RSO	A	RSO	A	RSO	A	RSO	A	RSO	A
RSO	B	OPT	A	OPT	AB	OPT	AB	LSC	B	OPT	A
LSC	C	LFT	B	LSC	B	LFT	BC	OPT	B	LFT	AB
SLK	D	LSC	C	LFT	C	LSC	C	LFT	B	LSC	BC
LFT	D	SLK	C	SLK	D	SLK	C	SLK	C	SLK	C
BCP	E	BCP	D	BCP	E	BCP	D	BCP	D	BCP	D
DCF	F	DCF	E	DCF	F	DCF	E	DCF	E	DCF	E
		NRW									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
RSO	A	OPT	A	OPT	A	OPT	A	RSO	A	OPT	A
OPT	A	RSO	A	RSO	A	RSO	A	OPT	A	RSO	A
LSC	B	LSC	B	LSC	B	LSC	B	LFT	B	LFT	B
LFT	C	LFT	B	LFT	C	LFT	B	LSC	B	SLK	C
SLK	D	SLK	B	SLK	D	SLK	B	SLK	B	LSC	C
BCP	E	BCP	C	BCP	E	BCP	C	BCP	C	BCP	D
DCF	F	DCF	D	DCF	F	DCF	D	DCF	D	DCF	E

While complete information is presented for all variables in the tables and figures, when the performance against individual variables is presented, the discussion of the results will be limited to ADUR, WADC, and POOC. The ratio variables RDUR and POOR will be discussed in a limited fashion, only when they behave in interesting ways. Results with respect to the NPV measures will be presented only when interesting or unanticipated behaviors are present. The WADC measure reflects most of the behaviors of WADL and WADE, and will represent the family of "deviation based" stability measures. POOC is selected to represent the "resource based" stability measures. The behavior of POOC and POIC are similar, and as POOC represents an "overage" or overuse type of measure, this indicator is probably more relevant to project management practitioners.

4.5.1 Scheduling Method Performance by Execution Method

Multiple comparisons were performed on the rank performance of the scheduling methods within each execution method and combinations of disruption type and variability level. An aggregate presentation of the multiple comparison rank data is presented in Table 4.14, Relative Top Rankings (Scheduling Methods). This table presents tallies of how many times each scheduling method was found in the top performing group for each performance variable. The tallies are broken down by disruption type (left column; none, frequent-short, and infrequent-long) and variability level (right column; none and some).

Table 4.14: Relative Top Rankings (Scheduling Methods)

DIS	VAR	EXEC	OPT	SLK	LFT	RSO	LSC	DCF	BCP
none	none	FRN	9	7	7	1	0	7	7
		FRW	2	0	0	1	0	0	0
		NRN	1	0	1	0	0	1	7
		NRW	2	0	0	1	0	0	0
	some	FRN	7	6	6	1	1	2	2
		FRW	3	6	6	5	6	3	0
		NRN	1	1	6	1	0	3	0
		NRW	0	2	6	4	6	3	2
frequent-short	none	FRN	7	1	5	2	1	9	8
		FRW	2	4	4	7	4	3	6
		NRN	1	4	5	1	1	7	6
		NRW	8	0	4	7	4	4	6
	some	FRN	5	4	6	1	1	3	5
		FRW	1	2	6	4	5	3	0
		NRN	0	4	2	1	2	4	5
		NRW	1	2	4	5	4	3	2
Infrequent-long	none	FRN	8	1	5	2	1	5	8
		FRW	1	5	3	6	0	3	7
		NRN	0	5	6	1	1	3	8
		NRW	2	7	7	7	0	4	6
	some	FRN	6	3	5	2	1	3	8
		FRW	5	4	5	4	5	3	7
		NRN	1	2	7	1	1	3	6
		NRW	1	2	6	5	6	3	2

A more detailed breakdown of the multiple comparison rank data is shown in Table 4.15, Summary of Multiple Comparisons (Scheduling by Execution). For each variable, the table indicates the ability of the multiple comparison procedure to discriminate between individual methods (Discriminate Ability). Numbers in the columns represent the number of times (out of the total comparisons made) that the methods were separated into 1, 2-3, 4-5, or 6-7 distinct groups. A high tally of the numbers toward the low end indicates a weak ability to discriminate between the scheduling methods (a large number of comparisons which were unable to discriminate). Higher counts in the high end indicate a much stronger ability to discriminate between scheduling methods.

Table 4.15: Summary of Multiple Comparisons (Scheduling by Execution)

	Discrim. Ability (24)				Rank				Rank Diff	
Var	1	2-3	4-5	6-7	Top 2	Ratio	Bottom 2	Ratio	var	dis
ADUR	0	0	16	8	OPT RSO	47/48	BCP DCF	48/48	2/12	2/8
RDUR	3	7	11	3	DCF BCP	41/42	OPT RSO	31/42	4/12	2/8
ANPV	12	1	7	4	LFT OPT	19/24	LSC DCF	21/24	0/12	4/8
RNPV	14	4	3	3	DCF BCP	16/20	RSO LSC	17/20	0/12	3/8
WADE	12	4	4	4	OPT DCF	12/24	RSO LSC	24/24	2/12	3/8
WADL	3	11	9	1	LSC BCP DCF	37/42	OPT RSO	26/24	7/12	6/8
WADC	2	13	7	2	DCF BCP	27/44	RSO LSC	33/24	5/12	4/8
POIC	2	8	14	0	LFT BCP RSO	29/44	RSO LSC	24/44	6/12	7/8
POIR	2	7	15	0	LFT BCP RSO	29/44	RSO LSC	24/44	6/12	7/8
POOC	2	13	9	0	BCP RSO LFT	30/44	RSO LSC	24/44	5/12	6/8
POOR	2	13	9	0	BCP RSO LFT	30/44	RSO LSC	24/44	5/12	6/8

The "Top 2" and "Bottom 2" columns indicate which specific methods are found most often in the top (or bottom) two positions in the rankings. Membership in the top (bottom) two rank positions is tallied, and the top two scheduling methods (three in the event of a tie for second place) are listed along with the total number of times they are found in the top (bottom) two positions. This information indicates the relative superiority (inferiority) and consistency of performance of the scheduling methods. A high count (ratio) indicates that the top (bottom) two methods were found in the top (bottom) two positions for many individual comparisons. Complete results are presented in Appendix G, Nonparametric Comparisons.

The "Rank Differences" columns indicate the number of times that the rank order performance between multiple comparisons (Appendix G) differed. For each variable, the rank performance lists were compared within each combination of treatments and factors. If the ranked lists could not be made equal across variability (some or none), or if any one of the ranked lists could not be made identical to the others across disruption (none, frequent, or infrequent), the comparison was scored as a "difference." If ranked lists being compared could be made identical, by shifting equivalent methods within their significant difference bands, then the lists were considered to be "not different." The differences were tallied in tables contained in Appendix H, Differences in Ranked Performance. If the ranked lists differed significantly, then this would support the proposition that the relative performance of the scheduling methods were sensitive to variability (or disruption, respectively). A somewhat arbitrary rule was developed to classify the dependence of the variable upon the factor. For any individual variable, if greater than 75% of the cases show a difference, then it is inferred that the relative rank performance is highly dependent upon the factor. Strong dependence is inferred for between 50% and 75% of cases, and moderate dependence for 25% to 50%. No or weak dependence is inferred if fewer than 25% of cases exhibit different relative rank performance order. This arbitrary rule is used to simplify interpretation of results.

Traditional Measures. For the ADUR variable, a pattern is observed across all treatment-factor combinations. The RSO and OPT methods are clearly superior, and the DCF and BCP methods are clearly inferior. RSO and OPT are ranked either first or second in 47 of the 48 cases, and BCP and DCF are ranked sixth and seventh in 48 of 48 cases. LSC, LFT, and SLK (mainly in that order) fall into the middle. The rank sum comparison method showed a strong ability to discriminate between scheduling methods, separating the seven methods into five or six statistically significantly different groups in most cases. This provides strong evidence that performance on ADUR is dependent upon the scheduling method used. As the pattern is consistent across all levels of variability and disruption, no evidence is provided that relative schedule performance on ADUR is dependent upon these factors. In addition, the number of cases where the relative rankings differed (2/12 for variability, and 2/8 for disruption) were too low to support this proposition.

This ability to discriminate is reduced sharply for the RDUR measure. In many cases, the ranking procedure is only able to separate the methods into three groups (or less). Even in cases where the methods can be differentiated into five or more groups, there is overlap between members of the different groups. This is due in large part to the narrow range of values for RDUR (vice ADUR), as well as a lack of consistency in the performance of the methods. In three striking examples, the rank sums were exactly equal. When either Full Reservation or Waiting conditions were present, and there was no variability and no disruptions, the ADUR was exactly equal to SDUR; and RDUR was therefore unity. If, however, the execution method is changed to No Reservation-No Waiting (NRN), this allows individual tasks to seize resources out of order. When this happens, the schedule effectively disrupts itself and differences in performance become apparent. In total, this provides only moderate evidence that performance on RDUR is dependent on the scheduling method.

An additional phenomenon is observed in the ranked performance order under differing execution protocols for RDUR. At the bottom end of the performance ranking, separate patterns are observed between FRN/NRN and FRW/NRW. The presence or absence of the Waiting discipline changes which scheduling methods perform worst. Under a No Waiting system, OPT and RSO are usually last (19 out of 22 instances). Under a Waiting system, OPT improves slightly and LSC takes it's place (RSO and LSC in last two places; 17 out of 20 cases). This evidence suggests that the relative performance of the scheduling methods is sensitive to the execution method.

The most striking observation from an analysis of the ADUR and RDUR scheduling method comparisons is that the rank order is almost completely reversed between the two measures. Where RSO and OPT are the highest performing schedules on ADUR, they are poor performers on RDUR. Similarly, DCF and BCP perform last on ADUR but score very highly on RDUR, filling the top two positions 41 out of 42 times. LSC, LFT, and SLK continue to fill the middle positions on the rank list. This finding suggests that scheduling methods that result in shorter SDUR may also achieve shorter ADUR, but much larger (proportionally) differences between ADUR and SDUR. RSO and OPT deliver shorter actual durations, but promise scheduled durations much shorter than they can deliver. BCP and DCF promise and deliver longer durations, but they are more able to meet those promises. This suggests the existence of a trade-off between duration and the ability to meet schedule. Two feasible schedules of dissimilar duration may provide countervailing ability to meet their respective scheduled durations. No clear pattern exists across and between the variability and disruption levels; indicating that the evidence is unable to suggest that relative scheduling performance on RDUR is dependent upon these factors. This lack of support is reflected in the number of cases

where ranked lists differ (4/12 for variability and 2 out of 12 for disruption). The variability score (4/12) indicates a "moderate" level of dependence.

A similar phenomenon is observed between ANPV and RNPV; however, as predicted in section 4.2.4 (A Note About the Sensitivity of NPV to rt), difficulty is encountered in establishing significant differences between the performance of the competing methods. Whenever variability is present, differences are not large enough between the scheduling methods to be detectable for both the ANPV and RNPV measures (all methods ranked in the same group). This is seen in the low overall significance of the comparisons, and the inability of the comparison to differentiate between scheduling methods. In the majority of comparisons, the test was unable to separate the ranked performance into more than 1 group (all methods were equal). When variability is present, there is no evidence that performance on ANPV is dependent upon the scheduling method used.

When variability is "none," however, some discriminatory power exists and patterns emerge. Including only those 12 cases, 11 of the comparisons separate the methods into at least 4 groups. This provides strong evidence that performance on ANPV is dependent upon scheduling method when variability is absent (or perhaps low). This phenomenon also suggests the relative performance of the scheduling methods is dependent on the variability level. The rank order pattern is consistent across the disruption levels. This suggests that there is no evidence that the relative scheduling method performance is dependent upon the disruption level.

Also similar to RDUR, the execution method affects the ability to discriminate between scheduling methods for RNPV. When a Waiting system is used (FRW and NRW), and Disruption and Variability are none, ANPV is equal to SNPV and RNPV becomes unity. When activities are allowed to seize available resources ahead of schedule, however (No Waiting), differences in ANPV are possible and the performance of the scheduling methods can be differentiated. Patterns are similar between ANPV and RNPV (but with different methods). Under no variability, discriminatory power exists and this provides evidence that the RNPV performance is dependent upon scheduling method. When variability is present, the evidence fails to support this conclusion. This, in turn, suggests that the relative performance of the scheduling methods is dependent upon the variability level. The pattern is consistent across all levels of disruption, suggesting that the relative scheduling performance is not dependent upon disruption. This lack of evidence is clear from an inspection of the relative rank differences (0 out of 12 for relative differences due to variability). Some evidence suggests that the relative performance of scheduling methods on ANPV could be moderately dependent upon disruption type, however. The count of cases where the relative ranked performance differed (4 out of 8) indicates a moderate level of dependence.

In general, for ANPV the best performing methods are OPT and LFT when the execution method used is FRN, FRW, and NRW. Under NRN, the performance of OPT drops and BCP replaces it in the first or second ranking. At the other end of the spectrum, LSC and DCF are the poorest performers under FRN, FRW, and NRW. Under NRN, the performance of DCF improves, and RSO replaces it at the bottom of the rankings. When either a Full Reservation system or a Waiting system are in effect, the ranked performance of the various scheduling methods follow a pattern. When neither a Reservation system nor a Waiting system is used, the ranked performance of the various scheduling methods follows a different pattern. This phenomenon suggests that the relative performance of the scheduling methods is sensitive to the execution method used.

The ranked performance of the scheduling methods on RNPV differs significantly from the ranked performance of ANPV. Unlike the phenomenon observed between ADUR and RDUR, the rankings are not necessarily reversed. For RNPV (when variability is absent and differences are detectable), patterns in ranked performance are observed, but not to the same consistency as noted previously for ADUR, RDUR, and ANPV. Generally, DCF and BCP occupy the top two rank positions (16 out of 20 cases), and RSO and LSC occupy the two bottom rank positions (17 out of 20 cases). Exceptions are due to the movement of OPT (2 out of 20 top and 2 out of 20 bottom), SLK (1 out of 20 top), and LFT (1 out of 20 bottom). The cases where the relative ranked performance differed indicated no support for a relative dependence on variability (0 out of 12 cases). Moderate relative dependence is indicated for disruption type, with 3 out of 8 cases being different.

Stability Measures. One interesting overall result is noted regarding the performance of the RSO scheduling method on the resource profile offset measures (POOC, POOR, POIC, and POIR). RSO consistently places both in the "Top 2" and the "Bottom 2" categories. This is explained by an examination of the specific scheduling method performance by execution method tables in Appendix G. First, inability to discriminate creates somewhat broad categories at both the top and bottom of the rankings. Second, many of the other scheduling methods do not follow consistent or distinct patterns in their placement on the rankings. Against this backdrop, the RSO method ranks very highly when combined with the FRN and NRN execution methods. RSO ranks very low when applied under the FRW and NRW execution disciplines.

This can be explained by the nature of the RSO method. RSO involves the right-shifting of non-critical tasks until the schedule contains no slack. Under a "no waiting" discipline (FRN and NRN), these tasks would be performed ahead of schedule, creating potential instability. Conversely, under a "waiting" discipline (FRW and NRW), tasks which may be technically feasible would wait until their right-shifted scheduled time, reducing the potential instability. This phenomenon would not be present for the other schedules, as (by default) tasks are commonly scheduled as soon as they become feasible, in effect creating a left-shifted schedule. This implies that either a waiting discipline or left-shifting may prevent some instability; however, under left-shifting, each task is subject to instability induced by the late finishes of predecessor tasks. This in turn may suggest an approach to protecting a schedule from instability by properly allocating schedule slack on the non-critical tasks. A strategy of using a waiting execution discipline in conjunction with scheduling tasks "in the middle" between right and left shifted options may reduce the exposure of the schedule to instability.

The ability to discriminate for the combined earliness-lateness variable WADC was marginally better than the individual WADE and WADL. One of the comparisons moved from the 1 group into the 2-3 groups category, and one moved from the 4-5 groups category into the 6-7 groups category. This was offset by one of the 4-5 groups comparisons moving down into the 2-3 groups category. This provides moderate evidence that WADC performance is dependent upon the scheduling method used. DCF and BCP were the top performers, occupying the top two ranks 27 out of 44 times. RSO and LSC were the bottom performers, ranked in the last two positions 33 out of 44 times. These rankings varied somewhat; LFT, SLK, and LSC rose to the top 14 times but no discernible pattern was present with respect to either variability or disruption. The rank orders were different under variability in 5 out of 12 cases; and different under disruption in 4 out of 8 cases, showing moderate levels of dependence upon these factors.

Rank patterns for the overuse stability measures POOC and POOR were virtually identical, with the exception of minor differences in the ability to discriminate. General patterns were similar to those for POIC and POIR, except for the specific rank performances of the various scheduling methods. Both variables showed a moderate to strong ability to discriminate, providing evidence that project performance on POOC and POOR was dependent upon the scheduling methods. BCP, RSO and LFT were high performers 30 out of 44 times, and RSO and LSC were the lowest performers 24 out of 44 times. The many deviations to this pattern showed only a moderate consistency between and across variability and disruption type. Evidence for the rank order of scheduling methods being dependent on variability and disruption was therefore mixed. Interestingly, RSO and LSC were consistently in the bottom two positions for FRN and NRN, but not for FRW or NRW. When the waiting discipline was in use, no clear pattern existed. This suggests at least a mild dependence of the rank scheduling performance upon the execution method. The rank differences indicate that the relative performance of the scheduling methods was moderately dependent upon variability level (5 out of 12 cases), and strongly dependent upon disruption level (6 out of 8 cases).

Summary. Overall, the multiple comparisons provide some evidence that the performance outcomes are dependent upon the scheduling methods. This evidence is strong for ADUR, and strong for ANPV and RNPV (when variability is "none") and strong for WADE (under no waiting). For the remaining variables, the ability to discriminate suggests a moderate amount of support for the hypothesis that performance outcomes are dependent upon scheduling method.

Evidence also indicates that in many cases, the relative rank performance of the scheduling methods is dependent on the level of variability present. Scheduling method performance shows a strong dependence on variability for WADL. Moderate dependence is apparent for RDUR, WADC, POIC, POIR, POOC, and POOR. The relative rank order performance of scheduling methods for ADUR, ANPV, RNPV, and WADE do not appear to exhibit a dependence on variability.

More evidence supports the premise that the relative rank performance of the scheduling methods is dependent on the type of disruptions present. Relative scheduling performance is highly dependent upon disruption type for POIC and POIR. Strong dependence is evident for WADL, POOC, and POOR. Moderate evidence exists for ANPV, RNPV, WADE, and WADC. No or slight evidence appears for the remaining variables (ADUR and RDUR).

Two additional weak inferences can be drawn as a result of an analysis of the rank performance comparisons of the scheduling methods. First, the stability measures and the traditional measures do indeed seem to react differently to the various treatment and factor combinations. The performance of the methods differs slightly between the traditional and stability measures. Second, it has been noted that for some of the variables, the rank performances differ across the different execution methods. This premise will be tested more directly in the next section.

4.5.2 Execution Method Performance by Scheduling Method

Multiple comparisons were performed on the rank performance of the execution methods within each scheduling method and combinations of disruption type and variability level. Summary results are given in Table 4.16, Summary of Multiple Comparisons (Execution by Scheduling). The format of the table used is similar to that of the previous table, with two exceptions: first, instead of tallying the Top (Bottom) 2 methods, the table reports membership in the first (last) position. The top (bottom) two vote-getting methods are still given as before, but a tally is recorded only for membership in the absolute first (last) position on the multiple comparison. Second, the discriminate ability is tallied for the individual number of groups found, instead of tallies within a range of values. Complete results are presented in Appendix G, Nonparametric Comparisons.

As before, the "Rank Differences" columns indicate the number of times that the rank order performance between multiple comparisons (Appendix G) differed. For each variable, the rank performance lists were compared within each combination of treatments and factors. If the ranked lists could not be made equal across variability (some or none), or if any one of the ranked lists could not be made identical to the others across disruption (none, frequent, or infrequent), the comparison was scored as a "difference." If ranked lists being compared could be made identical, by shifting equivalent methods within their significant difference bands, then the lists were considered to be "not different." The differences were tallied in tables contained in Appendix H, Differences in Ranked Performance. If the ranked lists differed significantly, then this would support the proposition that the relative performance of the execution methods were sensitive to variability (or disruption, respectively). Once again, for any individual variable, if greater than 75% of the cases show a difference, then it is inferred that the relative rank performance is highly dependent upon the factor. Strong dependence is inferred for between 50% and 75% of cases, and moderate dependence for 25% to 50%. No or weak dependence is inferred if fewer than 25% of cases exhibit different relative rank performance order.

Table 4.16: Summary of Multiple Comparisons (Execution by Scheduling)

	Discrim. Ability (42)				Rank				Rank Diff	
Var	1	2	3	4	Top 1	Ratio	Bottom 1	Ratio	var	Dis
ADUR	0	13	19	10	NRN FRN	41/42	FRW NRW	28/42	12/21	10/14
RDUR	0	13	19	10	NRN FRN	41/42	FRW NRW	28/42	12/21	10/14
ANPV	0	21	19	2	NRN FRN	32/42	FRW FRN	27/42	15/21	5/14
RNPV	0	22	18	2	NRN FRN	33/42	FRW FRN	27/42	15/21	5/14
WADE	0	15	27	0	FRW FRN	42/42	NRN	42/42	0/21	0/14
WADL	1	12	18	11	FRN NRN	39/41	NRN FRN	34/41	15/21	12/14
WADC	0	14	14	14	NRW FRN	34/42	NRN	42/42	0/21	5/14
POIC	0	12	20	10	FRN NRW	31/42	NRN FRW	36/42	3/21	13/14
POIR	0	12	21	9	FRN NRW	31/42	NRN FRW	36/42	3/21	13/14
POOC	0	17	16	9	NRW FRN	33/42	NRN FRN	35/42	4/21	13/14
POOR	0	16	18	8	NRW FRN	33/42	NRN FRN	35/42	4/21	13/14

Traditional Measures. The duration variables ADUR and RDUR display identical ranked performance for execution methods within each scheduling method. This is in contrast to the reversed rankings between ADUR and RDUR observed for the scheduling methods previously noted. The no waiting (FRN and NRN) protocols were clearly superior to the waiting (FRW and NRW) methods. This suggests that allowing activities to seize resources as soon as they are technically feasible may result in decreased total project duration. While the choice of a reservation system (full or none) is equivocal (21 for none and 20 for full), this implies that a less structured approach to execution may be superior in terms of duration than the more structured strategies. This clear ability to separate the performance of the execution methods supports the hypothesis that project performance is dependent upon the execution method used.

Some additional (but inconclusive) patterns emerged (see Appendix G). In every case, the rank performance order changes across either disruption, variability, or both. In one case (LSC), the rank performance of the execution methods appears to change across disruption level. In the remaining cases, the performance order changes arbitrarily. This is supported by consideration of the rank difference tallies. For both ADUR and RDUR, the relative rank order was dependent upon variability in 12 out of 21 cases; and dependent upon disruption type in 10 out of 14 cases. This suggests a strong level of dependence for both variables and for both factors.

The time value of money variables (ANPV and RNPV) also behaved very closely to each other. The performance rankings were identical, except that in two cases the groupings and significance levels were different. Ability to discriminate was strong (although weaker than for ADUR and RDUR), indicating that rank performance is dependent upon execution method. FRN and NRN were ranked in first place 32 out of 42 times (similar to ADUR and RDUR). Surprisingly, FRN was also ranked in last place 12 times. FRN was ranked first when variability was "none" and disruptions were equal to "none" or "freq" (7 out of 14 times). FRN was not ranked last under these conditions. When disruption was "infq," FRN was not ranked first at all but was ranked last 11 out of 14 times (regardless of variability). This indicates that relative ranked performance depends in some part upon variability, and to a larger degree on disruption type. Similarly, NRN is ranked first when variability is "some" 17 times out of 25 (and never last), and only 8 times when variability is "none" (and ranked last 11 times out of 11). This suggests that for NRN, relative performance is dependent upon variability. In general, the relative rankings differed 15 out of 21 times under differing levels of variability, suggesting a strong dependence. The ordering was different 5 times out of 14 under varying disruption type, indicating a moderate level of dependence.

Stability Measures. WADE, WADL, and WADC do not behave in a cohesive manner. They each display at least a moderate ability to discriminate, indicating that performance is to some degree dependent upon execution method. This ability is weakest for WADL, and strongest for WADC. For WADE, the top performers were FRW and FRN, occupying the top rank 42 out of 42 times. In every case where FRN was the top performer, it's performance was statistically indistinguishable from that of NRW. NRN was the worst performer 42 out of 42 times. These results provide no evidence that relative rank performance is dependent upon either variability or disruption. This is also the case for the rank difference counts. For WADE, no differences were shown out of all cases for either variability or disruption.

For WADC, NRW or FRN were ranked first 34 out of 42 times, and NRN was ranked last 42 out of 42 times. When variability was none, and disruptions were none, FRN was ranked first 5 out of 7 times (NRW first 0 times). When variability was some, and disruptions were none, NRW was ranked first 7 out of 7 times (FRN first 0 times). This would suggest that the relative performance of the execution methods are sensitive to variability level; at least when disruptions are none. When disruptions were frequent, FRN was ranked first 10 out of 14 times (NRW first 0). When disruptions were infrequent, NRW was ranked first 12 out of 14 times (FRN first 0). The striking difference between relative rank order between the infrequent and frequent disruption levels suggests that the relative rank performance of the execution methods is dependent upon disruption. The rank difference counts indicate that while relative perforamcne is not dependent upon variability (0 out of 21 cases), at least a moderate level of dependence is indicated for disruption level (5 out of 14 cases).

The rank performance of the execution methods on POOC and POOR are very similar, with some minor differences in the ability to discriminate. While the actual ranks are identical, in two cases there was more discriminatory power for POOR. Overall, the ability to discriminate was fairly strong, suggesting that project performance is dependent upon execution method. When disruptions are none, and variability is none, FRN is ranked first 5 out of 7 times (NRW first 0). When variability is some, NRW is ranked first 7 times out of 7 (FRN first 0). This suggests that (at least when disruptions are none) relative ranked performance is dependent upon variability level. Again, as in the case of POIC and POIR, this is not supported by the rank difference counts (4 out of 21). When disruptions are frequent, FRN is ranked first 10 out of 14 times (NRW 2). When disruptions are infrequent, NRW is ranked first 9 of 14 times (FRN 0). This suggests that relative rank performance is dependent upon disruption level. This receives strong support from the rank different counts. POOC and POOR show that when disruption type varies, the relative rank performance order differs in 13 out of 14 cases. This suggests a high level of dependence.

Summary. Overall, the multiple comparisons provide some evidence that the performance outcomes are dependent upon the execution methods. This evidence is strong for the duration variables (ADUR and RDUR), and weak or equivocal for ANPV and RNPV. For the stability variables, the ability to discriminate is strong in all cases except for the earliness variable WADE (which shows a moderate or equivocal level of support).

Evidence also indicates that in many cases, the relative rank performance of the execution methods is dependent on the level of variability present. This evidence is strong under ADUR, RDUR, ANPV, RNPV, and WADL. Weak or no dependence is apparent for the remaining variables (WADE, WADC, POIC, POIR, POOC, and POOR).

Stronger evidence supports the premise that the rank performance of the execution methods is dependent on the type of disruptions present. A high degree of dependence is observed for WADL, POIC, POIR, POOC, and POOR. Strong dependence is inferred for

ADUR, and RDUR. ANPV, RNPV, and WADC each show moderate levels of dependence on disruption type. Weak or no dependence is observed only for WADE.

One additional inference is supported as a result of an analysis of the rank performance comparisons of the execution methods. As previously noted for the scheduling method comparisons, the stability measures and the traditional measures do indeed seem to react differently to the various treatment and factor combinations. The performance of the methods differs slightly between the traditional and stability measures.

4.6 Tests of Hypotheses

The data generated by the experiment and the subsequent analysis of that data has provided information relevant to the original research hypotheses. The following sections will address each hypothesis in turn, and propose conclusions about them.

4.6.1 H1: Stability Measures vs. Traditional Measures

The first hypothesis concerns the relationships between the traditional measures and the stability measures. Specifically, hypothesis 1 states "Stability measures are positively correlated with traditional measures." This hypothesis has been addressed in section 4.4.1, Biserial Correlations. In general, we find that while the data supports the hypothesis, several noteworthy characteristics are also observed.

First, the traditional measures clearly measure two distinct concepts: duration and value. The raw values ADUR-ANPV and the ratio variables RDUR-RNPV show strong correlations. When adjusted to take into account the project size (through the use of the ratio variables), this correlation is negative.

Second, the stability measures divide into two distinct groups, the offset measures and the deviation measures. Idleness and overuse appear to behave similarly; they covary both in raw and ratio form. The activity deviation measures seem to consist of a trivial earliness component, and a much more prevalent lateness component.

Third, between and among the traditional and stability measures, two phenomena seem to suggest that the two types of measures indeed constitute different classes of project performance characteristics. First, while the traditional and stability measures exhibit strong covariation in some areas, in others the relationships are weak. Second, the overall correlations between the types of measures are lower than those within each type of measure, indicating that perhaps there are differing degrees of commonality or overlap between and among the types of measures.

Overall, it can be said that duration, stability, and value are distinct aspects of project performance; and that these aspects are related to each other. In general, higher stability is associated with higher NPV and shorter (better) duration.

4.6.2 H2: Project Performance by Planning Method

Hypothesis 2 posits that "Project performance is significantly affected by the planning method used." Evidence relevant to this hypothesis was presented in section 4.5.1, Scheduling Method Performance by Execution Method. Multiple comparisons were used to distinguish between the performance of the scheduling methods under all combinations of the remaining treatments and factors. For a given test, if the performance between the scheduling methods was found to be significantly different, this would support the hypothesis. The dependence of a variable upon the planning method used is represented by the ability of the multiple comparison method to discriminate between them based on ranked performance against that variable.

"Highly dependent" cases were characterized by variables which had an ability to discriminate into 4 or more (out of 7) performance groups in more than 75% of all cases (18 out of 24), and fewer than 10% of the cases where performance was unable to be separated (3 out of 24). "Strongly dependent" cases were characterized by variables which had an ability to discriminate into 4 or more (out of 7) performance groups in more than 50% of all cases (12 out of 24), and fewer than 25% of the cases where performance was unable to be separated (6 out of 24). "Moderately dependent" cases were characterized by variables where fewer than 25% of all cases were unable to be discriminated (6 out of 24).

While the hypothesis was generally supported by the data, the variables responded differently to the influence of the scheduling methods. ADUR performance was highly dependent upon scheduling method. RDUR, POIC, and POIR were strongly dependent, and WADL, WADC, POOC, and POOR were moderately dependent. ANPV, RNPV, and WADE were only moderately dependent upon scheduling method; and only under certain circumstances.

4.6.3 H3: Project Performance by Execution Method

Hypothesis 3 posits that "Project performance is significantly affected by the execution method used." Evidence relevant to this hypothesis was presented in section 4.5.2, Execution Method Performance by Scheduling Method. Multiple comparisons were used to distinguish between the performance of the execution methods under all combinations of the remaining treatments and factors. For a given test, if the performance between the execution methods was found to be significantly different, this would support the hypothesis. The dependence of a variable upon the execution method used is represented by the ability of the multiple comparison method to discriminate between them based on ranked performance against that variable.

"Highly dependent" cases were characterized by variables which had an ability to discriminate into 3 or more (out of 4) performance groups in more than 75% of all cases (32 out of 42), and fewer than 10% of the cases where performance was unable to be separated (4 out of 42). "Strongly dependent" cases were characterized by variables which had an ability to discriminate into 3 or more (out of 4) performance groups in more than 50% of all cases (21 out of 42), and fewer than 25% of the cases where performance was unable to be separated (11 out of 42). "Moderately dependent" cases were characterized by variables where fewer than 25% of all cases were unable to be discriminated (11 out of 42).

This hypothesis was consistently and strongly supported by the data. All variables except for RDUR were strongly dependent upon execution method. RNPV was moderately dependent upon the choice of execution method, and missed being characterized as strongly dependent by only 1 case out of 42.

4.6.4 H4a: Relative Planning Performance by Variability

This hypothesis posits that "relative planning method performance is significantly affected by the presence of activity duration variability." Evidence to support this hypothesis would take the form of differences in rank order performance of the planning methods across the levels of the variability factor, within combinations of the other treatments and factors.

The evidence is presented in (previously discussed) Table 4.15, through an examination of the number of cases where the relative rank performance order was significantly different. Strong evidence in support of the hypothesis was indicated for the variable WADL. Only moderate evidence was seen for RDUR, WADC, POIC, POIR, POOC, and POOR. Weak or no support was indicated for ADUR, ANPV, RNPV, and WADE. It would seem that the overall evidence in support of this hypothesis is equivocal and variable-specific.

4.6.5 H4b: Relative Planning Performance by Disruption

This hypothesis posits that "relative planning method performance is significantly affected by the type of resource disruption." Evidence to support this hypothesis would take the form of differences in rank order performance of the planning methods across the types of the disruption factor, within combinations of the other treatments and factors.

The evidence is presented in (previously discussed) Table 4.15, through an examination of the number of cases where the relative rank performance order was significantly different. Strong evidence in support of the hypothesis (highly dependent or strong dependence) was indicated for the variable WADL, POIC, and POIR. Only moderate evidence was seen for ANPV, RNPV, WADE, and WADC. Weak or no support was indicated for ADUR, and RDUR. It would seem that the overall evidence in support of this hypothesis is moderately strong and general in nature- with the exception of the duration variables.

4.6.6 H4c: Relative Execution Performance by Variability

This hypothesis posits that "relative execution method performance is significantly affected by the presence of activity duration variability." Evidence to support this hypothesis would take the form of differences in rank order performance of the execution methods across the levels of the variability factor, within combinations of the other treatments and factors.

The evidence is presented in (previously discussed) Table 4.16, through an examination of the number of cases where the relative rank performance order was significantly different. Strong evidence in support of the hypothesis was indicated for the variable ADUR, RDUR, ANPV, RNPV, and WADL. Weak or no support was indicated for the remainder of the stability variables. The overall evidence in support of this hypothesis is strong for the traditional variables of duration and value; but nonexistent for the stability measures.

4.6.7 H4d: Relative Execution Performance by Disruption

This hypothesis states that "relative execution method performance is significantly affected by the type of resource disruption." Evidence to support this hypothesis would take the form of differences in rank order performance of the planning methods across the types of the disruption factor, within combinations of the other treatments and factors.

The evidence is presented in (previously discussed) Table 4.16, through an examination of the number of cases where the relative rank performance order was significantly different. Strong evidence in support of the hypothesis (highly dependent or strong dependence) was indicated for the variables ADUR, RDUR, WADL, POIC, POIR, POOC, and POOR. Moderate evidence was seen for ANPV, RNPV, and WADC. Weak or no support was indicated only for WADE. It would seem that the overall evidence in support of this hypothesis is strong and general in nature, across variables of all types.

4.7 Summary of Data Analysis

A summary of the analysis of the multiple comparison tables with respect to the research hypotheses is presented below in Table 4.17, Summary of Multiple Comparisons (Overall). For each variable, inferences are drawn with respect to the level of support provided to hypotheses 2, 3, and 4 as previously discussed in sections 4.4 through 4.6.

Additionally, evidence was found to support H1; but while the traditional variables and the stability variables covaried as expected, the relationships were not clear. The stability variables seemed to be measuring something "intrinsically different" from either duration or value. The implications of this evidence will be discussed in Chapter 5, *Conclusions and Recommendations.*

Table 4.17: Summary of Multiple Comparisons (Overall)

	H2	H3	H4a	H4b	H4c	H4d
ADUR	++	+	-	-	+	+
RDUR	+	+	~	-	+	+
ANPV	-[1]	+	-	~	+	~
RNPV	-[1]	~	-	~	+	~
WADE	-[2]	+	-	~	-	-
WADL	~	+	+	+	+	++
WADC	~	+	~	~	-	~
POIC	+	+	~	++	-	++
POIR	+	+	~	++	-	++
POOC	~	+	~	+	-	++
POOR	~	+	~	+	-	++
Support: ++ very strong + high ~moderate - weak or none						

[1] supported under variability = none [2] supported under no waiting

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This research investigated the effects of variability and disruption upon the management of projects. The purpose of this effort was to explore the usefulness of various techniques in reducing the negative effects of variability and disruption. A project consists of a series of tasks or activities that must be performed by resources, in a specific order, to achieve a desired result. Variability refers to uncertainty in the project task times. Disruptions to the project consist of the unplanned unavailability of resources. When a project is subject to variability and disruption, the project may begin to take longer, cost more, and achieve less than planned. These negative effects are very important, and the issue has received much study by academics and practitioners alike.

Coping mechanisms to avoid the consequences of variability and disruption can generally take two forms. The first is to schedule or plan the resources and activities carefully in order to make the project less sensitive. The second is to execute the schedule in such a way as to mitigate the damage done as it occurs. It is proposed that some scheduling techniques generate plans that are less sensitive to variability and disruption (more stable) than others. In addition, it is proposed that some execution techniques are more effective at absorbing or dampening the effects of disruption than others. The stability of the project may come at the expense of other desirable project outcomes, however. A more stable project may take longer to complete, or be more costly. These issues have not yet been investigated in any detail. This research has addressed and started to resolve some of the fundamental questions and problems surrounding the performance and stability of projects, subject to variability and disruptions, under a variety of conditions.

5.2 Research Questions

Several questions were asked at the beginning of this effort, and they have been addressed through the collection and analysis of the data with respect to the hypotheses (specific hypotheses addressed in Chapter 4, *Results and Analysis*). The questions are presented here again, and answered.

What is the nature of the tradeoff (if one exists) between schedule stability and schedule performance with respect to the traditional measures in the project?

This research question was most directly associated with hypothesis H1, "Stability measures are positively correlated with traditional measures." Evidence in support of this hypothesis was presented and discussed in section 4.4.1, *Biserial Correlation*, and summarized in section 4.6.1, *H1: Stability Measures vs. Traditional Measures.*

The evidence indicated that while the stability measures were related to the traditional measures, these relationships were complex. Duration and Net Present Value were negatively correlated when correcting for schedule differences. Among the stability measures, the task deviation measures and resource deviation measures were correlated strongly within themselves, and somewhat less so between them. Activity earliness was an exception to this, not being correlated strongly with any of the other stability measures. Between the stability and traditional measures, several additional relationships were noted. Lateness measures were inversely related to RNPV, and positively related to RDUR. The resource deviation measures were positively related to ADUR, and less so with RDUR. In conjunction with the biserial scatterplots (Appendix E) this information indicates that the stability, duration, and value variables capture distinct but related concepts. The duration and stability variables covary, and are inversely related to value. The evidence also suggests that stability is somewhat multi-dimensional.

How are planning methods affected by variability and disruption?

This research question was most directly associated with hypothesis H2, "Project performance is significantly affected by the planning method used." Evidence in support of this hypothesis was presented and discussed in sections 4.2.2, *Formal Test Results*, 4.3.2, *Treatment Cell Means*, 4.5.1, *Scheduling Method Performance by Execution Method*, and 4.6.2, *H2: Project Performance by Planning Method.*

While the hypothesis was generally supported by the data, the variables responded differently to the influence of the scheduling methods. ADUR performance was highly dependent upon scheduling method. RDUR, POIC, and POIR were strongly dependent, and WADL, WADC, POOC, and POOR were moderately dependent. ANPV, RNPV, and WADE were only moderately dependent upon scheduling method; and only under certain circumstances. The value measures were dependent upon scheduling method when variability was "none." When variability is present, the effect of scheduling method on NPV was overwhelmed by the "background" variance. WADE was dependent only under "no waiting" (as would be expected- earliness would be prevented under a waiting discipline). Project performance on duration and resource idleness is dependent upon scheduling method used, and performance on other stability measures is weakly dependent.

How are execution methods affected by variability and disruption?

This research question was most directly associated with hypothesis H3, "Project performance is significantly affected by the execution method used." Evidence in support of this hypothesis was presented and discussed in sections 4.2.2, *Formal Test Results*, 4.3.2, *Treatment Cell Means*, 4.5.2, *Execution Method Performance by Scheduling Method*, and 4.6.3, *H3: Project Performance by Execution Method.*

This hypothesis was consistently and strongly supported by the data. All variables except for RDUR were strongly dependent upon execution method. RNPV was moderately dependent upon the choice of execution method, and missed being characterized as strongly dependent by only 1 case out of 42. Project performance on virtually all measures was dependent upon choice of execution method; perhaps more so than by choice of scheduling method.

Are schedules developed by certain heuristics/scheduling rules more sensitive to variability?

This research question was most directly associated with hypothesis H4a, "Relative planning method performance is significantly affected by the presence of activity duration variability." Evidence in support of this hypothesis was presented and discussed in sections 4.3.2, *Treatment Cell Means*, 4.5.1, *Scheduling Method Performance by Execution Method*, and 4.6.4, *H4a: Relative Planning Performance by Variability.*

Strong evidence in support of the hypothesis was indicated for the variable WADL. Only moderate evidence was seen for RDUR, WADC, POIC, POIR, POOC, and POOR.

Weak or no support was indicated for ADUR, ANPV, RNPV, and WADE. It would seem that the overall evidence in support of this hypothesis is equivocal and variable-specific. The relative performance of the scheduling methods is apparently not dependent upon task time variability.

Are schedules developed by certain heuristics/scheduling rules more sensitive to disruption?

This research question was most directly associated with hypothesis H4b, "Relative planning method performance is significantly affected by the nature of the resource disruptions." Evidence in support of this hypothesis was presented and discussed in sections 4.3.2, *Treatment Cell Means*, 4.5.1, *Scheduling Method Performance by Execution Method*, and 4.6.5, *H4b: Relative Planning Performance by Disruption.*

Strong evidence in support of the hypothesis (highly dependent or strong dependence) was indicated for the variable WADL, POIC, and POIR. Only moderate evidence was seen for ANPV, RNPV, WADE, and WADC. Weak or no support was indicated for ADUR, and RDUR. It would seem that the overall evidence in support of this hypothesis is moderately strong and general in nature- with the exception of the duration variables. The relative performance of the scheduling methods on value and stability is dependent upon disruption type, but not duration.

Do certain execution techniques help minimize the effects of variability?

This research question was most directly associated with hypothesis H4c, "Relative execution method performance is significantly affected by the presence of activity duration variability." Evidence in support of this hypothesis was presented and discussed in sections 4.3.2, *Treatment Cell Means*, 4.5.2, *Execution Method Performance by Scheduling Method*, and 4.6.6, *H4c: Relative Execution Performance by Variability.*

Strong evidence in support of the hypothesis was indicated for the variable ADUR, RDUR, ANPV, RNPV, and WADL. Weak or no support was indicated for the remainder of the stability variables. The overall evidence in support of this hypothesis is strong for the traditional variables of duration and value; but nonexistent for the stability measures. The relative performance of the execution techniques on duration and value is dependent upon variability, but not stability.

Do certain execution techniques help minimize the effects of disruption?

This research question was most directly associated with hypothesis H4d, "Relative execution method performance is significantly affected by the nature of the resource disruptions." Evidence in support of this hypothesis was presented and discussed in sections 4.3.2, *Treatment Cell Means*, 4.5.2, *Execution Method Performance by Scheduling Method*, and 4.6.7, *H4d: Relative Execution Performance by Disruption.*

Strong evidence in support of the hypothesis (highly dependent or strong dependence) was indicated for the variables ADUR, RDUR, WADL, POIC, POIR, POOC, and POOR. Moderate evidence was seen for ANPV, RNPV, and WADC. Weak or no support was indicated only for WADE.. It would seem that the overall evidence in support of this hypothesis is strong and general in nature, across variables of all types. The relative performance of the execution methods against duration, value, and stability measures is dependent upon disruption type.

5.3 Additional Notes on the Effects of Variability and Disruption

It has been established that project duration and stability are degraded by the presence of variability and disruption. What has not been presented in any detail is how significant this degradation may be. It would be instructive to examine the percent changes in key variables between the no variability and some variability cases, and between the three disruption types.

ADUR is a uni-dimensional variable (a simple measure of time). A percent change between two values would be calculated as the ratio of the differences over the initial value. To calculate the percent change between "none" and "some" variability, ADUR under "some" was subtracted from ADUR under "none" to get a difference. This difference was divided by ADUR under "none" and multiplied by 100 to calculate a percent change in ADUR. A similar calculation was performed to get the percent change between the three disruption types.

WADC is already a multi-dimensional (ratio) variable. From Chapter 3, WADC is calculated as the ratio of earliness and lateness to the total time scheduled. WADC already represents a percentage; the percentage of lateness and earliness out of total time. To calculate a WADC "percent change" would be problematic in cases where the initial value in the ratio were small (or zero). The percent change would approach infinity as the initial value approached zero. As WADC under "none" variability and "none" disruption was zero, and as WADC is already a ratio variable, the percent change for WADC was calculated as the difference between the two values. The percent changes between the three different types of disruption were calculated in the same way.

The percent change for POOR was calculated in the same way as WADC. POOR is also a ratio variable; the ratio of resource overuse to scheduled resource use. POOR is already a percentage; the percentage of resource overuse out of total use.

Table 5.1: Percent Change (variability none-some)

		ADUR	avg	WADC	avg	POOR	avg
OPT	FRN	-1.9	-2.2	-29.8	-28.3	-5.3	-4.9
	FRW	-2.9		-31.2		-5.5	
	NRN	-1.3		-23.5		-3.8	
	NRW	-2.7		-28.5		-4.9	
SLK	FRN	-1.6	-1.9	-29.8	-22.9	-5.3	-5.1
	FRW	-2.7		-31.7		-5.6	
	NRN	-1.1		-27.5		-4.6	
	NRW	-2.2		-27.6		-5.0	
LFT	FRN	-1.5	-3.8	-28.2	-27.8	-5.1	-4.9
	FRW	-2.6		-30.6		-5.4	
	NRN	-9.0		-24.9		-4.2	
	NRW	-2.2		-27.3		-4.9	
RSO	FRN	-2.1	-3.8	-26.1	-25.8	-2.9	-3.4
	FRW	-3.2		-31.4		-5.1	
	NRN	-1.3		-17.2		-1.3	
	NRW	-2.9		-28.4		-4.4	
LSC	FRN	-1.6	-2.1	-24.0	-25.9	-2.5	-3.4
	FRW	-2.8		-30.0		-5.0	
	NRN	-1.5		-23.8		-1.9	
	NRW	-2.6		-25.6		-4.3	
DCF	FRN	-1.1	-3.0	-28.0	-25.4	-5.9	-5.3
	FRW	-2.2		-28.5		-5.9	
	NRN	-7.2		-20.8		-4.4	
	NRW	-1.5		-24.4		-5.0	
BCP	FRN	-1.5	-2.9	-31.9	-30.2	-5.6	-5.3
	FRW	-2.6		-32.8		-5.8	
	NRN	-5.2		-28.0		-4.6	
	NRW	-2.1		-28.4		-5.1	

Table 5.1, Percent Change (variability some-none) presents the percent differences between the "none" variability and "some" variability cases. Cases were paired according to none and some variability along all other factors including scheduling

method, execution method, disruption type, project problem, and run number. Results were grouped by scheduling and execution method.

The results indicate that the presence of variability increases ADUR by 1.1 (DCF/FRN or SLK/NRN) to 9.0 (LFT/NRN) percent, with most values near 2.0 percent (median value 2.2; half of all values between 1.5 and 2.5). With respect to the scheduling and execution methods, two patterns emerge. First, LFT and RSO experience the greatest degradation in duration (3.8 percent). SLK appears least sensitive to variability, at 1.9 percent increase in ADUR. Second, for most scheduling methods (OPT, SLK, RSO, and LSC), the execution methods from least to most sensitive follow the order NRN-FRN-NRW-FRW. Rank order placement of the four methods follows waiting policy first, into the top two (no waiting) vs. bottom two (waiting) places. This implies that a "waiting" policy is more sensitive to variability in terms of overall project duration growth. Within the waiting policy, the reservation policy also seems to matter. Within each waiting policy, no reservation seems to provide better results than full reservation. A "reservation" policy also appears sensitive to variability, but the waiting policy has more of an effect than the reservation policy.

The exceptions to this execution method sensitivity pattern occur for scheduling methods LFT, DCF, and BCP. For each of these, the (least to worst) pattern is FRN-NRW-FRW-NRN. FRN is the least sensitive, and NRN is the most sensitive. NRN was the least sensitive (best choice) for OPT, SLK, RSO, LSC; and is here the worst choice. FRN, on the other hand, was the second best choice for OPT, SLK, RSO, and LSC and is the best choice here.

Overall, the implications for the decision maker are somewhat less than clear. The top two combinations are SLK-NRN and DCF-FRN. The best scheduling method is SLK. For most scheduling methods, the best execution method is NRN, but this is the worst choice for the others; where FRN is the best. This would suggest that selection of the scheduling and execution method combination is highly situational. However, the difference between the best combination and the 13th best combination (out of the 28 total) is only 1 percent. A general conclusion that may be reached here is that variability may not actually be that important a criteria to consider when selecting a scheduling and execution method combination to use when trying to minimize the degradation of actual duration.

A similar analysis can be performed for the two stability measures WADC and POOR. When variability is present (*vice* absent), WADC increases from 17.2 percent (RSO-NRN) to 32.8 percent (BCP-FRW). The median value is 28 percent, and half of all values range between 15 and 30 percent. The least amount of average increase (loss of stability) is experienced under the SLK scheduling method (average 22.9 percent), and the greatest amount of average increase occurs under BCP (30.2 percent). The "optimum" schedule (OPT) fared poorly (at 28.3%, in sixth place), while the right-shifted optimum (RSO) did fairly well (25.8%; third place). Overall performance (least to most degradation) was ordered SLK-DCF-RSO-LSC-LFT-OPT-BCP.

Performance degradation of the POOR stability measure under the scheduling methods follows a different pattern from WADC. Overall, when variability is present, the range of degradation runs from 1.3% (RSO-NRN) to 5.9% (DCF-FRW). The median value is 5.0%, and half of all values range between 4.3% and 5.3%. The "optimum" schedule (OPT) was placed third overall (4.9%) and the right-shifted optimum (RSO) was ranked first. Overall rank order was RSO-LSC-OPT-LFT-SLK-DCF-BCP.

With respect to the execution methods, patterns emerge. The dominant pattern in the increase in WADC from no variability to some variability is (least to most): NRN-NRW-FRN-FRW. This pattern holds for OPT, SLK, LFT, DCF, and BCP. This pattern suggests that the reservation policy is the dominant part of the execution method, with both "no reservation" execution methods being better than the methods with "full reservation" systems. The waiting policy appears to be less important; with "no waiting" giving better results than "waiting." LSC and RSO share a different pattern; NRN-FRN-NRW-FRW (least to most). For these scheduling methods, the waiting policy appears to be more important, with "no waiting" providing better results. The "no reservation" system also seems to be less sensitive to variability (increases in WADC) than the "full reservation" system under this pattern for LSC and RSO. This pattern was the same for both the WADC and POOR stability measures.

These findings support and extend the general finding that project performance, and the performance of the scheduling and execution methods, are affected by the presence of variability in the task times. Both overall duration (ADUR) and stability (WADC and POOR) are degraded under the presence of variability. While it appears that stability is affected more than duration, and the WADC measure is more affected than the POOR measure, direct comparisons cannot be made due to differences in the way the percent changes were calculated.

This degradation is worse for some scheduling and execution methods than others. While some patterns emerge and have been discussed, no clear conclusions can be drawn due to the strong interactions present between the scheduling and execution methods. An interesting observation can be made, however. Patterns in the sensitivity of the execution methods with respect to the reservation system and waiting policy were noted. These patterns were consistent within the stability degradation measures, and differed from the duration degradation measure. In either case, two patterns emerged. There existed a "dominant" pattern for the majority of scheduling methods, and a "secondary" pattern for the remainder of the scheduling methods. No rationale for this is offered at this time, and this phenomenon merits further investigation. It is posited that (currently unidentified) characteristics of the scheduling and execution methods may provide a more robust "fit" when used together. Further development of an appropriate "fit" model is warranted.

With respect to the disruption types, tables were constructed and are included in Appendix M, Degradation (Percent Change). Findings were similar to those for variability. One additional observation was that the degradation from infrequent/long disruptions was greater (3% greater for ADUR, 40% greater for WADC, and 3% greater for POOR) than the degradation from frequent/short disruptions. Patterns among and between the scheduling and execution methods were observed similar to those seen for the effect of variability.

5.4 Conclusions

Several conclusions can be drawn from the results just summarized. The stability, duration, and value variables capture distinct but related concepts. The duration and stability variables covary, and are inversely related to value. Stability may be somewhat multi-dimensional. Project performance on duration and resource idleness is dependent upon scheduling method used, and performance on other stability measures is weakly dependent. Performance on virtually all measures was dependent upon choice of execution method; perhaps more so than choice of scheduling method. The relative performance of the scheduling methods is apparently not dependent upon task time variability. The relative performance of the scheduling methods on value and stability (but not duration) is dependent upon disruption type. The relative performance of the execution techniques on duration and value is dependent upon variability, but performance on stability is not. The relative performance of the execution methods against duration, value, and stability measures is dependent upon disruption type. The theoretical and practical implications of these conclusions will now be discussed.

5.4.1 Theoretical

A review of the literature (Chapter 2, *Significant Prior Research*) established the position of this current effort with respect to previous research. Any results must therefore be considered in the larger context of the resource constrained, project scheduling problem (RCPSP). The research model was constructed to investigate a single problem, with multiple, constrained resources; solved heuristically to achieve multiple objectives, and with single mode resource activity functions. A benchmark set of well-established problems with known, optimal (for minimum duration) solutions was used, with specific problems selected to represent a broad spectrum of the most relevant problem characteristics. The experiment itself was designed to investigate the performance of various scheduling and execution techniques under varying conditions of task time variability and resource disruption. In this way, the study was firmly anchored to many previous studies on the performance of scheduling methods. It proposed a new heuristic (the BCP), and included previously recognized high performers against the traditional measures of duration and NPV. Research on the scheduling methods has been extensive; investigation into the role and performance of execution methods has been less detailed. This research extended and sought to validate the recent research; particularly the efforts of Partovi and Burton (1993) and Yang (1996).

With respect to the role of the scheduling and execution methods, current theory has emphasized the role of the scheduling methods in determining project outcomes. This has been challenged somewhat recently, and indeed, this current research supports the idea that the execution methods are at least (if not more) important than the scheduling techniques. Also, the relative performance of the scheduling methods with respect to project conditions (project characteristics and environmental characteristics) has been equivocal. Previous studies found no or weak influence from these characteristics on relative planning method performance. The current research found similar results with respect to the scheduling methods and the environmental characteristics of variability and disruption (the problem characteristics were not explicitly studied). However, evidence was found to suggest that the relative performance of the execution methods is dependent upon variability (for the duration measures) and disruption type (for both the duration and stability measures). These findings would suggest the potential to develop a "fit model" for the use of various execution methods. Certain environmental conditions may necessitate the use of one type of execution method over another. The influence of the project characteristics upon execution method may also be an important factor in the development of a "fit model;" but the current research does not address these factors.

In addition to validating and extending the previous research into scheduling and execution method performance, this effort opened a new avenue into the role of stability in projects. Evidence suggests that stability represents a distinct class of performance. Several metrics were developed and studied, and the findings support that the metrics could be developed and implemented. The stability measures exhibited behaviors that were both similar to and different from the traditional measures. However, the role of project stability in the management of projects has not yet been established.

5.4.2 Practical

Bearing in mind the issues surrounding the limitations of the model employed in the study, some of the theoretical conclusions imply practical consequences. First, while the importance of the scheduling method used to plan the project has historically been paramount, the contribution of execution policies has not been recognized. Perhaps the current emphasis on developing and using more sophisticated planning methods is misguided. Second, practitioners currently employ a host of metrics that can generally be categorized as related to either "cost, schedule, or performance (quality)" with an emphasis on total cost and total duration. Key schedule and cost milestones are established, and closely monitored. Great effort is sometimes taken to ensure that milestones are met. The assumption seems to be that if the milestones are met, the overall performance will follow. This research suggests that while intuitively appealing, the relationship between schedule conformance on the milestone level and performance at the overall project level might not be as straightforward as it might seem. Measures related to project stability may eventually fill the role of management to the naïve milestone technique. Finally, it has not been reported that significant time or effort is spent on trying to identify either project or environmental characteristics in order to improve decisions taken regarding project implementation. While this research has not challenged that practice with respect to the relative performance of the planning methods, evidence suggests that the relative performance of execution strategies may be affected by these characteristics. Conclusions in this area would be premature, as further research is needed.

5.5 Recommendations

As a result of the findings of this research, several recommendations can be made. The recommendations fall into two general categories: research recommendations and practical recommendations. They will be presented in that order in the following two sections.

5.5.1 Future Research

Several avenues of additional research should be pursued in order to capitalize on these initial results. This initial study was limited in it's generalizability (refer to section 3.7, *Limitations and Key Assumptions*), and additional research should be conducted to resolve this. Two major limitations were that only small and medium sized projects were used, and only in a single project environment. While useful for conducting an initial, exploratory study, these two conditions are somewhat unrealistic in practice. Extending the generalizability of the findings would require an investigation using larger projects, and more than one project being executed at the same time. Studies of this nature would broaden the application of the findings. The findings could change under these more realistic conditions.

The validity of the study was reduced by additional limitations. Validity questions surround the behavior of the model, and the role of the stability measures. The behavior of the model did not allow pre-emption of resources by higher priority tasks; reasonable perhaps in a single project environment but unreasonable in practice. Future research should include the use of pre-emption; perhaps with several different rules included as additional execution techniques. Empirical research should be conducted to study execution policies in greater detail. While the current effort looked at some basic execution policies, there are a wide variety of potential policies that could be used. Practioners should be surveyed in order to determine which execution policies are being used, and to what effect. A more comprehensive family of policies can then be programmed into the model.

The role of the stability measures should also be investigated. The current effort proposed some measures, but there are many more in use. Financial measures of stability (of the budget/cost variance type) should be included in future studies. It would be useful to survey practitioners for additional stability-type measures that are currently in use. Similarly, the importance and role of stability measures in managing and controlling project execution should be investigated. While a certain emphasis on stability seems reasonable, how important or useful are stability measures in practice?

This research has provided evidence that suggests that the relative performance of the execution methods may be dependent on environmental characteristics (variability level and disruption type). If the performance of the execution methods depends on these factors, it might be possible to develop a model that describes the "best fit" between the project environment and the method used. The role of problem characteristics in

de
co
in

re
im
de
al
a
e
p
c
a
s

l
s
t

e
c
e
c

determining relative performance was not studied, and should be investigated in conjunction with the environmental characteristics. Future research should be conducted in order to establish the validity of an execution method selection model.

In order to address the issues of generalizability and validity, future research is recommended. Empirical studies should be conducted to both establish the role and importance of stability in managing projects, and refine the definition of stability and the development of stability measures. Execution policies employed by practitioners should also be studied, and included in future models. Laboratory studies should be continued, and should incorporate the findings of the empirical work. The new models should extend generalizability by using larger, more realistic project problems in a simultaneous project execution environment. Finally, the role of project and environmental characteristics on relative execution method performance should be investigated in an attempt to assess the validity of a "fit model" for use by practioners.

5.5.2 Managerial Recommendations

Additional research is needed before strong recommendations to practioners would be justified. However, some preliminary judgements can be made. First, managers should explore the effect of various execution policies on project management. Perhaps they should select a fast, easy, reasonable heuristic for rough scheduling, then spend a significant amount of time and energy in a deliberative process of selecting and employing appropriate execution policies. An understanding of the underlying characteristics of their projects and environment, and how they interact with the execution methods, may be a good start. These efforts should, of course be conducted cooperatively by academics and practioners alike.

S

perfo

consi

appro

whil

to be

cost

rele

5.6

Th

th

w

a

S

d

r

c

e

s

of

Second, practitioners could balance their reliance on current "cost, schedule, or performance (quality)" metrics associated with the execution of milestones with a consideration of better metrics for management. While the current milestone-based approach is useful for reporting, it may not be as helpful for actually managing the project while it is being executed. Again, this is an open question, and additional research needs to be done. The relationships between current measures and overall performance (total cost and total duration) are not clear. Measures related to project stability may be more relevant to day-to-day management of projects.

5.6 Summary

Project stability has not yet been studied explicitly; nor has the role of disruption. This research investigated the performance of both planning and execution techniques in the single project, constrained resource environment, under conditions of uncertainty, when subject to disruptions. Planning techniques included several of the most popular and successful heuristics for project planning and scheduling in the literature today. Similarly, execution techniques included a representative collection of allocation and decision making methods. A known, benchmark set of project scheduling problems representing a broad spectrum of project characteristics were simulated at multiple levels of variability and disruption. The performance of each combination of planning and execution technique has been measured with respect to time, net present value, and stability.

In summary, instability in a project may lead to many negative effects. First, the loss of a resource (or a delay in its availability) may idle other resources, and result in a direct loss in productivity or efficiency. Second, the project could experience a loss of synchronization of the activities and resources, resulting in a degradation of the effectiveness of the project. Third, disruptions to resources may incur additional costs, degrade project efficiency, or lead to late completion. Finally, project instability can result in deviations in the accomplishment of project milestones, which may affect the financial evaluation of the project or the firm responsible for the project. Disruptions could spread throughout the system, resulting in many of the negative effects described previously. An apparently minor disruption to an apparently minor resource could lead to grave effects on the project as a whole. The degree to which this "ripple effect" creates overall problems is a reflection of the stability of the project as scheduled and executed.

This research sought to extend the concept of the effects of resource unavailability and activity duration variability into the realm of schedule and resource stability. Certain factors shape the ultimate performance of the project with respect to the desired outcomes. Technical and resource dependencies serve to limit or bound the potential achievement of the project. Variability in activity durations and disruptions in resources will influence the degree of achievement of project goals. The planning and execution methods used to schedule and perform the project activities have also been noted to have a significant effect on the overall project performance. While these factors have been studied with respect to their effects on the traditional project performance outcomes, no study has investigated these factors as they relate to project stability.

As a first step, this research defined several project management stability measures. The study tried to provide insight into the relationships between the traditional factors of project performance. These traditional factors included the nature of the project environment (activity variability and resource disruption), and the scheduling and execution methods used to manage the project. Hopefully, insight was provided into the nature of the relationships between these factors and project stability. Finally, the knowledge gained in studying both project stability and the relationships between project stability, other outcome measures, and the traditional factors of project performance could be extended into practical significance for the management of projects. Ultimately, it is hoped that the descriptive theories built initially can be translated into prescriptions to assist managers in achieving higher levels of performance from the projects under their control.

THE EFFECTS OF VARIABILITY AND DISRUPTION
ON
PROJECT STABILITY, DURATION, AND NET PRESENT VALUE

VOLUME II

By

Stephen M. Swartz

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Marketing and Supply Chain Management

1999

APPENDICES

APPENDIX A

HISTOGRAMS OF AGGREGATE STATISTICS

Figure A-1: Aggregate Histogram, ADUR

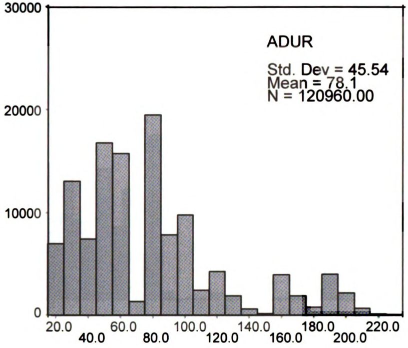


Figure A-2: Aggregate Histogram, RDUR

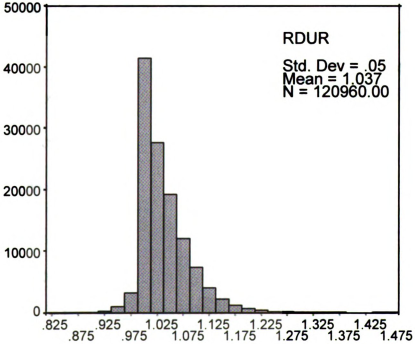


Figure A-3: Aggregate Histogram, ANPV

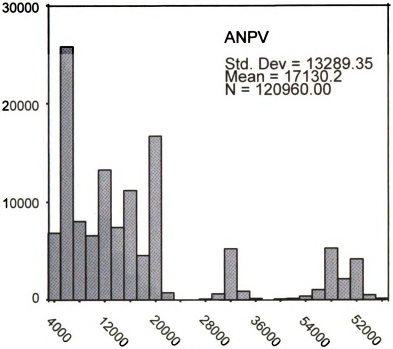


Figure A-4: Aggregate Histogram, RNPV

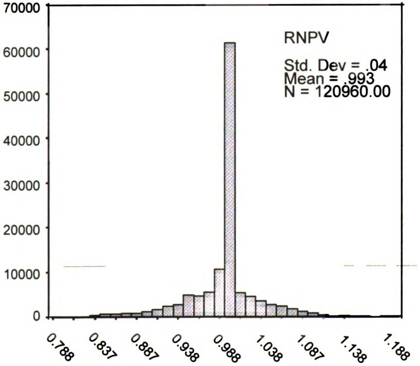


Figure A-5: Aggregate Histogram, POIC

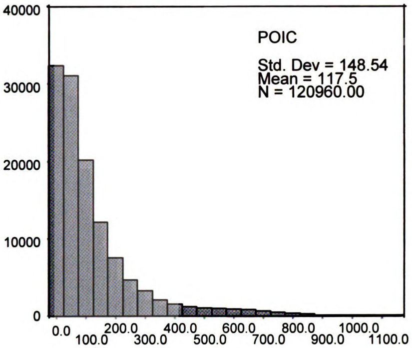


Figure A-6: Aggregate Histogram, POIR

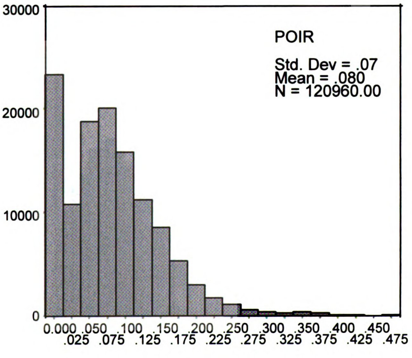


Figure A-7: Aggregate Histogram, POOC

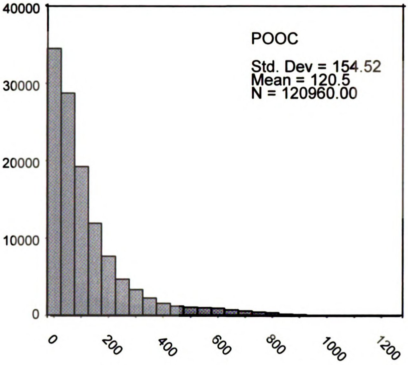


Figure A-8: Aggregate Histogram, POOR

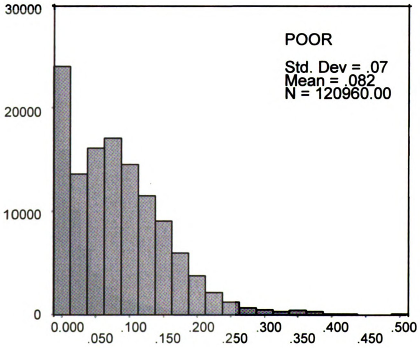


Figure A-9: Aggregate Histogram, WADE

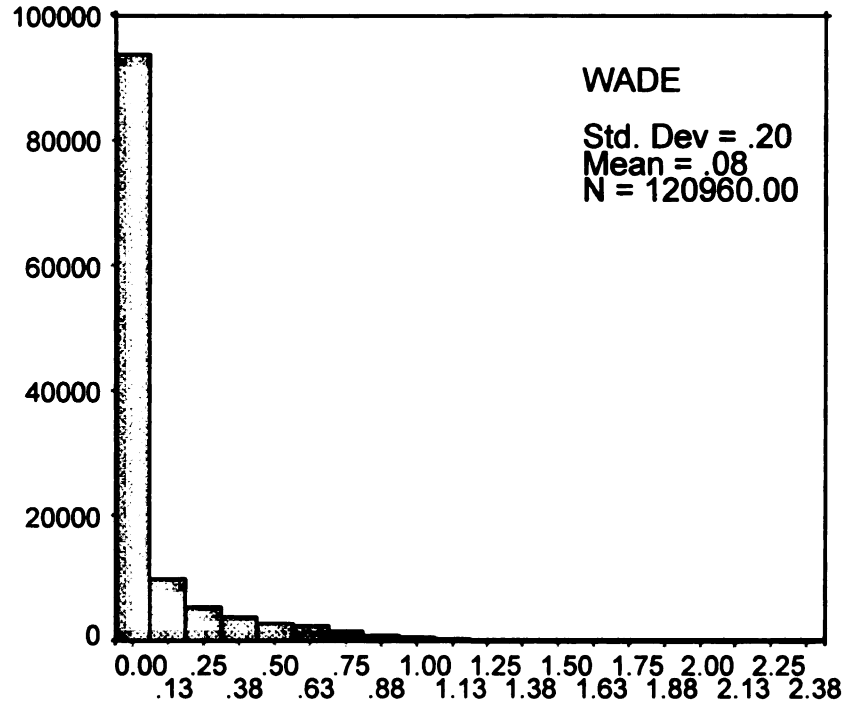


Figure A-10: Aggregate Histogram, WADL

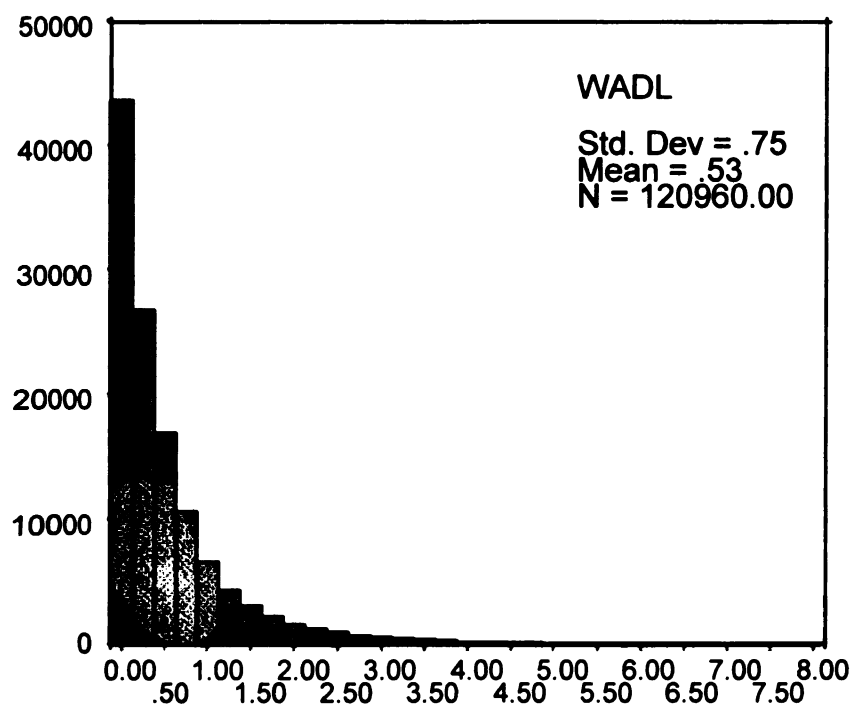
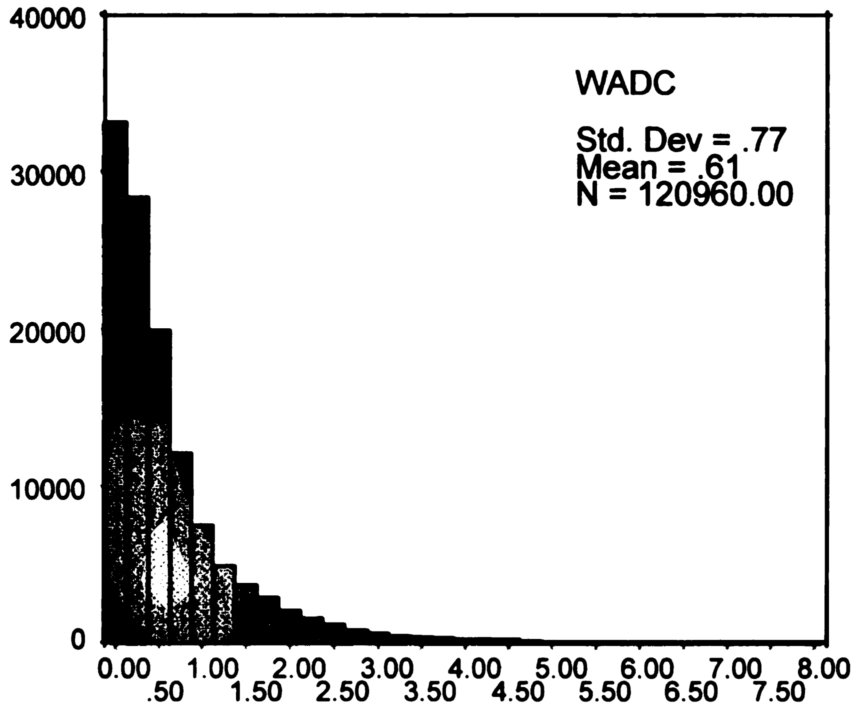


Figure A-11: Aggregate Histogram, WADC



APPENDIX B

TREATMENT MEANS

Table B-1:
Means: ADUR by Scheduling, Execution, Disruption, Variability

ADUR		some			none		
Sched	Exec	none	freq	infq	none	freq	infq
opt	frn	74.53	76.03	79.79	73.33	74.91	78.84
	frw	75.45	76.51	79.64	73.33	74.93	78.29
	nrn	75.40	77.21	78.70	74.44	76.39	78.49
	nrw	75.35	77.02	79.37	73.33	75.39	78.31
slk	frn	76.22	77.74	81.57	75.17	76.82	80.67
	frw	77.23	78.32	81.46	75.17	76.78	80.00
	nrn	76.12	77.77	79.53	75.22	77.13	78.87
	nrw	76.94	78.49	81.00	75.17	77.26	79.80
lft	frn	75.75	77.23	80.89	74.72	76.38	80.12
	frw	76.74	77.83	81.10	74.72	76.39	79.58
	nrn	75.47	77.45	78.69	74.83	76.83	78.31
	nrw	76.58	78.13	80.23	74.72	76.81	79.19
rso	frn	74.55	75.99	79.70	73.28	74.84	78.73
	frw	75.58	76.61	79.78	73.28	74.90	78.26
	nrn	75.34	77.00	78.76	74.56	76.30	78.13
	nrw	75.40	76.96	79.48	73.28	75.38	78.00
lsc	frn	75.78	77.31	81.03	74.78	76.40	80.20
	frw	76.99	78.08	81.24	74.78	76.48	79.83
	nrn	75.94	77.58	79.11	75.22	76.61	78.40
	nrw	76.73	78.31	80.99	74.78	76.92	79.66
dcf	frn	80.45	81.86	85.49	79.67	81.14	84.91
	frw	81.62	82.57	85.74	79.67	81.20	84.47
	nrn	79.57	81.07	83.65	79.00	80.64	83.25
	nrw	81.13	82.62	84.99	79.67	81.64	84.35
bcp	frn	77.26	78.56	82.22	76.22	77.70	81.41
	frw	78.28	79.25	82.32	76.22	77.79	80.90
	nrn	76.69	77.99	79.76	76.28	77.53	79.57
	nrw	77.95	79.64	82.03	76.22	78.30	80.82

Table B-2:
Means: RDUR by Scheduling, Execution, Disruption, Variability

RDUR Sched	Exec	some none	some freq	some infq	none none	none freq	none infq
opt	frn	1.0224	1.0413	1.0827	1.0000	1.0213	1.0653
	frw	1.0354	1.0497	1.0850	1.0000	1.0215	1.0606
	nrn	1.0343	1.0589	1.0780	1.0161	1.0460	1.0702
	nrw	1.0322	1.0549	1.0856	1.0000	1.0273	1.0643
slk	frn	1.0181	1.0358	1.0794	1.0000	1.0203	1.0636
	frw	1.0322	1.0457	1.0812	1.0000	1.0204	1.0576
	nrn	1.0167	1.0382	1.0582	1.0025	1.0293	1.0484
	nrw	1.0266	1.0453	1.0755	1.0000	1.0254	1.0557
lft	frn	1.0182	1.0345	1.0752	1.0000	1.0197	1.0624
	frw	1.0321	1.0450	1.0810	1.0000	1.0212	1.0570
	nrn	1.0137	1.0385	1.0541	1.0045	1.0299	1.0459
	nrw	1.0280	1.0471	1.0720	1.0000	1.0260	1.0544
rso	frn	1.0244	1.0411	1.0826	1.0000	1.0211	1.0648
	frw	1.0394	1.0527	1.0893	1.0000	1.0224	1.0626
	nrn	1.0342	1.0569	1.0781	1.0193	1.0450	1.0656
	nrw	1.0348	1.0560	1.0880	1.0000	1.0284	1.0624
lsc	frn	1.0177	1.0368	1.0790	1.0000	1.0206	1.0645
	frw	1.0361	1.0499	1.0863	1.0000	1.0230	1.0637
	nrn	1.0230	1.0443	1.0636	1.0083	1.0295	1.0497
	nrw	1.0317	1.0510	1.0851	1.0000	1.0279	1.0625
dcf	frn	1.0125	1.0284	1.0672	1.0000	1.0170	1.0576
	frw	1.0278	1.0385	1.0725	1.0000	1.0177	1.0532
	nrn	0.9952	1.0112	1.0373	0.9876	1.0052	1.0322
	nrw	1.0196	1.0353	1.0623	1.0000	1.0222	1.0512
bcp	frn	1.0177	1.0316	1.0703	1.0000	1.0176	1.0567
	frw	1.0313	1.0427	1.0759	1.0000	1.0195	1.0528
	nrn	1.0085	1.0223	1.0407	1.0021	1.0172	1.0382
	nrw	1.0247	1.0441	1.0701	1.0000	1.0239	1.0525

Table B-3:
Means: ANPV by Scheduling, Execution, Disruption, Variability

ANPV		some			none		
Sched	Exec	none	freq	infq	none	freq	infq
opt	frn	17037.46	17001.37	16900.35	17268.32	17232.59	17129.57
	frw	17021.27	16998.79	16917.90	17268.32	17233.97	17147.87
	nrn	17154.39	17109.52	17134.54	17257.72	17223.92	17167.16
	nrw	17145.51	17101.00	17111.03	17268.32	17221.60	17156.64
slk	frn	17032.49	16996.30	16897.60	17262.64	17224.09	17124.68
	frw	17015.99	16993.13	16914.93	17262.64	17227.79	17147.55
	nrn	17158.50	17117.19	17129.04	17263.34	17228.71	17178.18
	nrw	17142.78	17097.51	17100.13	17262.64	17212.38	17153.37
lft	frn	17034.88	16998.49	16903.88	17264.62	17224.70	17129.92
	frw	17018.39	16995.00	16910.83	17264.62	17228.42	17148.87
	nrn	17162.38	17119.11	17145.76	17263.45	17232.40	17189.03
	nrw	17144.12	17098.50	17111.68	17264.62	17216.47	17161.62
rso	frn	17033.08	16997.38	16897.31	17265.01	17229.21	17127.57
	frw	17017.46	16995.24	16914.05	17266.75	17231.91	17146.39
	nrn	17149.50	17106.78	17124.93	17251.77	17218.17	17169.92
	nrw	17142.24	17099.99	17104.06	17266.75	17218.72	17160.08
lsc	frn	17028.83	16992.86	16895.82	17258.85	17220.98	17122.76
	frw	17012.72	16989.82	16911.59	17261.14	17225.19	17144.21
	nrn	17151.97	17109.95	17133.24	17253.71	17227.01	17177.18
	nrw	17139.10	17092.21	17091.67	17261.14	17211.34	17147.58
dcf	frn	17027.37	16993.98	16903.57	17254.56	17219.84	17127.07
	frw	17010.95	16990.87	16912.65	17254.56	17220.97	17141.89
	nrn	17160.89	17113.53	17105.07	17261.16	17221.28	17149.46
	nrw	17137.88	17092.01	17096.57	17254.56	17206.94	17138.52
bcp	frn	17031.54	16996.95	16898.54	17260.64	17224.80	17122.84
	frw	17014.51	16992.99	16911.92	17260.64	17225.96	17141.66
	nrn	17162.41	17119.18	17130.51	17260.40	17229.71	17170.19
	nrw	17140.54	17089.69	17092.25	17260.64	17208.77	17149.44

Table B-4:
Means: RNPV by Scheduling, Execution, Disruption, Variability

RNPV		some			none		
Sched	Exec	none	freq	infq	none	freq	infq
opt	frn	0.9866	0.9853	0.9822	1.0000	0.9987	0.9954
	frw	0.9859	0.9851	0.9825	1.0000	0.9987	0.9958
	nrn	0.9940	0.9919	0.9910	0.9990	0.9974	0.9956
	nrw	0.9941	0.9922	0.9906	1.0000	0.9983	0.9958
slk	frn	0.9867	0.9854	0.9822	1.0000	0.9986	0.9953
	frw	0.9859	0.9851	0.9824	1.0000	0.9987	0.9959
	nrn	0.9949	0.9930	0.9919	1.0000	0.9984	0.9969
	nrw	0.9944	0.9926	0.9909	1.0000	0.9983	0.9962
lft	frn	0.9867	0.9855	0.9825	1.0000	0.9986	0.9955
	frw	0.9860	0.9851	0.9824	1.0000	0.9986	0.9960
	nrn	0.9951	0.9929	0.9922	0.9999	0.9983	0.9970
	nrw	0.9943	0.9925	0.9912	1.0000	0.9983	0.9963
rso	frn	0.9863	0.9851	0.9820	0.9998	0.9985	0.9952
	frw	0.9857	0.9849	0.9822	1.0000	0.9987	0.9958
	nrn	0.9936	0.9917	0.9906	0.9985	0.9971	0.9955
	nrw	0.9940	0.9921	0.9904	1.0000	0.9982	0.9960
lsc	frn	0.9865	0.9852	0.9820	0.9997	0.9984	0.9951
	frw	0.9858	0.9849	0.9822	1.0000	0.9986	0.9956
	nrn	0.9943	0.9924	0.9915	0.9992	0.9981	0.9965
	nrw	0.9941	0.9923	0.9904	1.0000	0.9982	0.9959
dcf	frn	0.9869	0.9858	0.9828	1.0000	0.9988	0.9957
	frw	0.9861	0.9854	0.9828	1.0000	0.9988	0.9961
	nrn	0.9959	0.9941	0.9924	1.0007	0.9993	0.9971
	nrw	0.9947	0.9929	0.9915	1.0000	0.9984	0.9962
bcp	frn	0.9867	0.9856	0.9825	1.0000	0.9988	0.9955
	frw	0.9860	0.9852	0.9826	1.0000	0.9987	0.9960
	nrn	0.9954	0.9937	0.9926	1.0000	0.9989	0.9971
	nrw	0.9944	0.9924	0.9909	1.0000	0.9982	0.9961

Table B-5:

Means: WADE by Scheduling, Execution, Disruption, Variability

WADE		some			none		
Sched	Exec	none	freq	infq	none	freq	infq
opt	frn	0.1136	0.0620	0.0364	0.0000	0.0003	0.0004
	frw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	nrn	0.1968	0.2877	0.2524	0.0802	0.2249	0.1973
	nrw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
slk	frn	0.1311	0.0723	0.0368	0.0000	0.0008	0.0005
	frw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	nrn	0.1856	0.3142	0.2725	0.0177	0.2528	0.2106
	nrw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
lft	frn	0.1247	0.0696	0.0373	0.0000	0.0004	0.0006
	frw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	nrn	0.1721	0.2904	0.2428	0.0195	0.2266	0.1829
	nrw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
rso	frn	0.1905	0.1391	0.1075	0.1040	0.0972	0.0837
	frw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	nrn	0.3329	0.4137	0.3720	0.2590	0.3852	0.3537
	nrw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
lsc	frn	0.2401	0.1743	0.1320	0.1462	0.1286	0.1163
	frw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	nrn	0.3577	0.5018	0.4374	0.2384	0.4489	0.4005
	nrw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
dcf	frn	0.1375	0.0801	0.0503	0.0000	0.0000	0.0001
	frw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	nrn	0.1959	0.2597	0.2052	0.0890	0.2034	0.1509
	nrw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
bcp	frn	0.1256	0.0782	0.0474	0.0000	0.0001	0.0005
	frw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	nrn	0.2107	0.4447	0.3769	0.0067	0.3616	0.3022
	nrw	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table B-6:
Means: WADL by Scheduling, Execution, Disruption, Variability

WADL		some			none		
Sched	Exec	none	freq	infq	none	freq	infq
opt	frn	0.2923	0.5139	1.1214	0.0000	0.2837	0.9600
	frw	0.3784	0.5925	1.1316	0.0000	0.3008	0.8662
	nrn	0.4104	0.7907	0.9965	0.1704	0.6225	0.9330
	nrw	0.3623	0.6662	1.0526	0.0000	0.3723	0.8542
slk	frn	0.2793	0.5080	1.1480	0.0000	0.3009	0.9779
	frw	0.3732	0.5965	1.1594	0.0000	0.3088	0.8702
	nrn	0.2912	0.6114	0.8346	0.0326	0.4686	0.7017
	nrw	0.3411	0.6333	1.0506	0.0000	0.3768	0.8201
lft	frn	0.2733	0.4879	1.1092	0.0000	0.2992	0.9572
	frw	0.3646	0.5818	1.1561	0.0000	0.3057	0.8798
	nrn	0.2591	0.6760	0.8053	0.0293	0.5227	0.7189
	nrw	0.3524	0.6391	1.0139	0.0000	0.3822	0.8046
rso	frn	0.2731	0.4822	1.0821	0.0000	0.2709	0.9356
	frw	0.3785	0.5839	1.1252	0.0000	0.2939	0.8516
	nrn	0.3683	0.7108	0.9673	0.1760	0.6084	0.8671
	nrw	0.3382	0.6288	1.0414	0.0000	0.3680	0.7869
lsc	frn	0.2406	0.4620	1.0864	0.0000	0.2839	0.9403
	frw	0.3601	0.5774	1.1406	0.0000	0.3042	0.8735
	nrn	0.2587	0.5752	0.7769	0.0535	0.4080	0.6443
	nrw	0.3179	0.6019	1.0367	0.0000	0.3680	0.8213
dcf	frn	0.2554	0.4600	1.0716	0.0000	0.2646	0.9360
	frw	0.3523	0.5504	1.1045	0.0000	0.2865	0.8652
	nrn	0.2106	0.5955	0.9703	0.0274	0.4782	0.8650
	nrw	0.3135	0.6161	1.0789	0.0000	0.3880	0.8896
bcp	frn	0.2906	0.4808	1.0947	0.0000	0.2655	0.8949
	frw	0.3857	0.5846	1.1257	0.0000	0.2917	0.8191
	nrn	0.2542	0.5247	0.7574	0.0144	0.3858	0.6575
	nrw	0.3332	0.6294	1.0393	0.0000	0.3611	0.7897

Table B-7:
Means: WADC by Scheduling, Execution, Disruption, Variability

WADC		some			none		
Sched	Exec	none	freq	infq	none	freq	infq
opt	frn	0.4059	0.5759	1.1578	0.0000	0.2840	0.9604
	frw	0.3784	0.5925	1.1316	0.0000	0.3008	0.8662
	nrn	0.6073	1.0784	1.2489	0.2505	0.8474	1.1303
	nrw	0.3623	0.6662	1.0526	0.0000	0.3723	0.8542
slk	frn	0.4104	0.5803	1.1848	0.0000	0.3017	0.9783
	frw	0.3732	0.5965	1.1594	0.0000	0.3088	0.8702
	nrn	0.4769	0.9256	1.1071	0.0502	0.7214	0.9123
	nrw	0.3411	0.6333	1.0506	0.0000	0.3768	0.8201
lft	frn	0.3981	0.5575	1.1465	0.0000	0.2996	0.9578
	frw	0.3646	0.5818	1.1561	0.0000	0.3057	0.8798
	nrn	0.4312	0.9664	1.0481	0.0488	0.7493	0.9018
	nrw	0.3524	0.6391	1.0139	0.0000	0.3822	0.8046
rso	frn	0.4636	0.6213	1.1896	0.1040	0.3682	1.0193
	frw	0.3785	0.5839	1.1252	0.0000	0.2939	0.8516
	nrn	0.7012	1.1245	1.3394	0.4349	0.9936	1.2208
	nrw	0.3382	0.6288	1.0414	0.0000	0.3680	0.7869
lsc	frn	0.4807	0.6362	1.2184	0.1462	0.4125	1.0567
	frw	0.3601	0.5774	1.1406	0.0000	0.3042	0.8735
	nrn	0.6164	1.0770	1.2143	0.2919	0.8569	1.0448
	nrw	0.3179	0.6019	1.0367	0.0000	0.3680	0.8213
dcf	frn	0.3929	0.5401	1.1219	0.0000	0.2646	0.9360
	frw	0.3523	0.5504	1.1045	0.0000	0.2865	0.8652
	nrn	0.4064	0.8552	1.1755	0.1163	0.6816	1.0159
	nrw	0.3135	0.6161	1.0789	0.0000	0.3880	0.8896
bcp	frn	0.4162	0.5590	1.1422	0.0000	0.2656	0.8953
	frw	0.3857	0.5846	1.1257	0.0000	0.2917	0.8191
	nrn	0.4649	0.9694	1.1343	0.0210	0.7474	0.9598
	nrw	0.3332	0.6294	1.0393	0.0000	0.3611	0.7897

Table B-8:
Means: POIC by Scheduling, Execution, Disruption, Variability

POIC		some			none		
Sched	Exec	none	freq	infq	none	freq	infq
opt	frn	83.49	122.75	210.63	0.00	79.47	189.49
	frw	85.91	130.93	207.30	0.00	88.33	180.43
	nrn	95.56	149.32	181.12	23.61	123.02	169.02
	nrw	83.87	140.13	193.73	0.00	98.15	169.39
slk	frn	83.88	121.68	210.47	0.00	82.13	188.69
	frw	85.57	129.83	207.27	0.00	86.11	174.86
	nrn	88.41	133.82	170.67	5.83	103.78	147.86
	nrw	81.93	138.87	197.45	0.00	98.63	164.98
lft	frn	78.62	115.60	204.16	0.00	80.11	182.21
	frw	81.57	124.81	204.17	0.00	82.99	172.26
	nrn	80.74	135.55	159.70	9.78	105.24	141.31
	nrw	78.95	131.18	187.00	0.00	92.03	158.16
rso	frn	97.23	134.17	219.44	37.83	107.48	208.18
	frw	81.53	125.69	202.97	0.00	85.53	175.61
	nrn	111.08	158.39	193.55	65.94	150.56	186.51
	nrw	77.03	132.40	187.46	0.00	96.73	158.70
lsc	frn	102.42	135.39	221.73	46.06	115.81	212.15
	frw	81.42	124.09	202.14	0.00	83.79	172.59
	nrn	109.92	153.37	184.20	57.94	133.50	174.61
	nrw	75.44	132.74	191.82	0.00	95.10	163.00
dcf	frn	90.79	131.06	221.27	0.00	85.03	198.56
	frw	91.41	139.05	221.91	0.00	92.35	191.16
	nrn	91.34	145.30	202.84	13.00	113.59	178.56
	nrw	84.46	145.80	210.22	0.00	105.94	181.48
bcp	frn	87.84	123.34	205.24	0.00	78.22	180.10
	frw	90.36	133.66	205.69	0.00	86.35	170.98
	nrn	89.90	137.88	175.70	2.00	107.01	155.39
	nrw	85.29	145.76	204.31	0.00	99.41	166.76

Table B-9:
Means: POIR by Scheduling, Execution, Disruption, Variability

POIR		some			none		
Sched	Exec	none	freq	infq	none	freq	infq
opt	frn	0.0673	0.0881	0.1305	0.0000	0.0442	0.1011
	frw	0.0679	0.0923	0.1306	0.0000	0.0477	0.0968
	nrn	0.0836	0.1155	0.1299	0.0271	0.0856	0.1085
	nrw	0.0662	0.0956	0.1260	0.0000	0.0518	0.0953
slk	frn	0.0678	0.0887	0.1331	0.0000	0.0455	0.1030
	frw	0.0674	0.0923	0.1325	0.0000	0.0477	0.0967
	nrn	0.0759	0.1047	0.1207	0.0083	0.0713	0.0921
	nrw	0.0657	0.0945	0.1261	0.0000	0.0525	0.0920
lft	frn	0.0653	0.0850	0.1303	0.0000	0.0445	0.1014
	frw	0.0658	0.0900	0.1319	0.0000	0.0479	0.0958
	nrn	0.0708	0.1067	0.1172	0.0117	0.0734	0.0906
	nrw	0.0647	0.0923	0.1225	0.0000	0.0507	0.0894
rso	frn	0.0890	0.1076	0.1472	0.0524	0.0878	0.1362
	frw	0.0620	0.0854	0.1248	0.0000	0.0449	0.0939
	nrn	0.1074	0.1347	0.1497	0.0874	0.1290	0.1435
	nrw	0.0575	0.0866	0.1178	0.0000	0.0492	0.0867
lsc	frn	0.0951	0.1115	0.1538	0.0632	0.0964	0.1453
	frw	0.0622	0.0854	0.1273	0.0000	0.0461	0.0974
	nrn	0.1062	0.1326	0.1454	0.0732	0.1192	0.1371
	nrw	0.0570	0.0868	0.1207	0.0000	0.0508	0.0910
dcf	frn	0.0764	0.0943	0.1406	0.0000	0.0441	0.1072
	frw	0.0725	0.0982	0.1429	0.0000	0.0497	0.1054
	nrn	0.0757	0.1062	0.1312	0.0193	0.0694	0.1021
	nrw	0.0697	0.0981	0.1340	0.0000	0.0520	0.1003
bcp	frn	0.0706	0.0878	0.1276	0.0000	0.0417	0.0954
	frw	0.0711	0.0937	0.1306	0.0000	0.0470	0.0917
	nrn	0.0745	0.1011	0.1166	0.0042	0.0674	0.0896
	nrw	0.0663	0.0953	0.1259	0.0000	0.0507	0.0893

Table B-10:
Means: POOC by Scheduling, Execution, Disruption, Variability

POOC Sched	Exec	some none	freq	infq	none none	freq	infq
opt	frn	92.25	131.51	219.38	0.00	79.47	189.49
	frw	94.68	139.68	216.06	0.00	88.33	180.43
	nrn	99.37	153.57	182.75	23.61	123.02	169.02
	nrw	87.68	144.38	195.37	0.00	98.15	169.39
slk	frn	92.63	130.44	219.21	0.00	82.13	188.69
	frw	94.33	138.59	216.02	0.00	86.11	174.86
	nrn	92.22	138.06	172.30	5.83	103.78	147.86
	nrw	85.74	143.10	199.10	0.00	98.63	164.98
lft	frn	87.37	124.36	212.92	0.00	80.11	182.21
	frw	90.33	133.58	212.93	0.00	82.99	172.26
	nrn	84.55	139.80	161.33	9.78	105.24	141.31
	nrw	82.77	135.42	188.64	0.00	92.03	158.16
rso	frn	105.99	142.93	228.20	37.83	107.48	208.18
	frw	90.29	134.44	211.73	0.00	85.53	175.61
	nrn	114.89	162.65	195.20	65.94	150.56	186.51
	nrw	80.84	136.65	189.10	0.00	96.73	158.70
lsc	frn	111.18	144.16	230.48	46.06	115.81	212.15
	frw	90.18	132.85	210.88	0.00	83.79	172.59
	nrn	113.73	157.62	185.83	57.94	133.50	174.61
	nrw	79.25	136.97	193.46	0.00	95.10	163.00
dcf	frn	99.55	139.80	230.05	0.00	85.03	198.56
	frw	100.09	147.71	230.58	0.00	92.35	191.16
	nrn	95.14	149.54	204.47	13.00	113.59	178.56
	nrw	88.26	150.05	211.86	0.00	105.94	181.48
bcp	frn	96.60	132.10	214.00	0.00	78.22	180.10
	frw	99.11	142.42	214.44	0.00	86.35	170.98
	nrn	93.71	142.12	177.33	2.00	107.01	155.39
	nrw	89.11	150.00	205.94	0.00	99.41	166.76

Table B-11:
Means: POOR by Scheduling, Execution, Disruption, Variability

POOR		some			none		
Sched	Exec	none	freq	infq	none	freq	infq
opt	frn	0.0736	0.0943	0.1367	0.0000	0.0442	0.1011
	frw	0.0742	0.0986	0.1368	0.0000	0.0477	0.0968
	nrn	0.0858	0.1179	0.1321	0.0271	0.0856	0.1085
	nrw	0.0683	0.0981	0.1283	0.0000	0.0518	0.0953
slk	frn	0.0740	0.0949	0.1393	0.0000	0.0455	0.1030
	frw	0.0737	0.0985	0.1387	0.0000	0.0477	0.0967
	nrn	0.0781	0.1071	0.1230	0.0083	0.0713	0.0921
	nrw	0.0679	0.0969	0.1284	0.0000	0.0525	0.0920
lft	frn	0.0715	0.0912	0.1366	0.0000	0.0445	0.1014
	frw	0.0721	0.0963	0.1381	0.0000	0.0479	0.0958
	nrn	0.0729	0.1091	0.1195	0.0117	0.0734	0.0906
	nrw	0.0669	0.0947	0.1247	0.0000	0.0507	0.0894
rso	frn	0.0952	0.1139	0.1534	0.0524	0.0878	0.1362
	frw	0.0682	0.0916	0.1310	0.0000	0.0449	0.0939
	nrn	0.1095	0.1371	0.1519	0.0874	0.1290	0.1435
	nrw	0.0596	0.0891	0.1200	0.0000	0.0492	0.0867
lsc	frn	0.1013	0.1177	0.1601	0.0632	0.0964	0.1453
	frw	0.0684	0.0916	0.1335	0.0000	0.0461	0.0974
	nrn	0.1083	0.1350	0.1476	0.0732	0.1192	0.1371
	nrw	0.0592	0.0893	0.1230	0.0000	0.0508	0.0910
dcf	frn	0.0810	0.1005	0.1469	0.0000	0.0441	0.1072
	frw	0.0787	0.1044	0.1491	0.0000	0.0497	0.1054
	nrn	0.0797	0.1086	0.1335	0.0193	0.0695	0.1021
	nrw	0.0691	0.1005	0.1362	0.0000	0.0552	0.1003
bcp	frn	0.0768	0.0940	0.1338	0.0000	0.0417	0.0954
	frw	0.0774	0.1000	0.1368	0.0000	0.0470	0.0917
	nrn	0.0767	0.1036	0.1188	0.0042	0.0674	0.0896
	nrw	0.0684	0.0977	0.1281	0.0000	0.0507	0.0893

APPENDIX C

GRAPHICAL TREATMENT MEANS

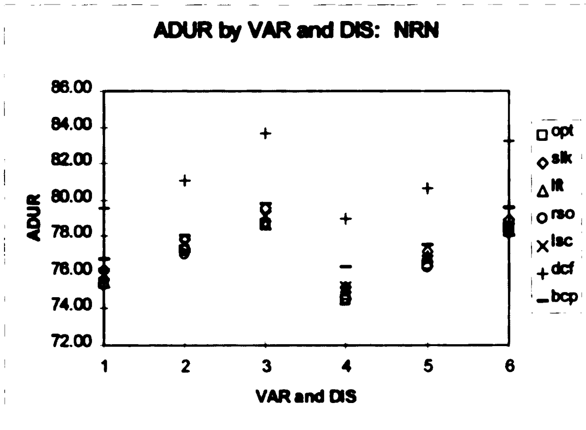


Figure C-1
Graphical Means, ADUR/NRN

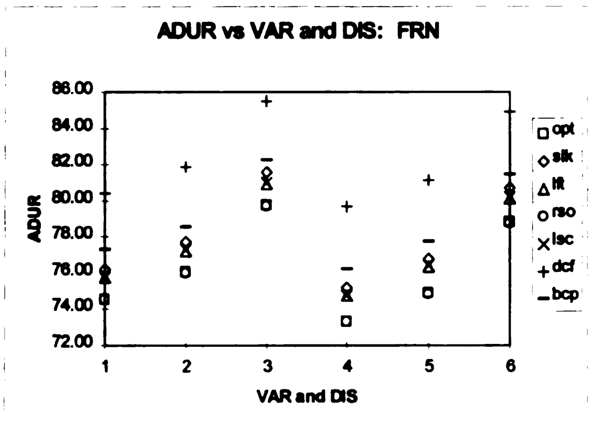


Figure C-2
Graphical Means, ADUR/FRN

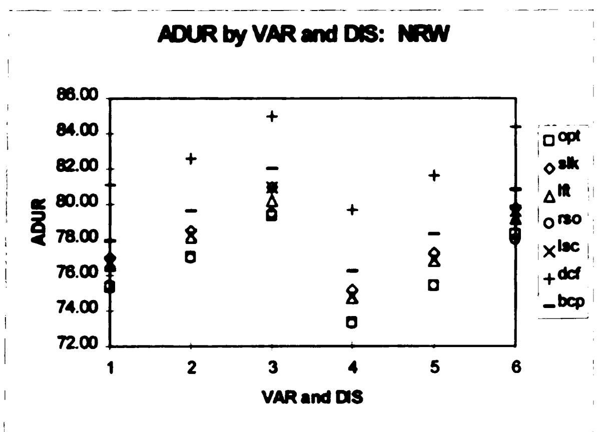


Figure C-3
Graphical Means, ADUR/NRW

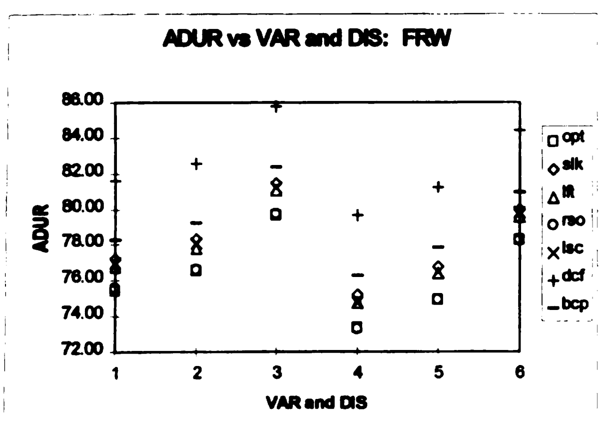


Figure C-4
Graphical Means, ADUR/FRW

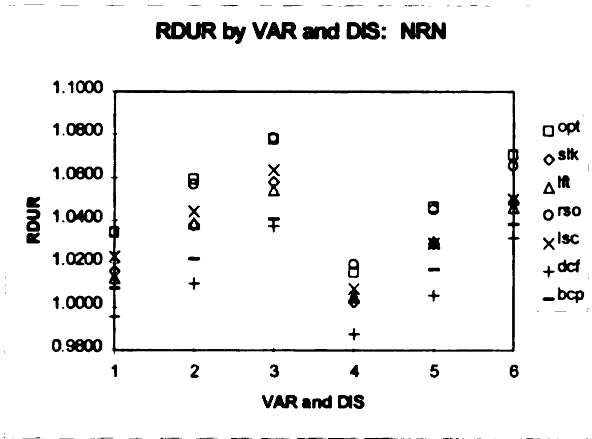


Figure C-5
Graphical Means, RDUR/NRN

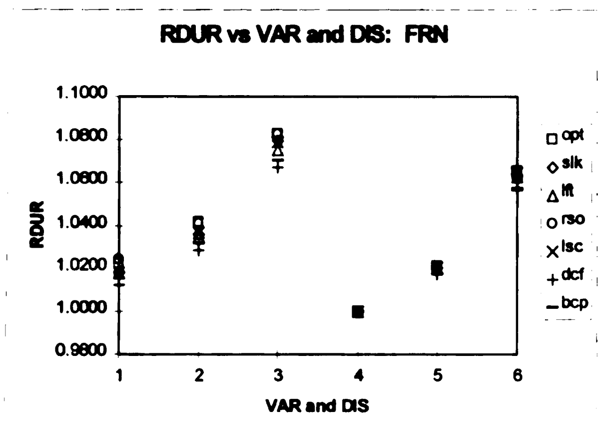


Figure C-6
Graphical Means, RDUR/FRN

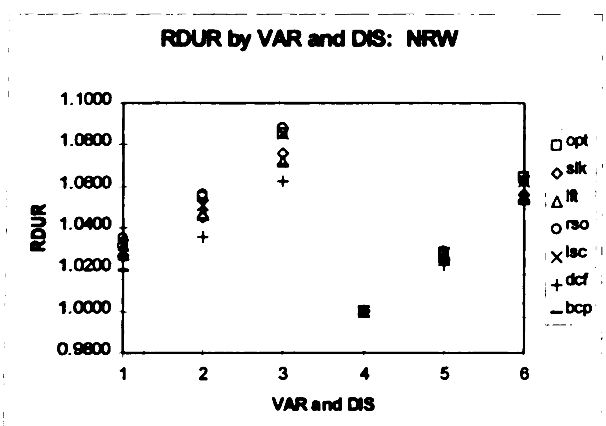


Figure C-7
Graphical Means, RDUR/NRW

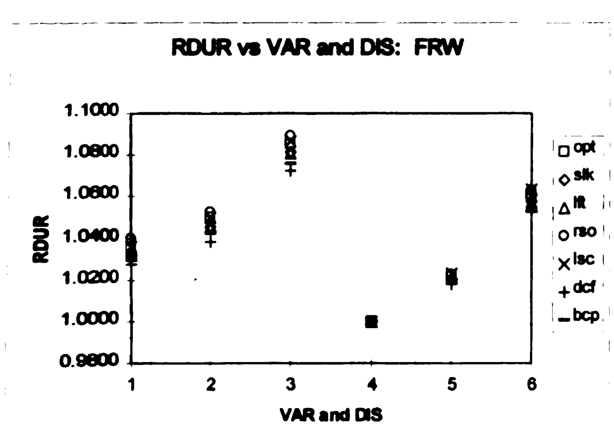


Figure C-8
Graphical Means, RDUR/FRW

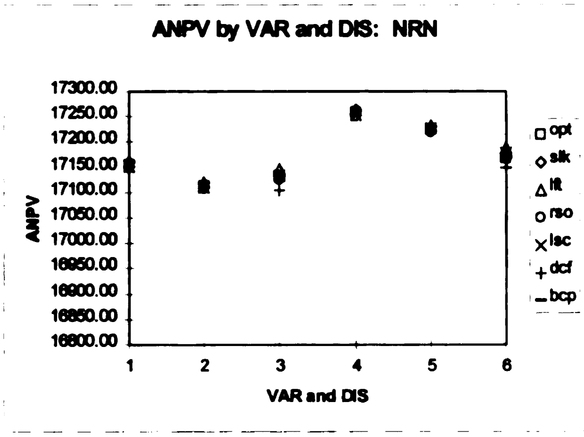


Figure C-9
Graphical Means, ANPV/NRN

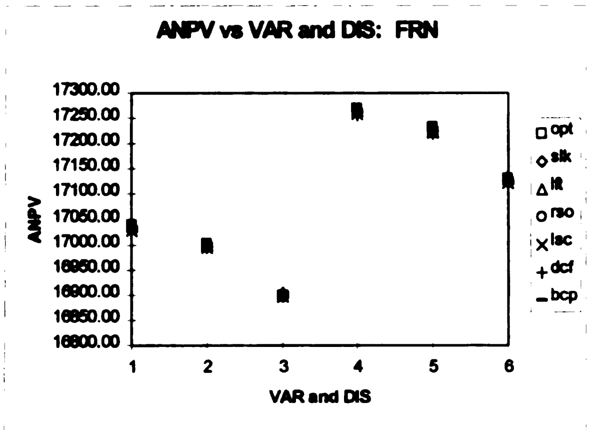


Figure C-10
Graphical Means, ANPV/FRN

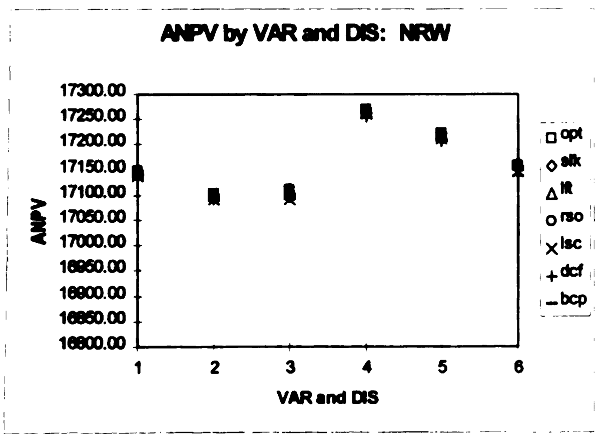


Figure C-11
Graphical Means, ANPV/NRW

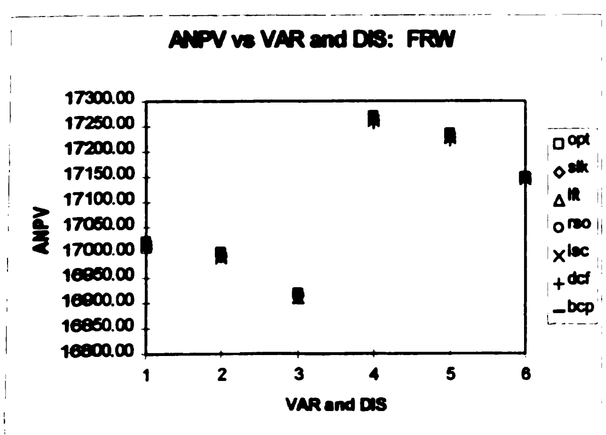


Figure C-12
Graphical Means, ANPV/FRW

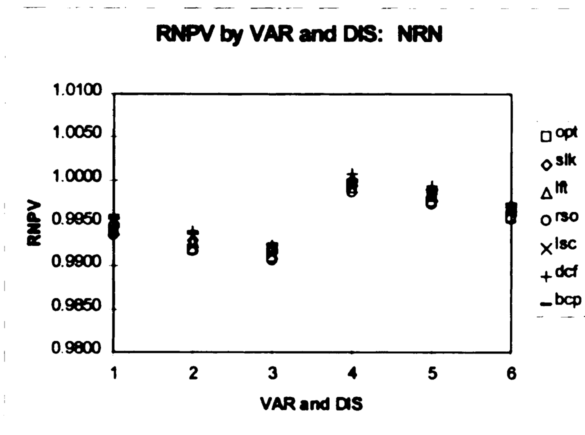


Figure C-13
Graphical Means, RNPV/NRN

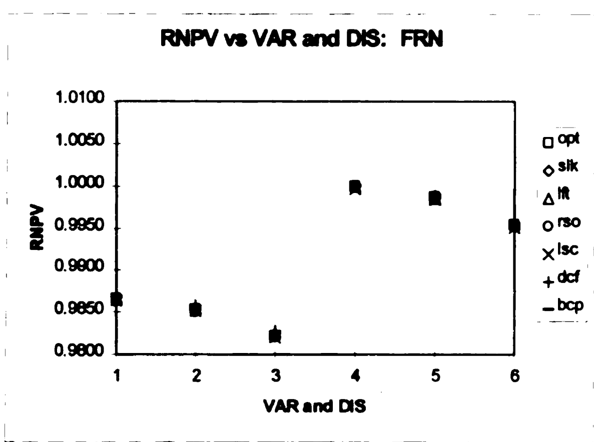


Figure C-14
Graphical Means, RNPV/FRN

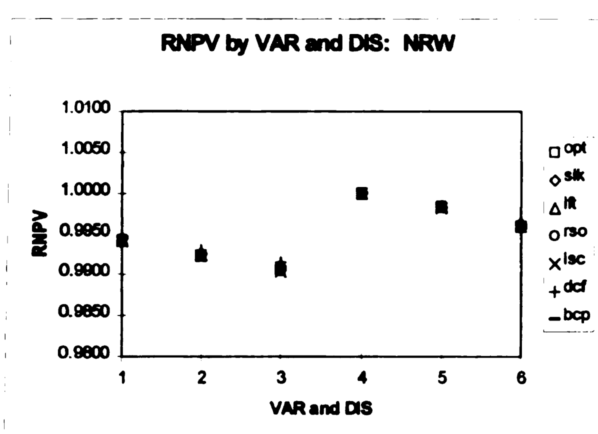


Figure C-15
Graphical Means, RNPV/NRW

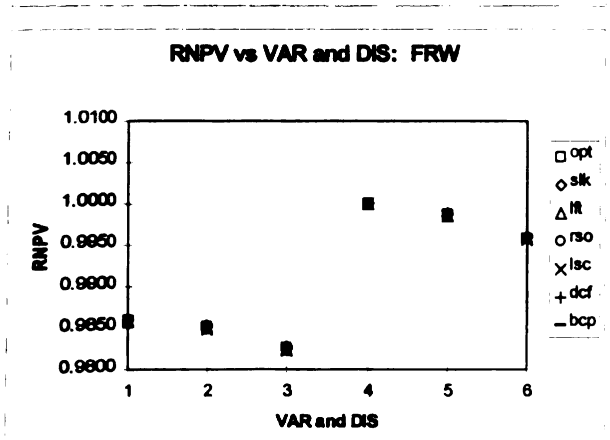


Figure C-16
Graphical Means, RNPV/FRW

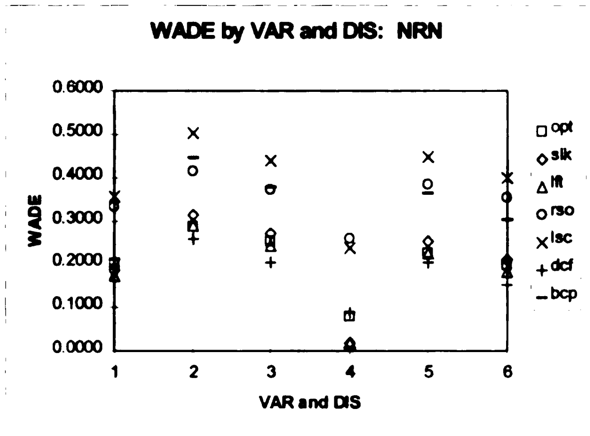


Figure C-17
Graphical Means, WADE/NRN

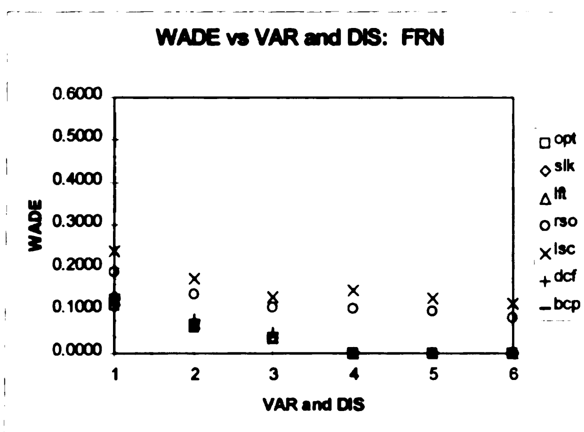


Figure C-18
Graphical Means, WADE/FRN

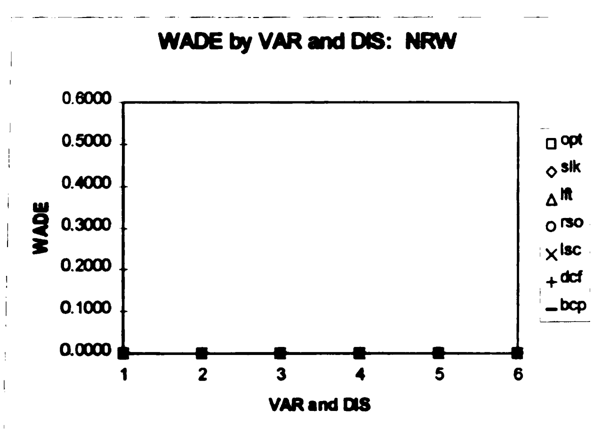


Figure C-19
Graphical Means, WADE/NRW

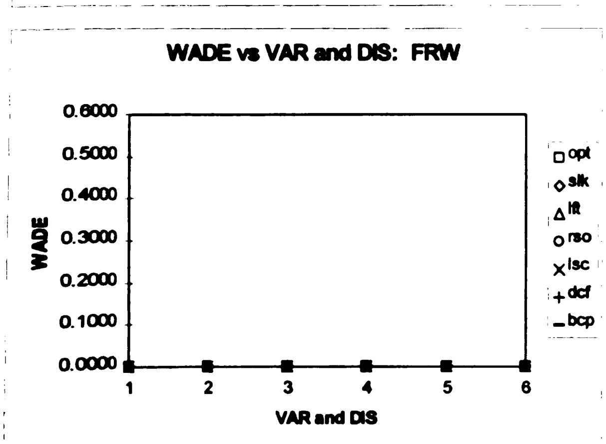


Figure C-20
Graphical Means, WADE/FRW

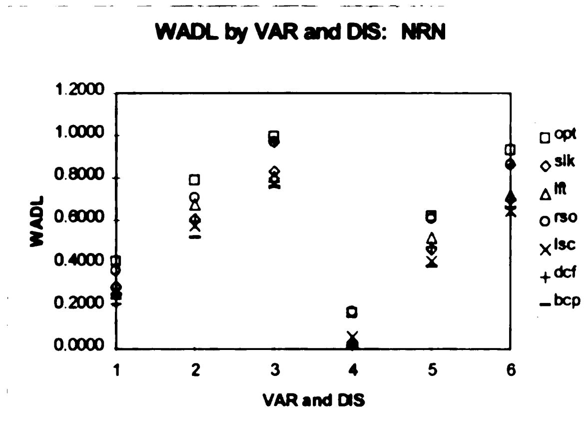


Figure C-21
Graphical Means, WADL/NRN

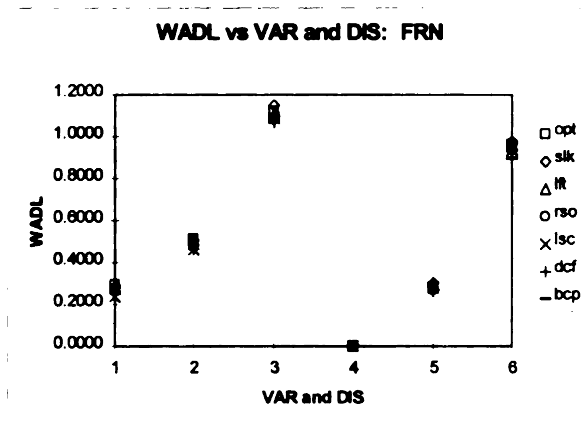


Figure C-22
Graphical Means, WADL/FRN

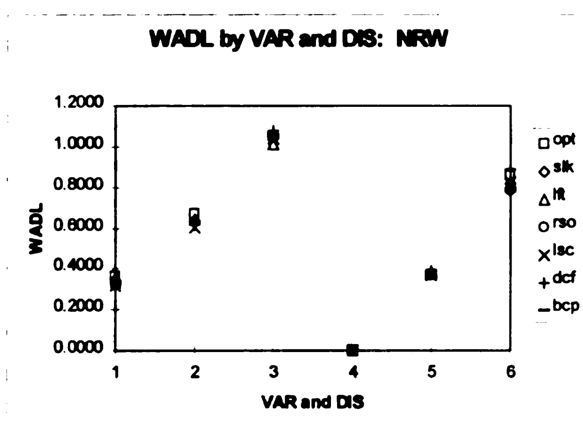


Figure C-23
Graphical Means, WADL/NRW

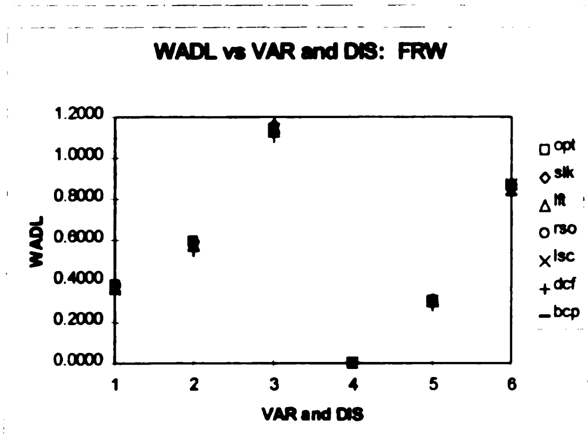


Figure C-24
Graphical Means, WADL/FRW

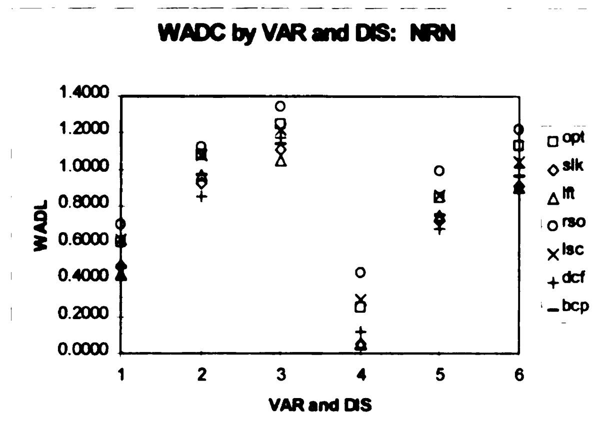


Figure C-25
Graphical Means, WADC/NRN

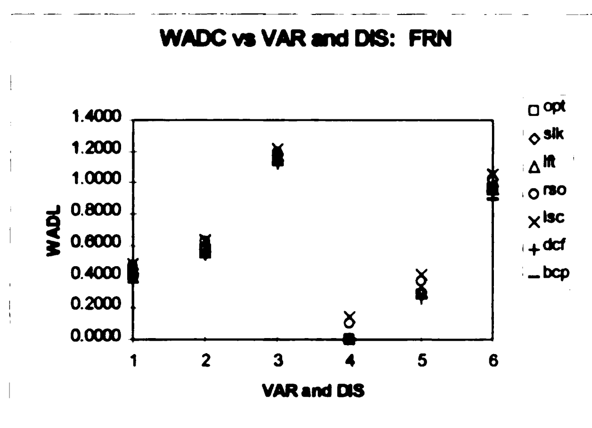


Figure C-26
Graphical Means, WADC/FRN

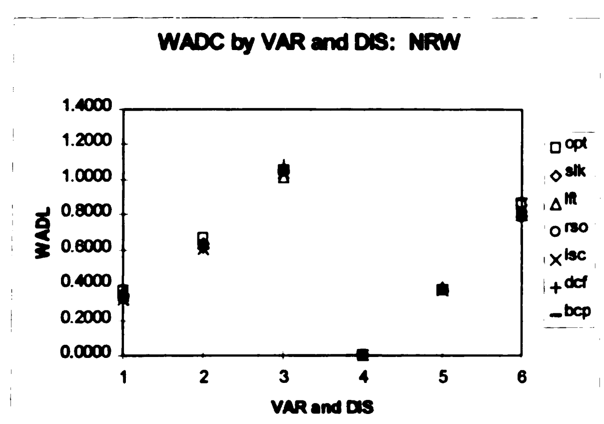


Figure C-27
Graphical Means, WADC/NRW

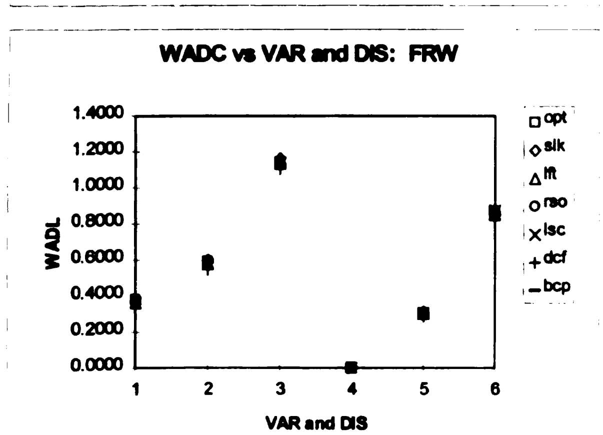


Figure C-28
Graphical Means, WADC/FRW

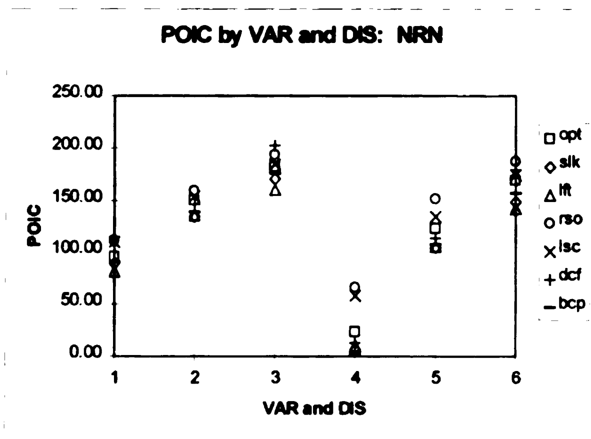


Figure C-29
Graphical Means, POIC/NRN

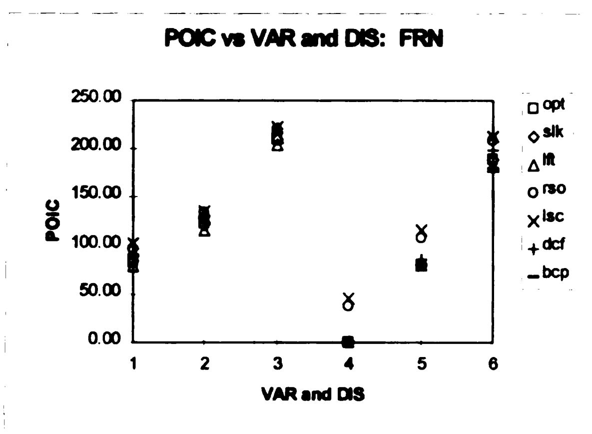


Figure C-30
Graphical Means, POIC/FRN

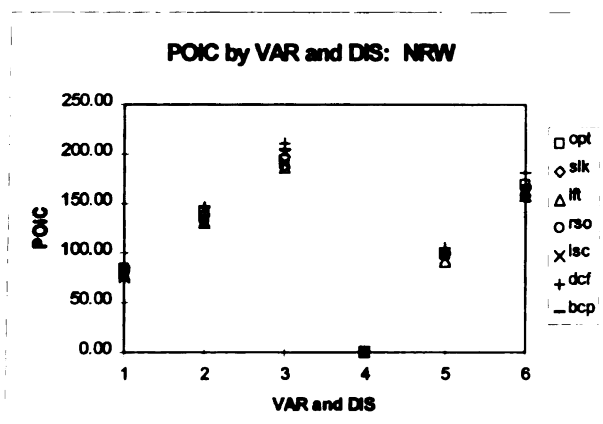


Figure C-31
Graphical Means, POIC/NRW

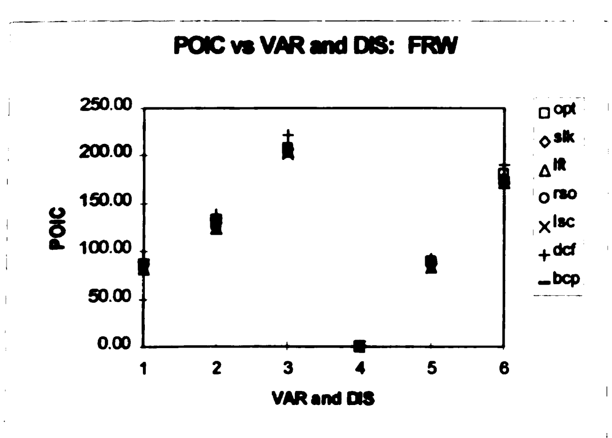


Figure C-32
Graphical Means, POIC/FRW

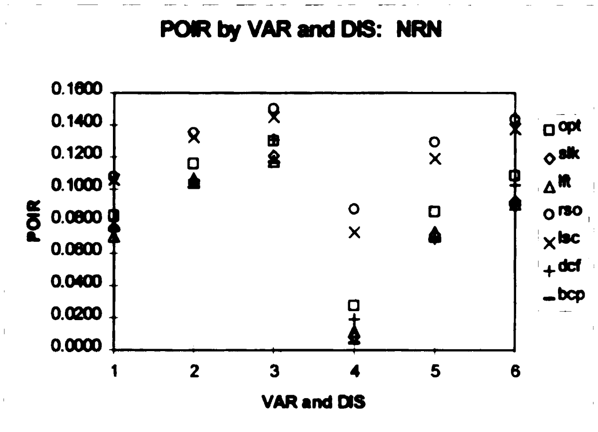


Figure C-33
Graphical Means, POIR/NRN

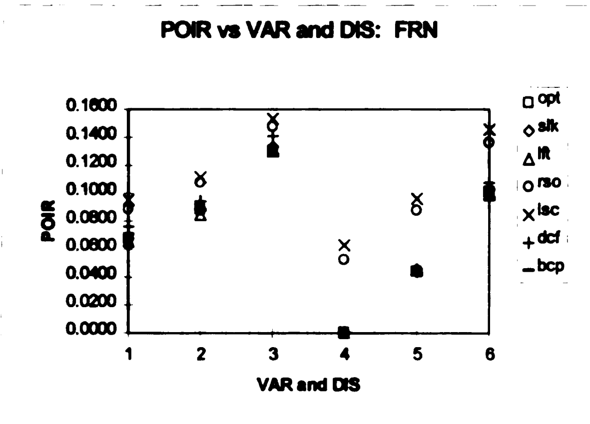


Figure C-34
Graphical Means, POIR/FRN

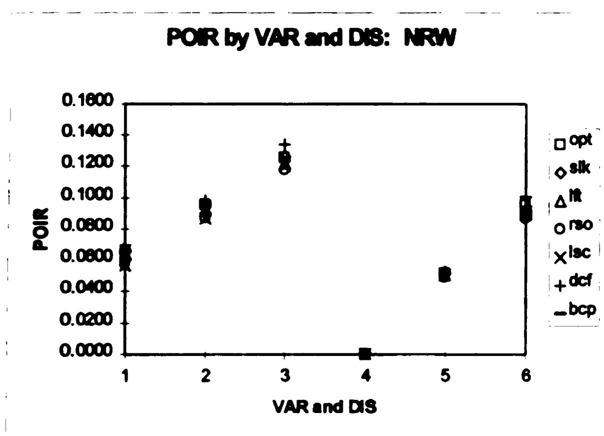


Figure C-35
Graphical Means, POIR/NRW

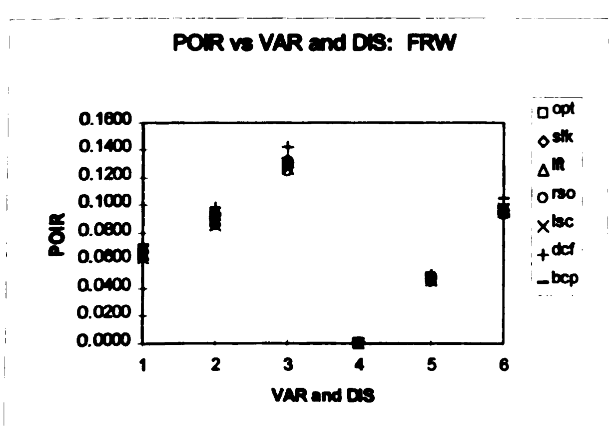


Figure C-36
Graphical Means, POIR/FRW

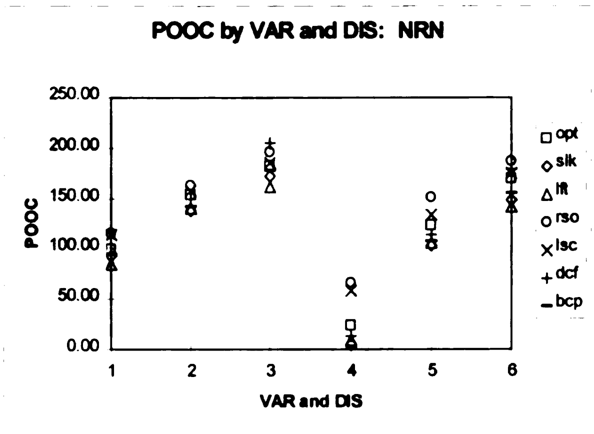


Figure C-37
Graphical Means, POOC/NRN

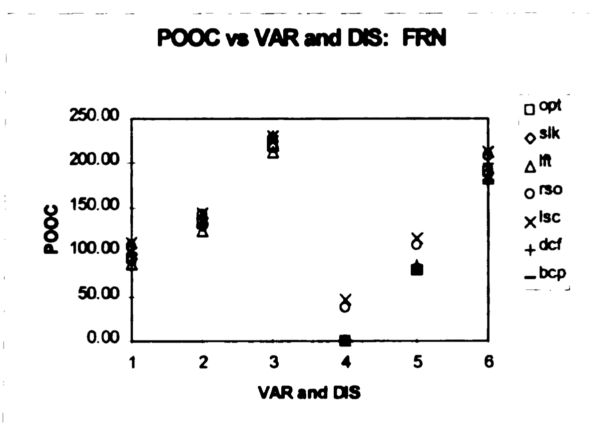


Figure C-38
Graphical Means, POOC/FRN

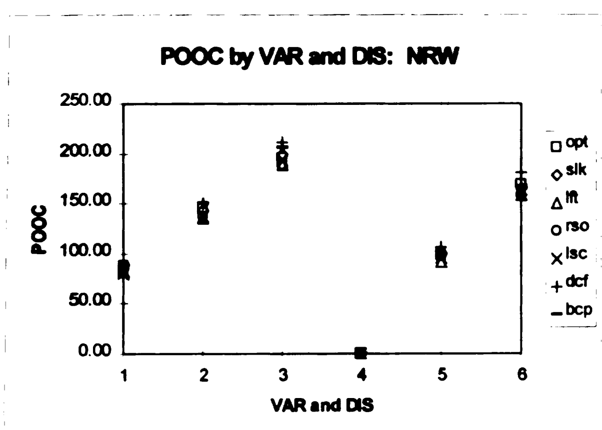


Figure C-39
Graphical Means, POOC/NRW

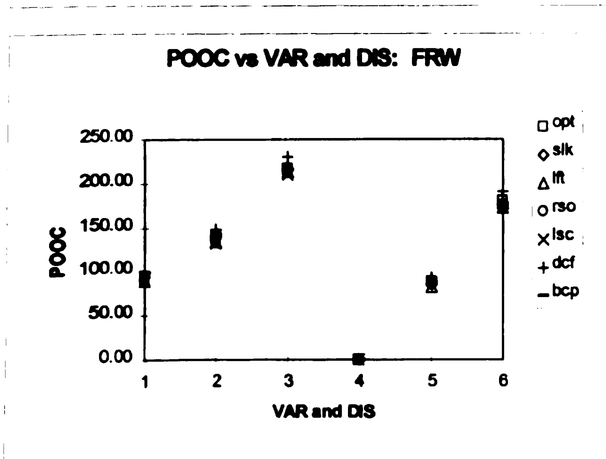


Figure C-40
Graphical Means, POOC/FRW

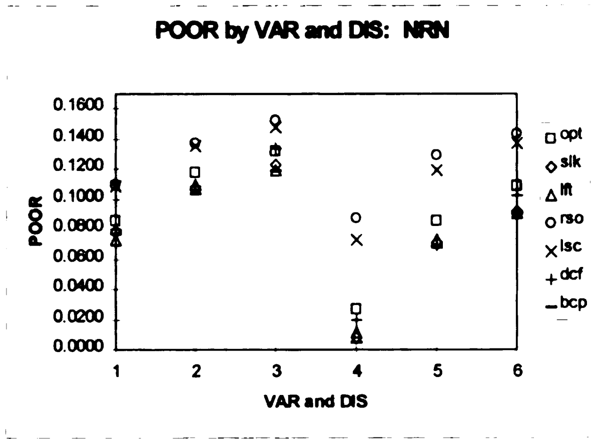


Figure C-41
Graphical Means, POOR/NRN

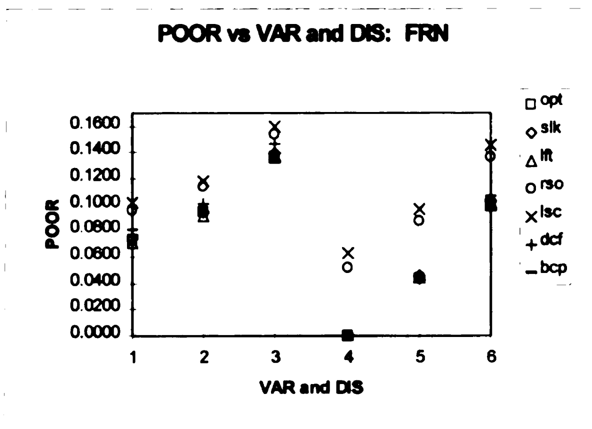


Figure C-42
Graphical Means, POOR/FRN

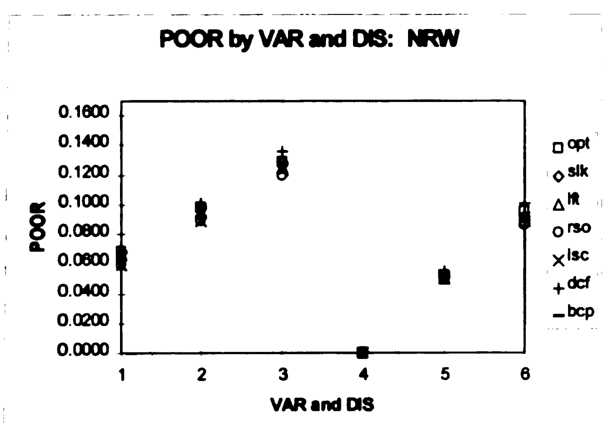


Figure C-43
Graphical Means, POOR/NRW

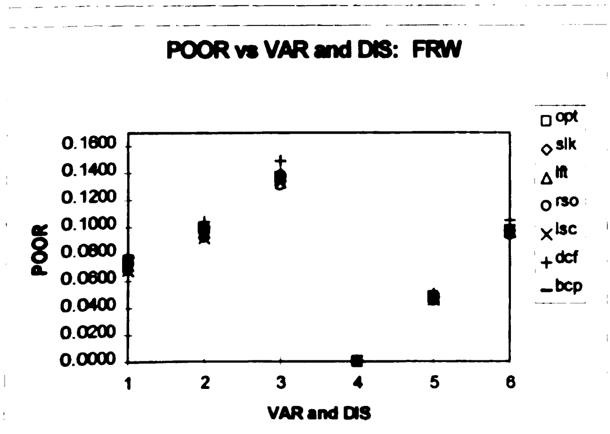


Figure C-44
Graphical Means, POOR/FRW

APPENDIX D

HISTOGRAMS OF NORMALITY AND HOMOSCEDASTICITY

Figure D-1: Normality, ADUR

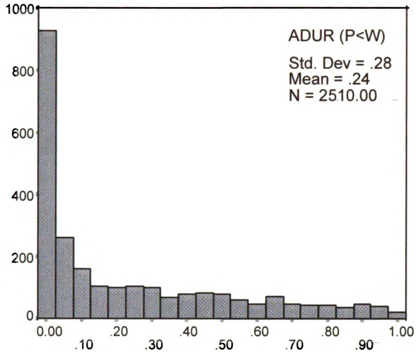


Figure D-2: Variance, ADUR

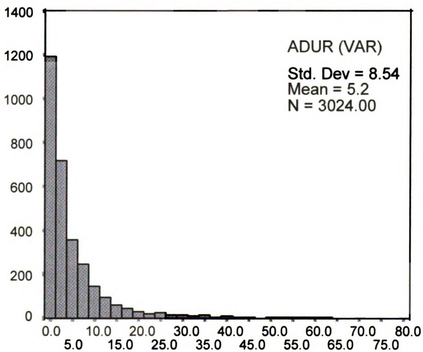


Figure D-3: Normality, RDUR

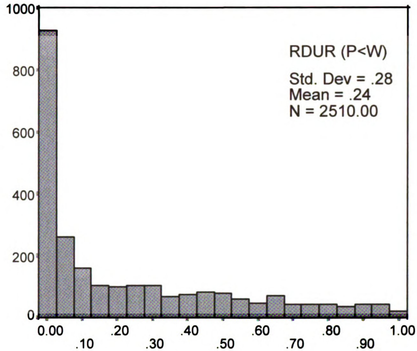


Figure D-4: Variance, RDUR

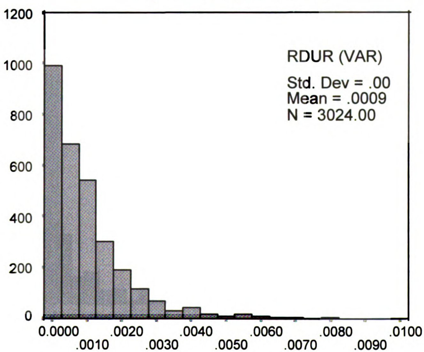


Figure D-5: Normality, ANPV

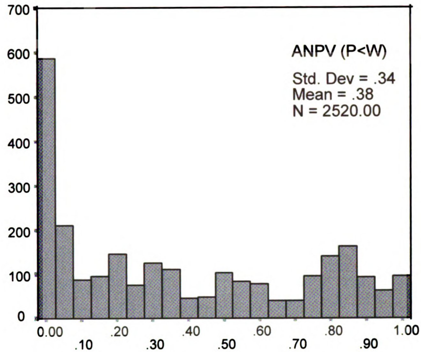


Figure D-6: Variance, ANPV

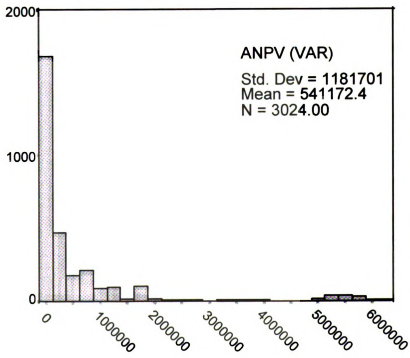


Figure D-7: Normality, RNPV

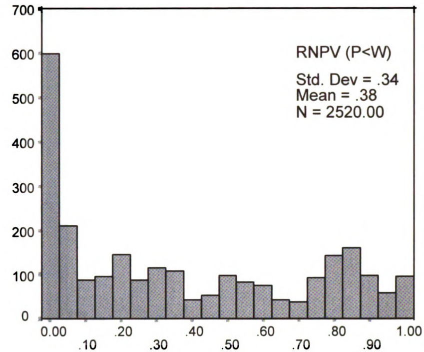


Figure D-8: Variance, RNPV

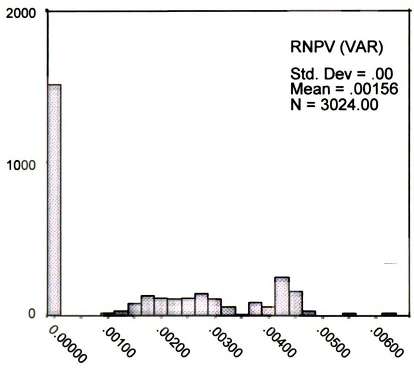


Figure D-9: Normality, WADE

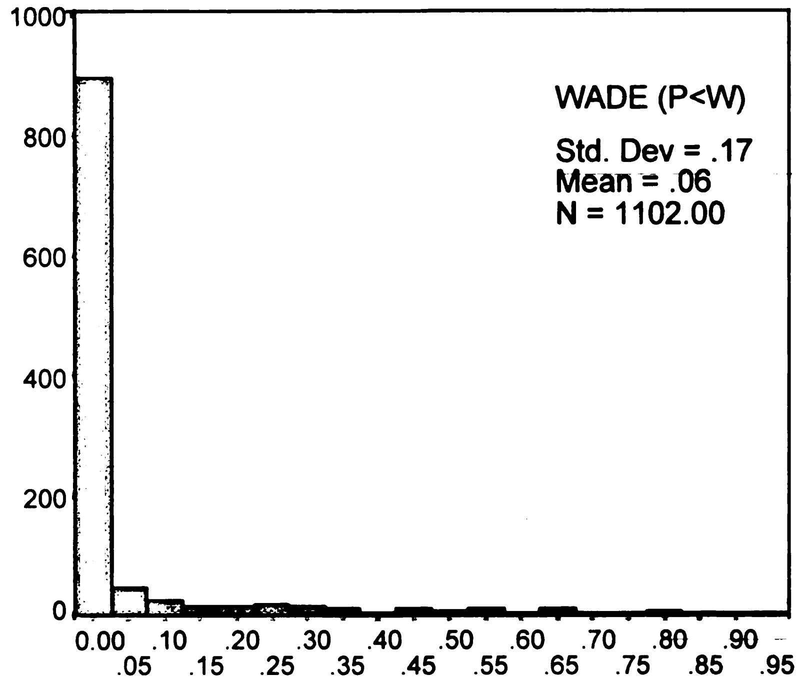


Figure D-10: Variance, WADE

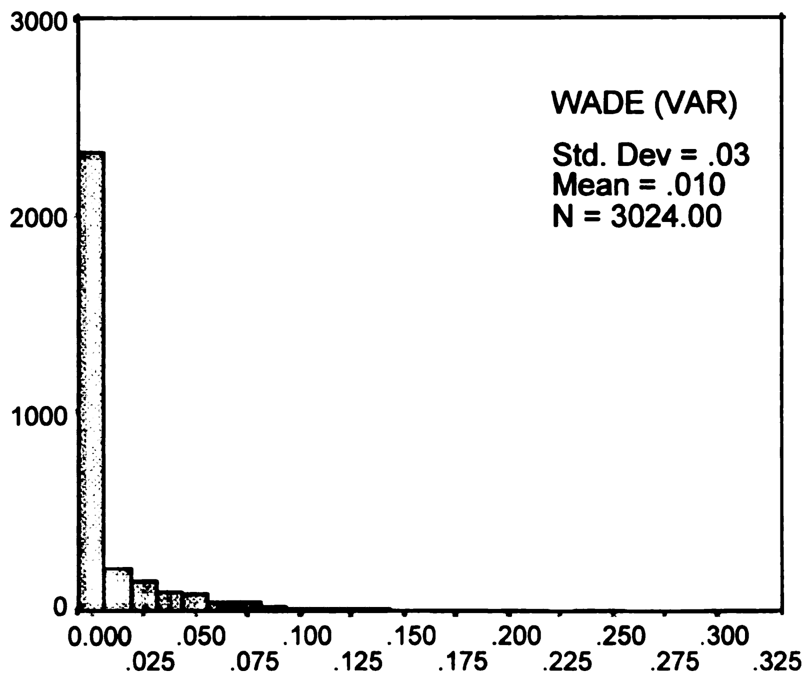


Figure D-11: Normality, WADL

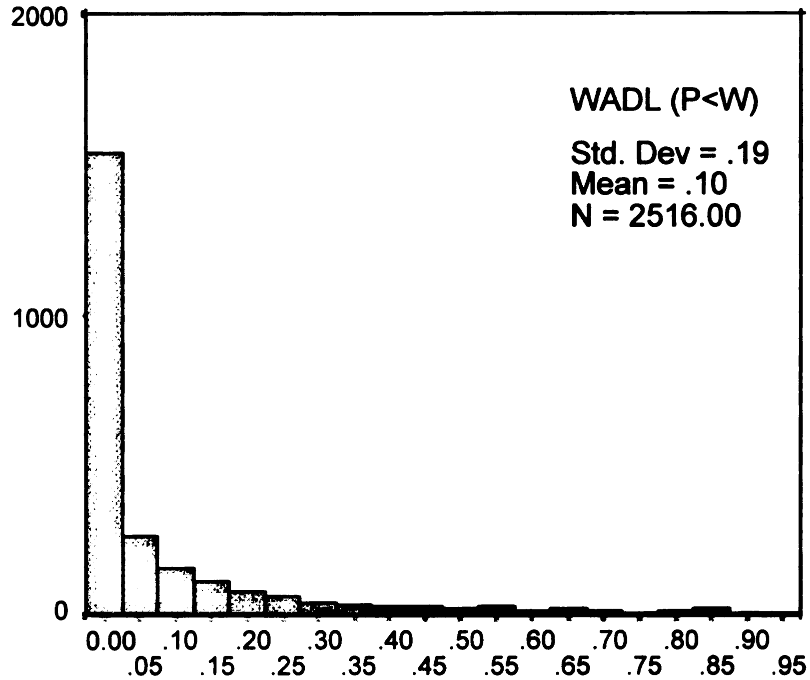


Figure D-12: Variance, WADL

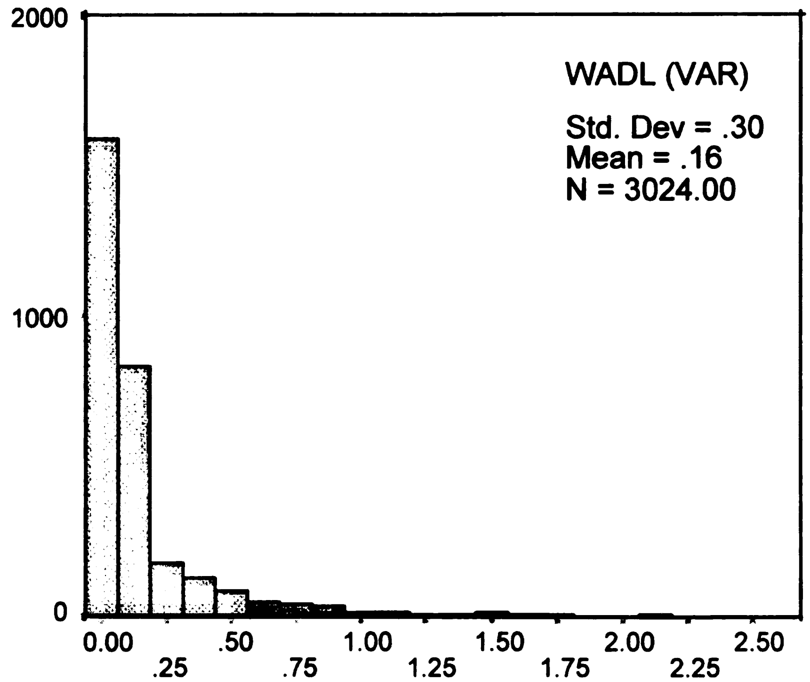


Figure D-13: Normality, WADC

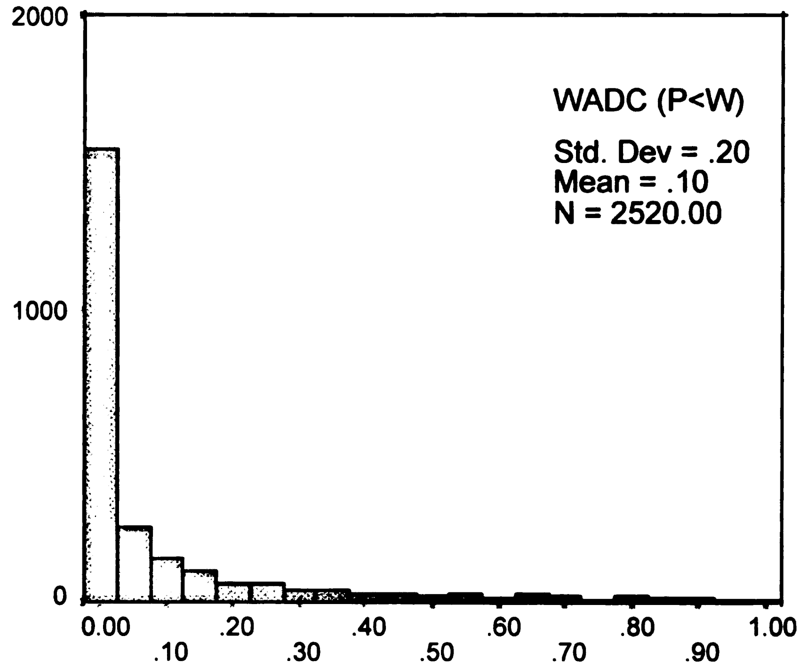


Figure D-14: Variance, WADC

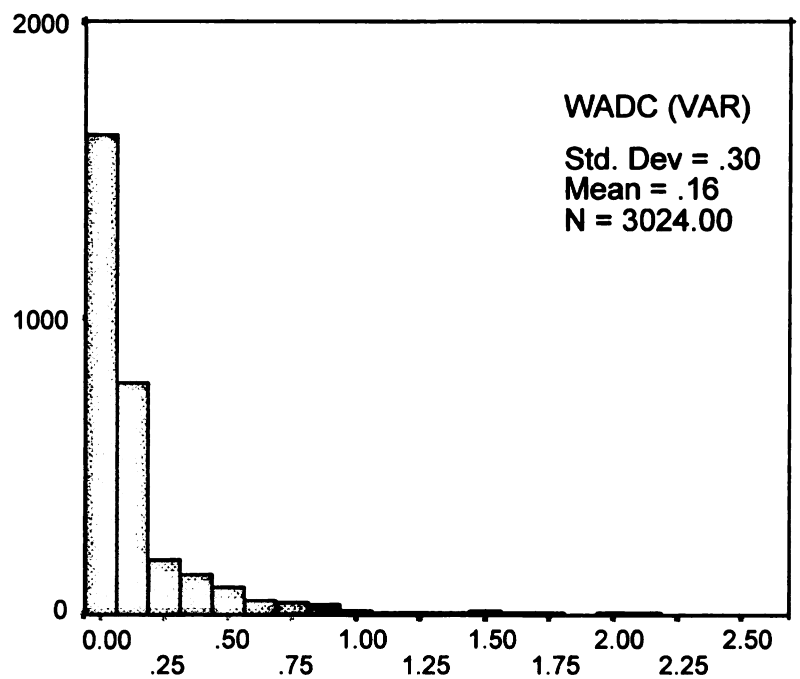


Figure D-15: Normality, POIC

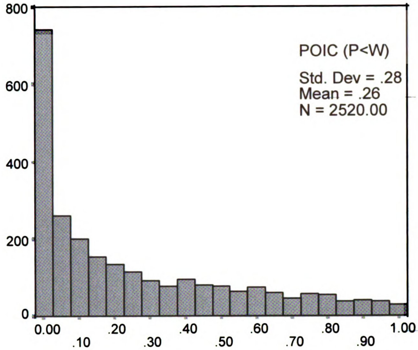


Figure D-16: Variance, POIC

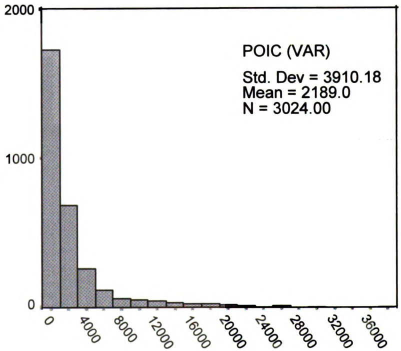


Figure D-17: Normality, POIR

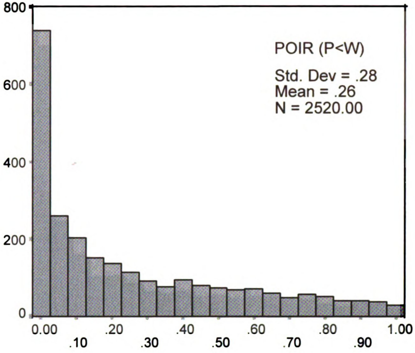


Figure D-18: Variance, POIR

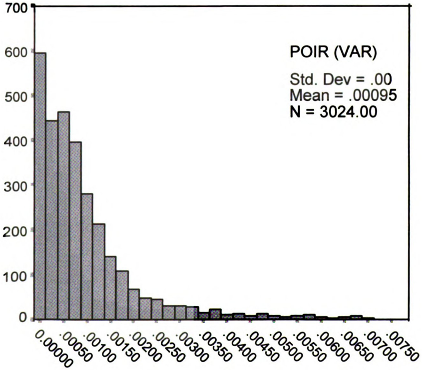


Figure D-19: Normality, POOC

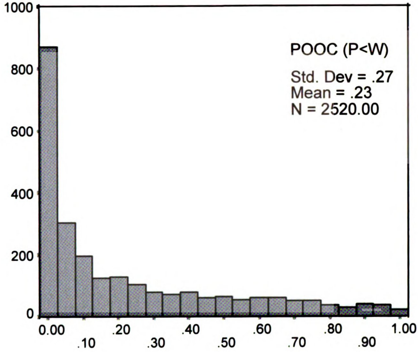


Figure D-20: Variance, POOC

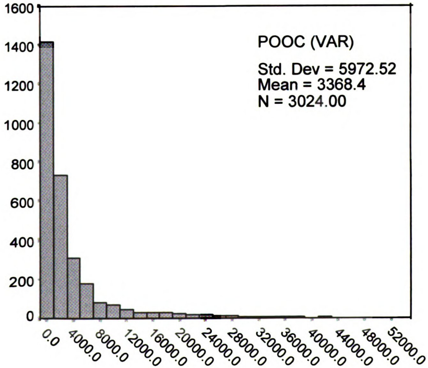


Figure D-21: Normality, POOR

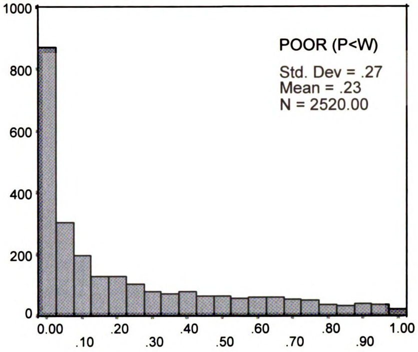
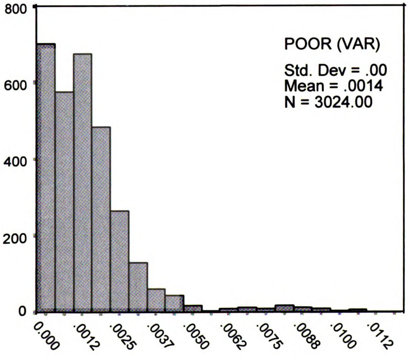


Figure D-22: Variance, POOR



APPENDIX E

BISERIAL SCATTERPLOTS

Figure E-1: Scatterplot, ADUR-RDUR

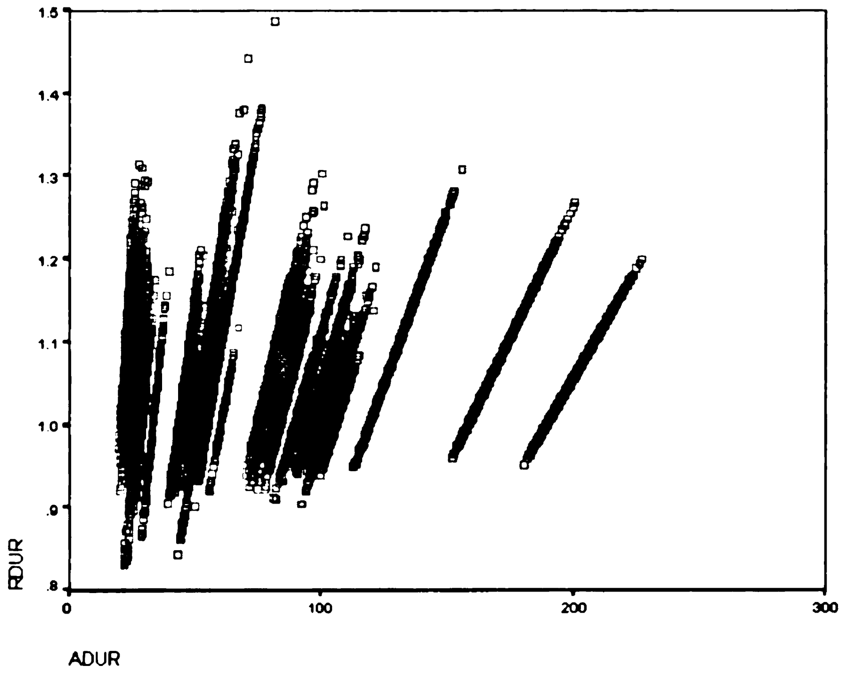


Figure E-2: Scatterplot, ANPV-RNPV

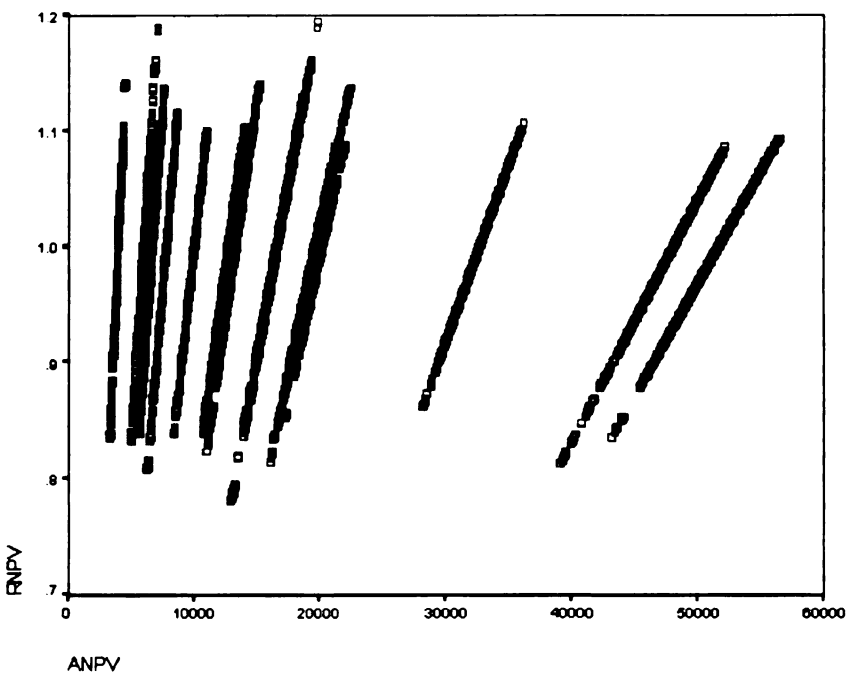


Figure E-3: Scatterplot, RNPV-RDUR

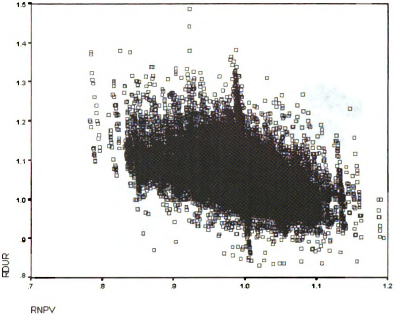


Figure E-4: Scatterplot, ANPV-RDUR

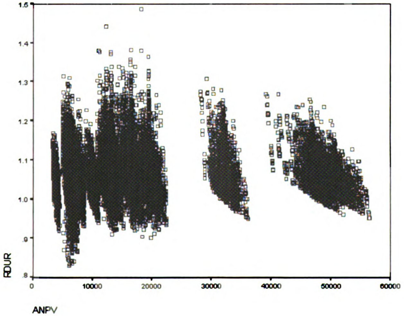


Figure E-5: Scatterplot, ANPV-ADUR

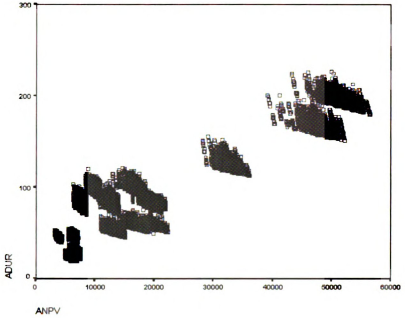


Figure E-6: Scatterplot, RNPV-ADUR

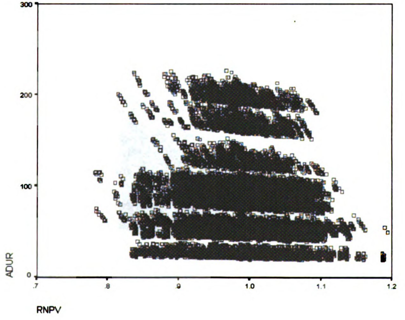


Figure E-7: Scatterplot, WADE-ADUR

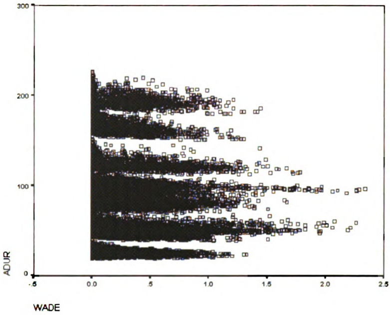


Figure E-8: Scatterplot, WADE-RDUR

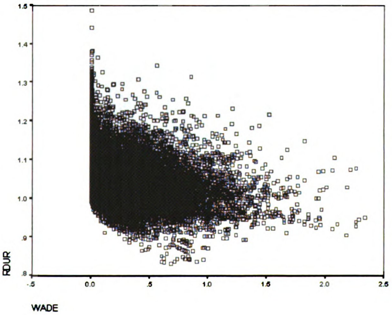


Figure E-9: Scatterplot, WADE-ANPV

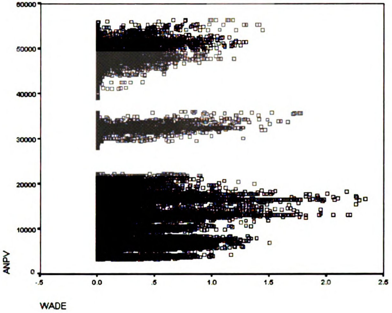


Figure E-10: Scatterplot, WADE-RNPV

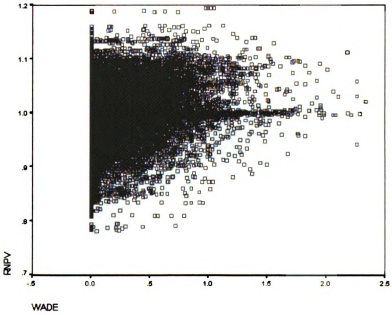


Figure E-11: Scatterplot, WADL-ADUR

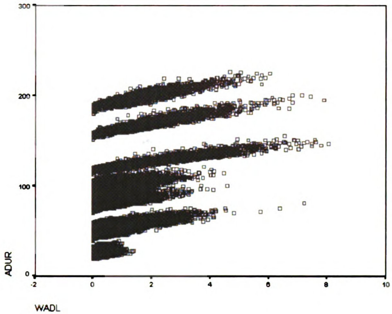


Figure E-12: Scatterplot, WADL-RDUR

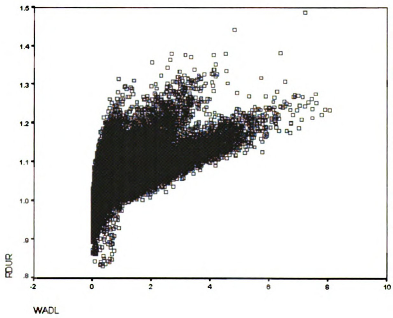


Figure E-13: Scatterplot, WADL-ANPV

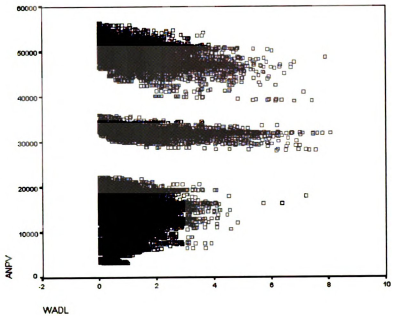


Figure E-14: Scatterplot, WADL-RNPV

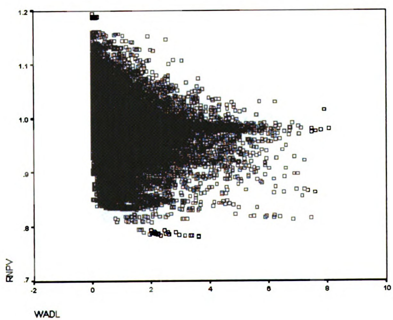


Figure E-15: Scatterplot, WADC-ADUR

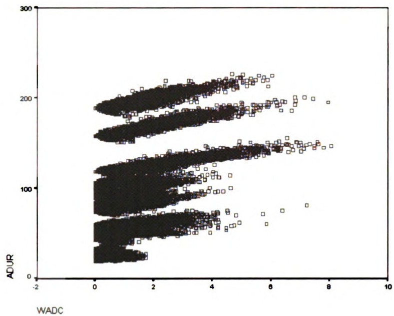


Figure E-16: Scatterplot, WADC-RDUR

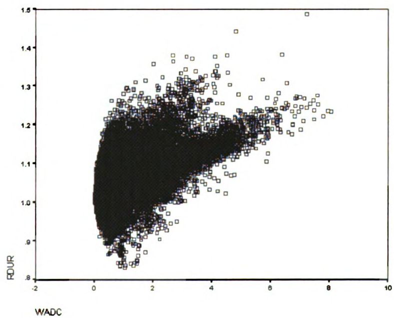


Figure E-17: Scatterplot, WADC-ANPV

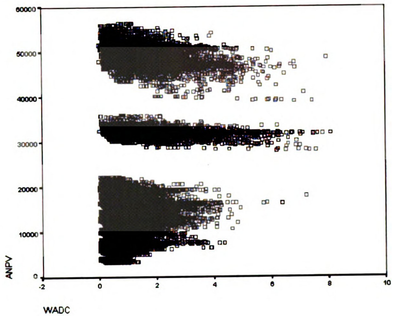


Figure E-18: Scatterplot, WADC-RNPV

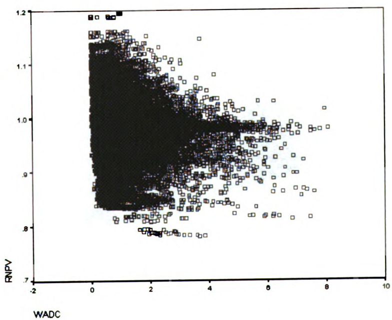


Figure E-19: Scatterplot, POIC-ADUR

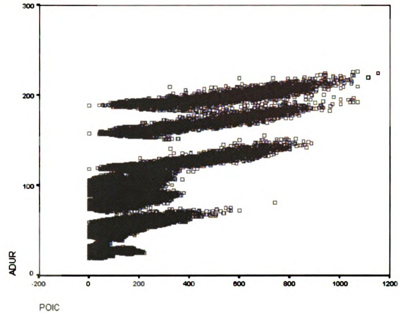


Figure E-20: Scatterplot, POIC-RDUR

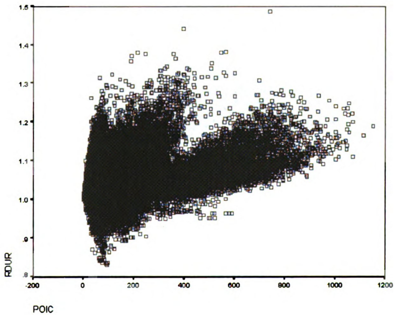


Figure E-21: Scatterplot, POIC-ANPV

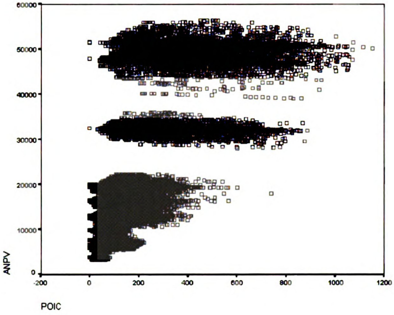


Figure E-22: Scatterplot, POIC-RNPV

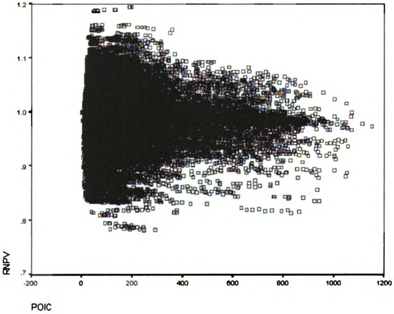


Figure E-23: Scatterplot, POIR-ADUR

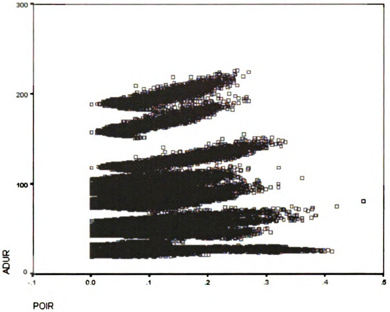


Figure E-24: Scatterplot, POIR-RDUR

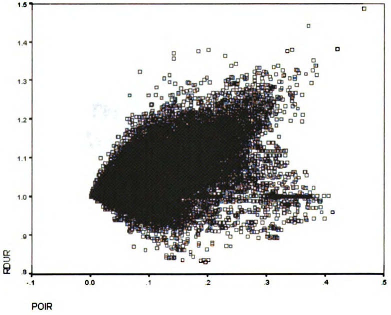


Figure E-25: Scatterplot, POIR-ANPV

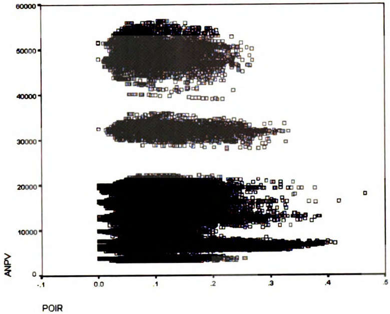


Figure E-26: Scatterplot, POIR-RNPV

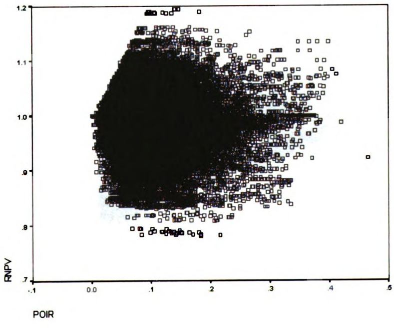


Figure E-27: Scatterplot, POOC-ADUR

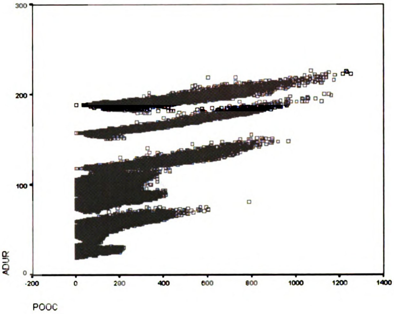


Figure E-28: Scatterplot, POOC-RDUR

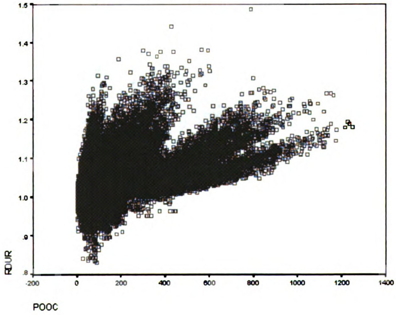


Figure E-29: Scatterplot, POOC-ANPV

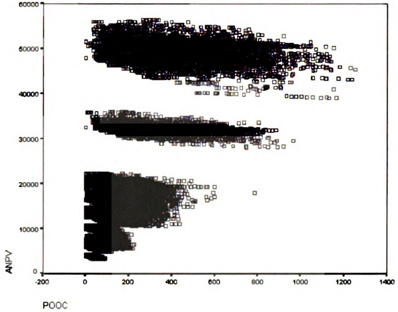


Figure E-30: Scatterplot, POOC-RNPV

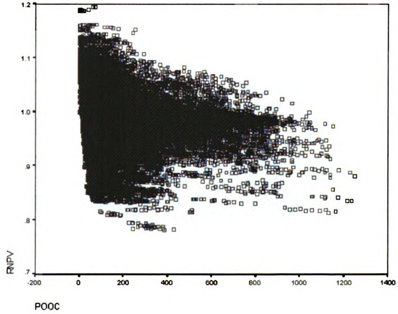


Figure E-31: Scatterplot, POOR-ADUR

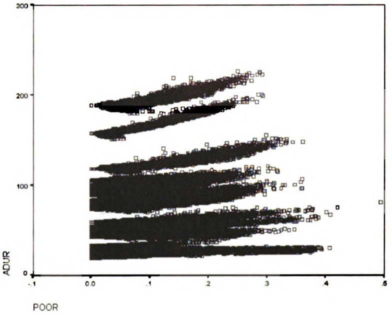


Figure E-32: Scatterplot, POOR-RDUR

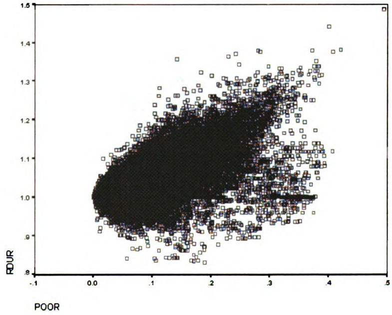


Figure E-33: Scatterplot, POOR-ANPV

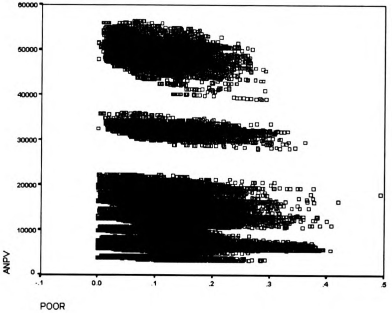
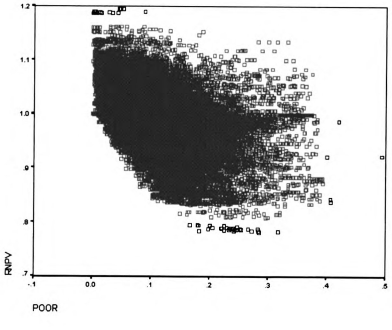


Figure E-34: Scatterplot, POOR-RNPV



APPENDIX F

ANOVA RESIDUAL PLOTS

Figure F-1: Predicted ADUR

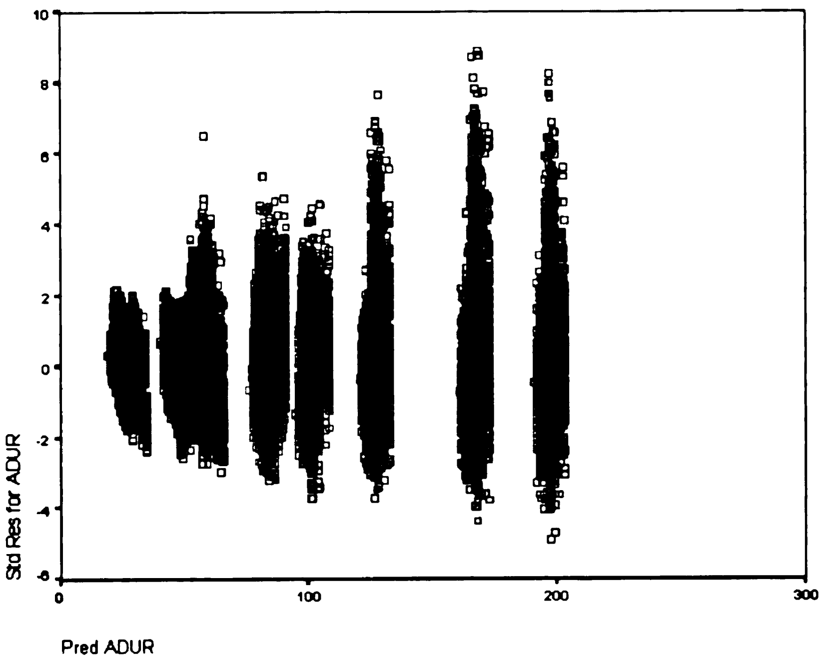


Figure F-2: QQ ADUR

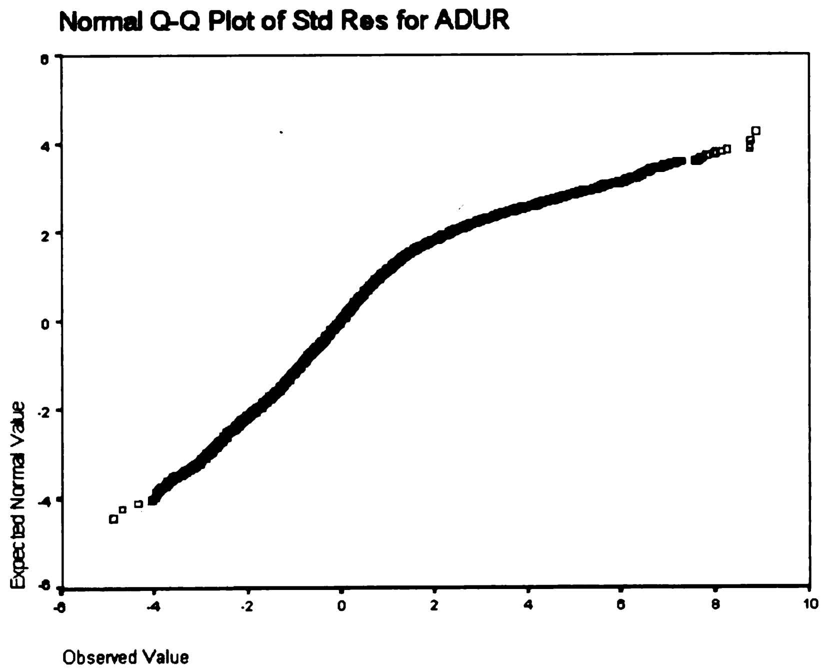


Figure F-3: Predicted RDUR

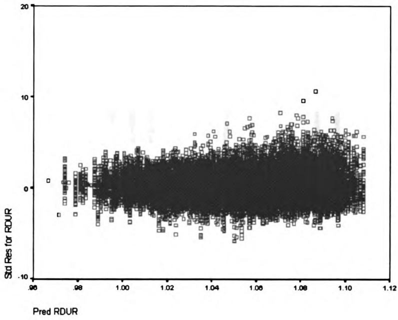


Figure F-4: QQ RDUR

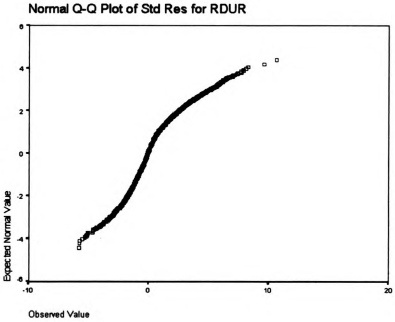


Figure F-5: Predicted ANPV

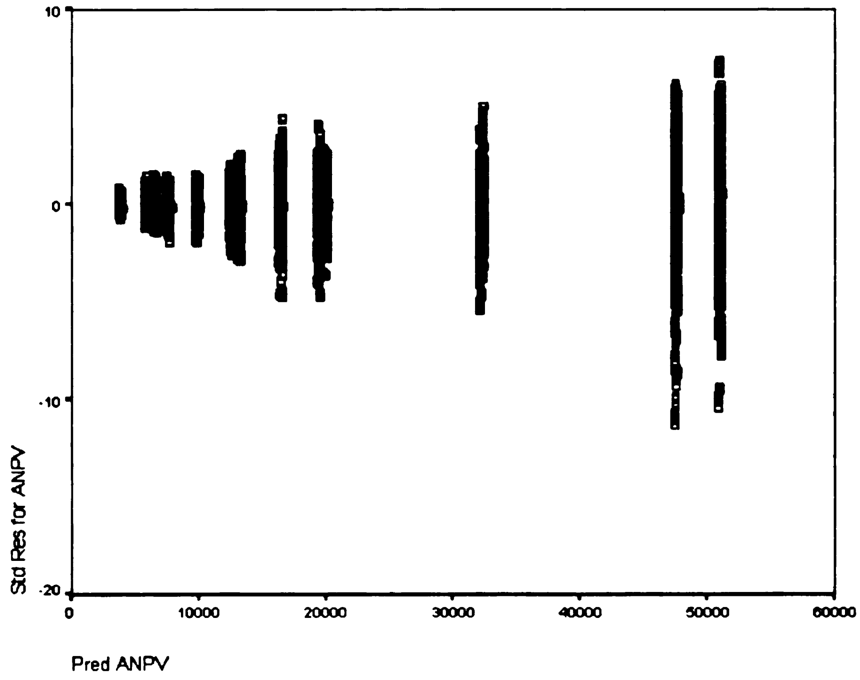


Figure F-6: QQ ANPV

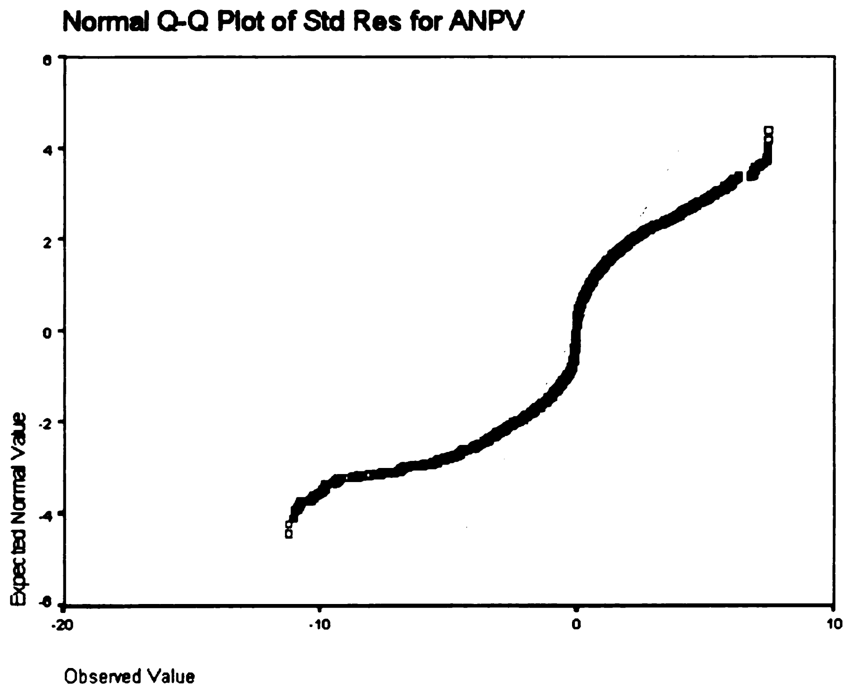


Figure F-7: Predicted RNPV

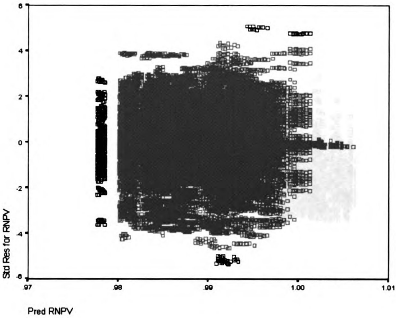


Figure F-8: QQ RNPV

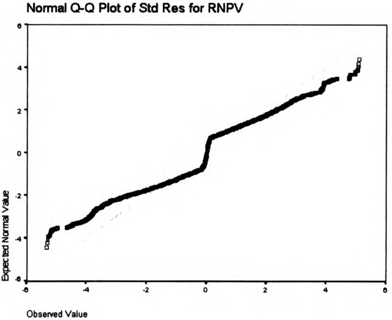


Figure F-9: Predicted WADE

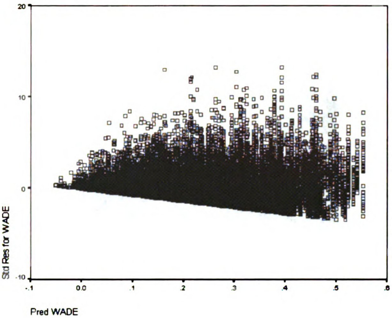


Figure F-10: QQ WADE

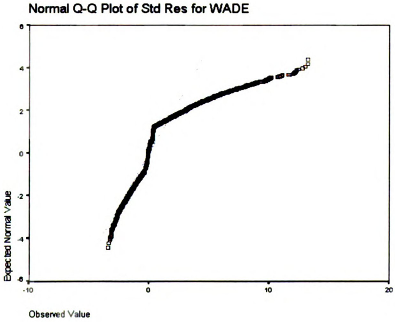


Figure F-11: Predicted WADL

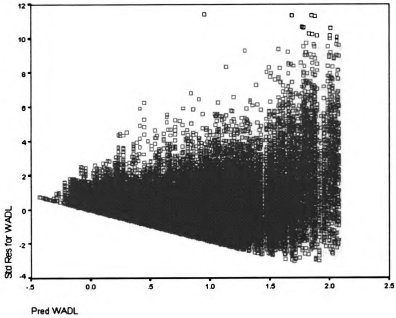


Figure F-12: QQ WADL

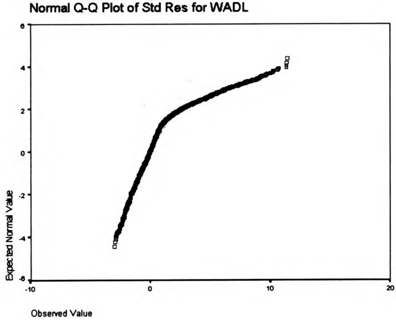


Figure F-13: Predicted WADC

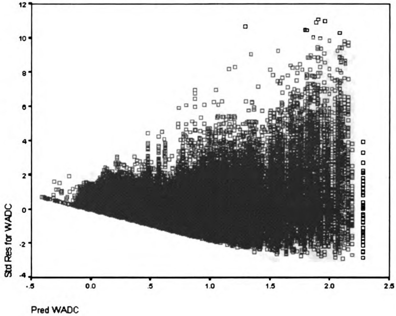


Figure F-14: QQ WADC

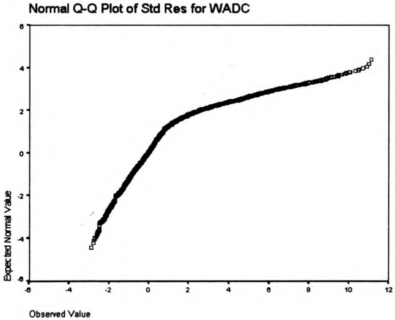


Figure F-15: Predicted POIC

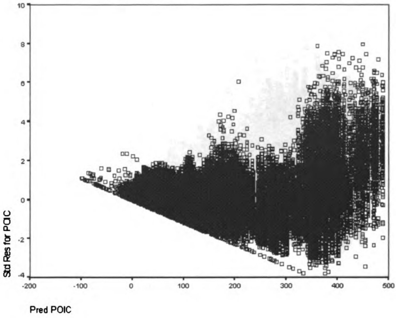


Figure F-16: QQ POIC

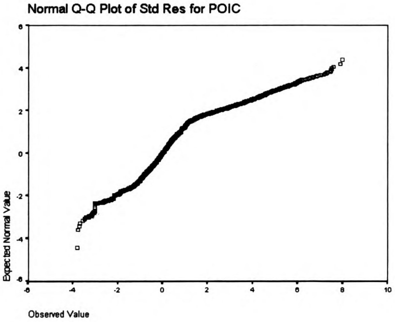


Figure F-17: Predicted POIR

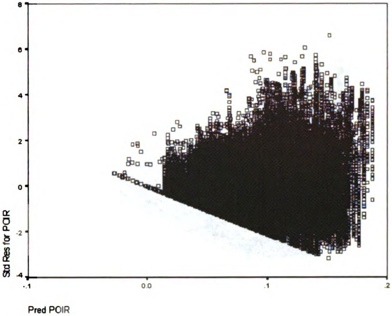


Figure F-18: QQ POIR

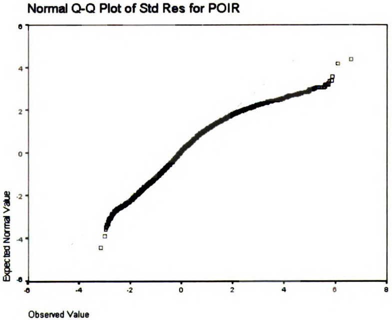


Figure F-19: Predicted POOC

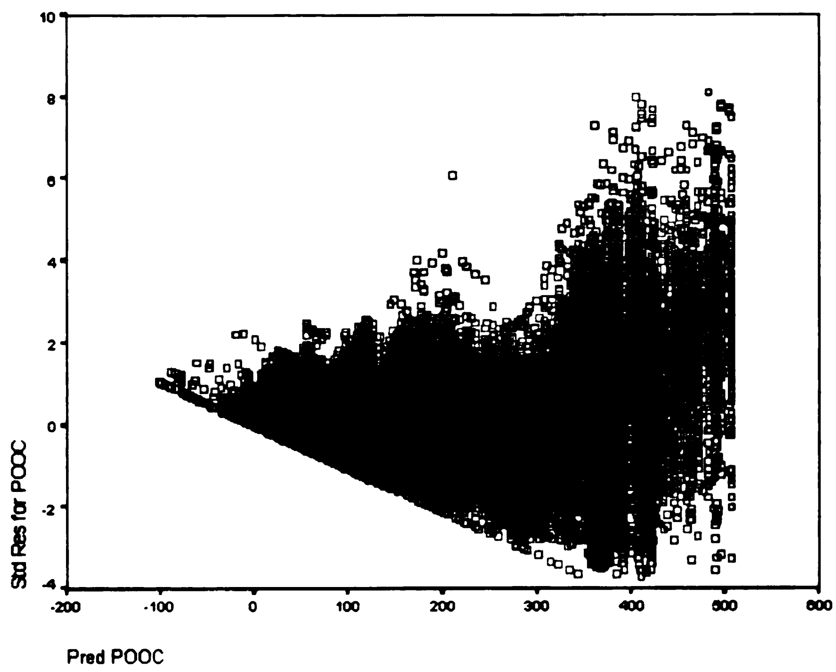


Figure F-20: QQ POOC

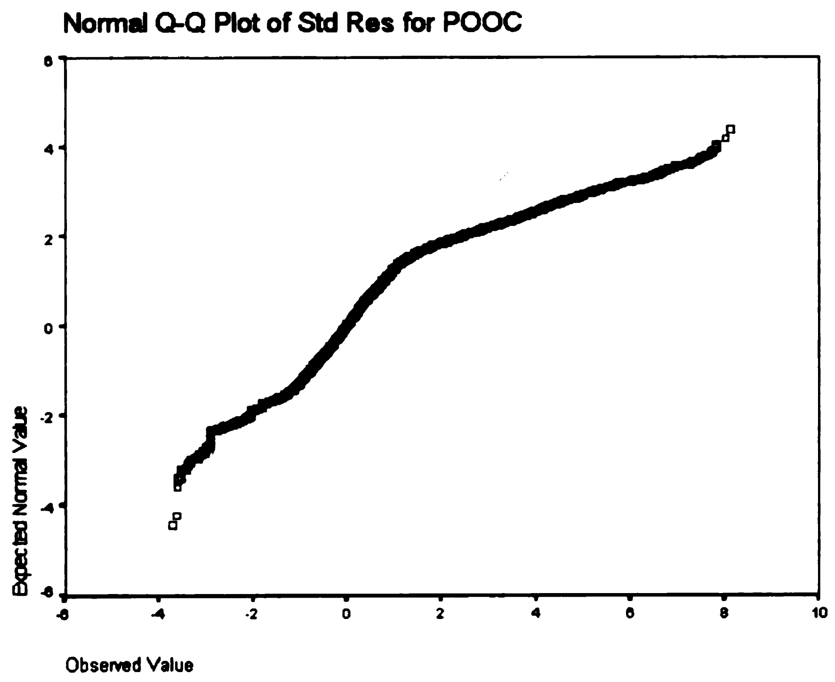


Figure F-21: Predicted POOR

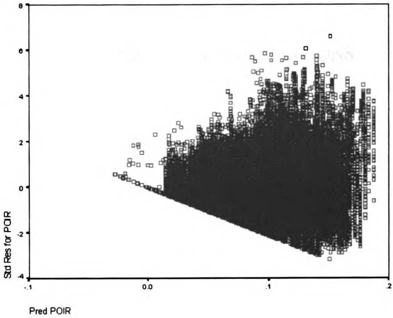
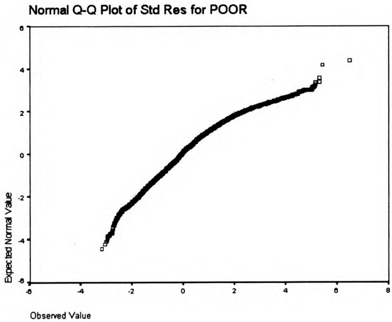


Figure F-22: QQ POOR



APPENDIX G

NONPARAMETRIC COMPARISONS

Table G-1:

Scheduling Method Performance by Execution Method for ADUR

ADUR		FRN									
NONE				FREQ				INFQ			
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
RSO	A	OPT	A	RSO	A	RSO	A	RSO	A	RSO	A
OPT	A	RSO	A	OPT	A	OPT	A	OPT	A	OPT	A
LSC	B	LSC	B	LSC	B	LSC	B	LSC	B	LSC	B
LFT	C	LFT	C	LFT	C	LFT	B	LFT	C	LFT	B
SLK	D	SLK	C	SLK	D	SLK	C	SLK	D	SLK	C
BCP	E	BCP	D	BCP	E	BCP	D	BCP	E	BCP	D
DCF	F	DCF	E	DCF	F	DCF	E	DCF	F	DCF	E
		FRW									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
RSO	A	OPT	A	OPT	A	OPT	A	OPT	A	OPT	A
OPT	A	RSO	A	RSO	A	RSO	A	RSO	A	RSO	A
LSC	B	LSC	B	LSC	B	LSC	B	LSC	B	LSC	B
LFT	C	LFT	BC	LFT	C	LFT	BC	LFT	B	LFT	B
SLK	D	SLK	C	SLK	C	SLK	C	SLK	B	SLK	B
BCP	E	BCP	D	BCP	D	BCP	D	BCP	C	BCP	C
DCF	F	DCF	E	DCF	E	DCF	E	DCF	D	DCF	D
		NRN									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
OPT	A	RSO	A	RSO	A	RSO	A	RSO	A	RSO	A
RSO	B	OPT	A	OPT	AB	OPT	AB	LSC	B	OPT	A
LSC	C	LFT	B	LSC	B	LFT	BC	OPT	B	LFT	AB
SLK	D	LSC	C	LFT	C	LSC	C	LFT	B	LSC	BC
LFT	D	SLK	C	SLK	D	SLK	C	SLK	C	SLK	C
BCP	E	BCP	D	BCP	E	BCP	D	BCP	D	BCP	D
DCF	F	DCF	E	DCF	F	DCF	E	DCF	E	DCF	E
		NRW									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
RSO	A	OPT	A	OPT	A	OPT	A	RSO	A	OPT	A
OPT	A	RSO	A	RSO	A	RSO	A	OPT	A	RSO	A
LSC	B	LSC	B	LSC	B	LSC	B	LFT	B	LFT	B
LFT	C	LFT	B	LFT	C	LFT	B	LSC	B	SLK	C
SLK	D	SLK	B	SLK	D	SLK	B	SLK	B	LSC	C
BCP	E	BCP	C	BCP	E	BCP	C	BCP	C	BCP	D
DCF	F	DCF	D	DCF	F	DCF	D	DCF	D	DCF	E

Table G-2:
Scheduling Method Performance by Execution Method for RDUR

RDUR		FRN									
NONE				FREQ				INFQ			
none		some	.000	none	.000	some	.000	none	.000	some	.000
A		DCF	A	DCF	A	DCF	A	DCF	A	DCF	A
L		LSC	B	BCP	A	BCP	AB	BCP	A	BCP	A
L	E	BCP	B	OPT	B	LFT	BC	LSC	B	LFT	B
	Q	SLK	B	RSO	B	SLK	C	RSO	B	LSC	BC
	U	LFT	B	LSC	B	LSC	CD	SLK	B	SLK	BC
	A	OPT	C	SLK	B	RSO	DE	LFT	B	RSO	C
	L	RSO	C	LFT	B	OPT	E	OPT	B	OPT	C
		FRW									
none		some	.000	none	.000	some	.000	none	.000	some	.000
A		DCF	A	DCF	A	DCF	A	DCF	A	DCF	A
L		BCP	B	BCP	B	BCP	B	BCP	AB	BCP	A
L	E	LFT	BC	SLK	BC	LFT	BC	SLK	BC	SLK	B
	Q	SLK	BC	OPT	BCD	SLK	CD	LFT	CD	LFT	B
	U	OPT	CD	LFT	CD	OPT	CE	OPT	DE	OPT	BC
	A	LSC	DE	RSO	D	LSC	EF	RSO	EF	LSC	CD
	L	RSO	E	LSC	E	RSO	F	LSC	F	RSO	D
		NRN									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
DCF	A	DCF	A	DCF	A	DCF	A	DCF	A	DCF	A
BCP	B	BCP	B	BCP	B	BCP	B	BCP	B	BCP	A
LFT	C	LFT	C	LSC	C	SLK	C	LFT	C	LFT	B
SLK	C	SLK	C	LFT	C	LFT	C	SLK	C	SLK	BC
LSC	D	LSC	D	SLK	C	LSC	D	LSC	C	LSC	C
OPT	E	RSO	E	RSO	D	RSO	E	RSO	D	RSO	D
RSO	F	OPT	E	OPT	D	OPT	E	OPT	E	OPT	D
		NRW									
none		some	.000	none	.000	some	.000	none	.000	some	.000
A		DCF	A	DCF	A	DCF	A	DCF	A	DCF	A
L		BCP	B	BCP	B	BCP	B	BCP	B	BCP	B
L	E	SLK	BC	SLK	BC	SLK	B	SLK	B	LFT	B
	Q	LFT	C	OPT	BC	LFT	B	LFT	B	SLK	B
	U	LSC	D	LFT	CD	LSC	C	RSO	C	OPT	C
	A	OPT	D	RSO	DE	OPT	C	OPT	C	LSC	C
	L	RSO	D	LSC	E	RSO	C	LSC	C	RSO	C

Table G-3:
Scheduling Method Performance by Execution Method for ANPV

ANPV		FRN									
	NONE				FREQ				INFQ		
none	**.000**	**some**	**.389**	**none**	**.000**	**some**	**.661**	**none**	**.000**	**some**	**.879**
OPT	A	OPT	A	OPT	A	OPT	A	OPT	A	OPT	A
LFT	B	LFT	A	LFT	B	LFT	A	LFT	B	LFT	A
RSO	C	BCP	A	BCP	BC	BCP	A	BCP	B	BCP	A
BCP	D	SLK	A	RSO	C	SLK	A	SLK	B	SLK	A
SLK	D	RSO	A	SLK	C	RSO	A	RSO	C	RSO	A
LSC	E	LSC	A	LSC	D	DCF	A	DCF	D	DCF	A
DCF	F	DCF	A	DCF	E	LSC	A	LSC	D	LSC	A
		FRW									
none	**.000**	**some**	**.336**	**none**	**.000**	**some**	**.645**	**none**	**.000**	**some**	**.816**
OPT	A	OPT	A	OPT	A	OPT	A	OPT	A	OPT	A
LFT	B	LFT	A	RSO	B	LFT	A	LFT	B	BCP	A
RSO	C	BCP	A	LFT	B	BCP	A	SLK	B	LFT	A
BCP	D	RSO	A	SLK	B	SLK	A	BCP	BC	SLK	A
SLK	E	SLK	A	BCP	C	RSO	A	RSO	C	RSO	A
LSC	F	LSC	A	LSC	D	DCF	A	LSC	D	DCF	A
DCF	G	DCF	A	DCF	E	LSC	A	DCF	D	LSC	A
		NRN									
none	**.000**	**some**	**.094**	**none**	**.000**	**some**	**.157**	**none**	**.000**	**some**	**.252**
LFT	A	LFT	A	BCP	A	BCP	A	BCP	A	LFT	A
BCP	B	BCP	A	LFT	A	DCF	A	LFT	A	BCP	A
SLK	B	DCF	A	SLK	B	LFT	A	SLK	B	SLK	A
OPT	C	SLK	A	DCF	B	SLK	A	DCF	B	DCF	A
DCF	D	OPT	A	OPT	C	OPT	A	OPT	C	OPT	A
RSO	E	LSC	A	LSC	C	LSC	A	LSC	C	LSC	A
LSC	F	RSO	A	RSO	D	RSO	A	RSO	D	RSO	A
		NRW									
none	**.000**	**some**	**.526**	**none**	**.000**	**some**	**.919**	**none**	**.000**	**some**	**.859**
OPT	A	OPT	A	OPT	A	OPT	A	LFT	A	LFT	A
LFT	B	LFT	A	LFT	B	LFT	A	SLK	A	OPT	A
RSO	C	BCP	A	SLK	BC	SLK	A	OPT	A	SLK	A
BCP	D	SLK	A	RSO	BC	RSO	A	BCP	A	BCP	A
SLK	E	RSO	A	BCP	C	BCP	A	RSO	B	DCF	A
LSC	F	DCF	A	LSC	D	DCF	A	DCF	C	RSO	A
DCF	G	LSC	A	DCF	E	LSC	A	LSC	C	LSC	A

Table G-4:
Scheduling Method Performance by Execution Method for RNPV

RNPV		FRN									
NONE				FREQ				INFQ			
none	**.000**	**some**	**.786**	**none**	**.000**	**some**	**.797**	**none**	**.000**	**some**	**.820**
OPT	A	DCF	A	DCF	A	DCF	A	DCF	A	DCF	A
SLK	A	SLK	A	BCP	AB	BCP	A	BCP	AB	BCP	A
LFT	A	LFT	A	OPT	BC	LFT	A	LFT	B	LFT	A
DCF	A	BCP	A	LFT	C	SLK	A	OPT	B	OPT	A
BCP	A	OPT	A	SLK	C	OPT	A	SLK	B	SLK	A
RSO	B	LSC	A	RSO	D	LSC	A	RSO	C	LSC	A
LSC	C	RSO	A	LSC	E	RSO	A	LSC	C	RSO	A
		FRW									
none		**some**	**.938**	**none**	**.000**	**some**	**.897**	**none**	**.000**	**some**	**.925**
A		DCF	A	DCF	A	DCF	A	DCF	A	DCF	A
L		BCP	A	OPT	B	BCP	A	BCP	A	BCP	A
L	E	SLK	A	SLK	BC	LFT	A	SLK	B	OPT	A
	Q	LFT	A	BCP	BCD	SLK	A	LFT	B	SLK	A
	U	OPT	A	RSO	CD	OPT	A	OPT	B	LFT	A
	A	LSC	A	LFT	D	RSO	A	RSO	C	RSO	A
	L	RSO	A	LSC	E	LSC	A	LSC	D	LSC	A
		NRN									
none	**.000**	**some**	**.009**	**none**	**.000**	**some**	**.009**	**none**	**.000**	**some**	**.084**
DCF	A	DCF	A	DCF	A	DCF	A	DCF	A	BCP	A
BCP	B	BCP	A	BCP	B	BCP	A	BCP	B	DCF	A
SLK	BC	LFT	A	LFT	C	SLK	A	LFT	BC	LFT	A
LFT	C	SLK	A	SLK	C	LFT	A	SLK	C	SLK	A
OPT	D	LSC	A	LSC	D	LSC	A	LSC	D	LSC	A
LSC	E	OPT	A	OPT	E	OPT	A	OPT	E	OPT	A
RSO	F	RSO	A	RSO	F	RSO	A	RSO	F	RSO	A
		NRW									
none		**some**	**.756**	**none**	**.000**	**some**	**.789**	**none**	**.000**	**some**	**.647**
A		DCF	A	DCF	A	DCF	A	DCF	A	DCF	A
L		BCP	A	BCP	B	SLK	A	SLK	B	LFT	A
L	E	SLK	A	OPT	B	LFT	A	BCP	B	SLK	A
	Q	LFT	A	SLK	B	BCP	A	LFT	B	BCP	A
	U	OPT	A	LFT	B	LSC	A	OPT	C	OPT	A
	A	LSC	A	RSO	C	OPT	A	RSO	C	LSC	A
	L	RSO	A	LSC	C	RSO	A	LSC	C	RSO	A

Table G-5:
Scheduling Method Performance by Execution Method for WADL

WDL		FRN									
NONE				FREQ				INFQ			
none		**some**	**.000**	**none**	**.000**	**some**	**.001**	**none**	**.000**	**some**	**.001**
A		LSC	A	RSO	A	LSC	A	RSO	A	LSC	A
L		DCF	B	LSC	A	DCF	AB	LSC	AB	DCF	AB
L	E	LFT	BC	DCF	AB	BCP	BC	DCF	AB	BCP	AB
	Q	SLK	BC	BCP	BC	RSO	BC	BCP	BC	RSO	AB
	U	RSO	BC	OPT	BD	LFT	BC	OPT	CD	LFT	BC
	A	BCP	C	LFT	DE	SLK	CD	LFT	D	SLK	C
	L	OPT	C	SLK	E	OPT	D	SLK	D	OPT	C
		FRW									
none		**some**	**.075**	**none**	**.001**	**some**	**.028**	**none**	**.001**	**some**	**.146**
A		DCF	A	DCF	A	DCF	A	BCP	A	DCF	A
L		LSC	AB	BCP	AB	LSC	AB	DCF	A	BCP	AB
L	E	LFT	AB	RSO	ABC	LFT	ABC	SLK	AB	LSC	AB
	Q	SLK	AB	OPT	BCD	BCP	BC	RSO	AB	LFT	AB
	U	OPT	B	SLK	CD	SLK	BC	OPT	B	SLK	AB
	A	BCP	B	LSC	CD	RSO	BC	LFT	B	RSO	B
	L	RSO	B	LFT	D	OPT	C	LSC	B	OPT	B
		NRN									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
BCP	A	DCF	A	LSC	A	BCP	A	LSC	A	BCP	A
LSC	B	BCP	B	BCP	A	DCF	A	BCP	A	LSC	AB
LFT	BC	LSC	BC	DCF	B	LSC	A	LFT	B	LFT	ABC
DCF	C	LFT	BC	SLK	B	SLK	B	DCF	B	DCF	BC
SLK	D	SLK	C	LFT	B	LFT	C	SLK	B	SLK	C
OPT	E	RSO	D	RSO	C	RSO	CD	RSO	C	RSO	D
RSO	F	OPT	E	OPT	D	OPT	D	OPT	D	OPT	E
		NRW									
none		**some**	**.024**	**none**	**.035**	**some**	**.004**	**none**	**.001**	**some**	**.025**
A		DCF	A	BCP	A	LSC	A	BCP	A	BCP	A
L		LSC	AB	RSO	AB	DCF	A	RSO	AB	LFT	A
L	E	BCP	ABC	DCF	ABC	BCP	A	SLK	AB	DCF	A
	Q	SLK	ABC	OPT	ABC	RSO	A	LFT	AB	LSC	A
	U	LFT	ABC	SLK	BC	SLK	A	DCF	AB	SLK	AB
	A	RSO	BC	LSC	C	LFT	A	LSC	BC	RSO	B
	L	OPT	C	LFT	C	OPT	B	OPT	C	OPT	B

Table G-6:
Scheduling Method Performance by Execution Method for WADE

WDE		FRN									
NONE				FREQ				INFQ			
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
OPT	A	OPT	A	BCP	A	OPT	A	DCF	A	SLK	A
SLK	A	BCP	A	DCF	A	SLK	AB	BCP	A	OPT	A
LFT	A	LFT	AB	LFT	A	LFT	AB	OPT	A	LFT	A
DCF	A	SLK	AB	OPT	A	BCP	AB	LFT	A	BCP	AB
BCP	A	DCF	B	SLK	A	DCF	B	SLK	A	DCF	B
RSO	B	RSO	C	RSO	B	RSO	C	RSO	B	RSO	C
LSC	C	LSC	D	LSC	C	LSC	D	LSC	C	LSC	D
		FRW									
none		**some**		**none**		**some**		**none**		**some**	
A		A		A		A		A		A	
L		L		L		L		L		L	
L	E	L	E	L	E	L	E	L	E	L	E
	Q		Q		Q		Q		Q		Q
	U		U		U		U		U		U
	A		A		A		A		A		A
	L		L		L		L		L		L
		NRN									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
BCP	A	LFT	A	DCF	A	DCF	A	DCF	A	DCF	A
LFT	B	SLK	AB	OPT	B	OPT	B	LFT	B	LFT	B
SLK	C	OPT	B	LFT	B	LFT	BC	OPT	B	OPT	B
OPT	D	BCP	B	SLK	C	SLK	C	SLK	B	SLK	C
DCF	E	DCF	B	BCP	D	BCP	D	BCP	C	BCP	D
LSC	F	RSO	C	RSO	E	RSO	E	RSO	D	RSO	E
RSO	G	LSC	C	LSC	F	LSC	F	LSC	E	LSC	F
		NRW									
none		**some**		**none**		**some**		**none**		**some**	
A		A		A		A		A		A	
L		L		L		L		L		L	
L	E	L	E	L	E	L	E	L	E	L	E
	Q		Q		Q		Q		Q		Q
	U		U		U		U		U		U
	A		A		A		A		A		A	
	L		L		L		L		L		L

Table G-7:
Scheduling Method Performance by Execution Method for WADC

WDC		FRN									
NONE				FREQ				INFQ			
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
OPT	A	LFT	A	DCF	A	DCF	A	DCF	A	BCP	A
SLK	A	DCF	A	BCP	AB	LFT	A	BCP	AB	DCF	AB
LFT	A	OPT	A	OPT	BC	BCP	A	OPT	BC	LFT	B
DCF	A	SLK	A	LFT	CD	SLK	A	LFT	C	SLK	B
BCP	A	BCP	A	SLK	D	OPT	A	SLK	C	OPT	B
RSO	B	RSO	B	RSO	E	RSO	B	RSO	D	RSO	C
LSC	C	LSC	B	LSC	F	LSC	B	LSC	E	LSC	C
		FRW									
none		**some**	**.075**	**none**	**.001**	**some**	**.028**	**none**	**.008**	**some**	**.146**
A		DCF	A	DCF	A	DCF	A	BCP	A	DCF	A
L		LSC	AB	BCP	AB	LSC	AB	DCF	AB	BCP	AB
L	E	LFT	AB	RSO	ABC	LFT	ABC	SLK	ABC	LSC	AB
	Q	SLK	AB	OPT	BCD	BCP	BC	RSO	ABC	LFT	AB
	U	OPT	B	SLK	CD	SLK	BC	OPT	BC	SLK	AB
	A	BCP	B	LSC	CD	RSO	BC	LFT	C	RSO	B
	L	RSO	B	LFT	D	OPT	C	LSC	C	OPT	B
		NRN									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
BCP	A	DCF	A	DCF	A	DCF	A	LFT	A	LFT	A
SLK	B	LFT	A	SLK	B	SLK	B	DCF	AB	DCF	A
LFT	B	BCP	B	LFT	B	LFT	B	SLK	AB	SLK	B
DCF	C	SLK	B	BCP	B	BCP	B	BCP	B	BCP	B
OPT	D	OPT	C	OPT	C	OPT	C	OPT	C	OPT	C
LSC	E	LSC	D	LSC	D	LSC	D	LSC	C	LSC	C
RSO	F	RSO	E	RSO	E	RSO	D	RSO	D	RSO	D
		NRW									
none		**some**	**.024**	**none**	**.035**	**some**	**.004**	**none**	**.001**	**some**	**.025**
A		DCF	A	BCP	A	LSC	A	BCP	A	BCP	A
L		LSC	AB	RSO	AB	DCF	A	RSO	AB	LFT	AB
L	E	BCP	ABC	DCF	ABC	BCP	A	SLK	AB	DCF	AB
	Q	SLK	ABC	OPT	ABC	RSO	A	LFT	AB	LSC	AB
	U	LFT	ABC	SLK	BC	SLK	A	DCF	AB	SLK	AB
	A	RSO	BC	LSC	C	LFT	AB	LSC	BC	RSO	BC
	L	OPT	C	LFT	C	OPT	B	OPT	C	OPT	C

Table G-8:

Scheduling Method Performance by Execution Method for POIC

POIC		FRN									
	NONE			FREQ				INFQ			
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
OPT	A	LFT	A	BCP	A	LFT	A	BCP	A	BCP	A
SLK	A	SLK	A	DCF	AB	SLK	B	LFT	AB	LFT	AB
LFT	A	OPT	A	OPT	AB	BCP	B	OPT	AB	OPT	AB
DCF	A	BCP	B	LFT	AB	OPT	B	SLK	B	SLK	B
BCP	A	DCF	B	SLK	B	DCF	C	DCF	B	DCF	C
RSO	B	RSO	C	RSO	C	RSO	D	RSO	C	RSO	D
LSC	C	LSC	D	LSC	D	LSC	D	LSC	D	LSC	E
		FRW									
none		**some**	**.000**	**none**	**.244**	**some**	**.000**	**none**	**.004**	**some**	**.000**
A		LSC	A	RSO	A	LSC	A	BCP	A	RSO	A
L		LFT	A	LSC	AB	RSO	AB	RSO	AB	LSC	AB
L	E	RSO	AB	BCP	AB	LFT	AB	SLK	AB	BCP	AB
	Q	SLK	AB	LFT	AB	SLK	BC	LFT	AB	OPT	AB
	U	OPT	B	SLK	AB	OPT	C	LSC	BC	LFT	B
	A	BCP	C	OPT	B	BCP	CD	OPT	BC	SLK	B
	L	DCF	C	DCF	B	DCF	D	DCF	C	DCF	C
		NRN									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
BCP	A	LFT	A	BCP	A	BCP	A	LFT	A	LFT	A
DCF	B	SLK	B	SLK	A	SLK	AB	BCP	A	BCP	A
LFT	B	BCP	B	LFT	A	LFT	BC	SLK	A	SLK	B
SLK	B	DCF	B	DCF	A	DCF	C	DCF	B	DCF	C
OPT	C	OPT	C	OPT	B	OPT	D	OPT	C	OPT	C
LSC	D	LSC	D	LSC	C	LSC	E	LSC	D	LSC	D
RSO	E	RSO	D	RSO	D	RSO	E	RSO	E	RSO	E
		NRW									
none		**some**	**.000**	**none**	**.055**	**some**	**.000**	**none**	**.000**	**some**	**.000**
A		LSC	A	RSO	A	LSC	A	RSO	A	RSO	A
L		RSO	A	LFT	AB	RSO	A	LFT	AB	LFT	A
L	E	LFT	AB	LSC	AB	LFT	AB	SLK	AB	LSC	AB
	Q	SLK	BC	BCP	AB	SLK	BC	BCP	AB	BCP	B
	U	BCP	CD	OPT	AB	BCP	CD	LSC	B	SLK	B
	A	OPT	CD	SLK	B	OPT	CD	OPT	C	OPT	B
	L	DCF	D	DCF	B	DCF	D	DCF	C	DCF	C

Table G-9:
Scheduling Method Performance by Execution Method for POIR

POIR		FRN									
NONE				FREQ				INFQ			
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
OPT	A	LFT	A	BCP	A	LFT	A	BCP	A	BCP	A
SLK	A	SLK	A	DCF	AB	SLK	B	LFT	AB	LFT	AB
LFT	A	OPT	AB	OPT	AB	BCP	B	OPT	AB	OPT	AB
DCF	A	BCP	BC	LFT	AB	OPT	B	SLK	B	SLK	B
BCP	A	DCF	C	SLK	B	DCF	C	DCF	B	DCF	C
RSO	B	RSO	D	RSO	C	RSO	D	RSO	C	RSO	D
LSC	C	LSC	E	LSC	D	LSC	D	LSC	D	LSC	E
		FRW									
none		**some**	**.000**	**none**	**.245**	**some**	**.000**	**none**	**.004**	**some**	**.000**
A		LSC	A	RSO	A	LSC	A	BCP	A	RSO	A
L		LFT	A	LSC	AB	RSO	AB	RSO	AB	LSC	AB
L	E	RSO	AB	BCP	AB	LFT	AB	SLK	AB	BCP	AB
	Q	SLK	AB	LFT	AB	SLK	BC	LFT	AB	OPT	AB
	U	OPT	B	SLK	AB	OPT	C	LSC	BC	LFT	B
	A	BCP	C	OPT	B	BCP	CD	OPT	BC	SLK	B
	L	DCF	C	DCF	B	DCF	D	DCF	C	DCF	C
		NRN									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
BCP	A	LFT	A	BCP	A	BCP	A	LFT	A	LFT	A
DCF	B	SLK	B	SLK	A	SLK	AB	BCP	A	BCP	A
LFT	B	BCP	B	LFT	A	LFT	BC	SLK	A	SLK	B
SLK	B	DCF	B	DCF	A	DCF	C	DCF	B	DCF	C
OPT	C	OPT	C	OPT	B	OPT	D	OPT	C	OPT	C
LSC	D	LSC	D	LSC	C	LSC	E	LSC	D	LSC	D
RSO	E	RSO	D	RSO	D	RSO	E	RSO	E	RSO	E
		NRW									
none		**some**	**.000**	**none**	**.056**	**some**	**.000**	**none**	**.000**	**some**	**.000**
A		LSC	A	RSO	A	LSC	A	RSO	A	RSO	A
L		RSO	A	LFT	AB	RSO	A	LFT	AB	LFT	A
L	E	LFT	AB	LSC	AB	LFT	AB	SLK	AB	LSC	AB
	Q	SLK	BC	BCP	AB	SLK	BC	BCP	AB	BCP	B
	U	BCP	CD	OPT	AB	BCP	CD	LSC	B	SLK	B
	A	OPT	CD	SLK	B	OPT	CD	OPT	C	OPT	B
	L	DCF	D	DCF	B	DCF	D	DCF	D	DCF	C

Table G-10:
Scheduling Method Performance by Execution Method for POOC

POOC		FRN									
	NONE				FREQ				INFQ		
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
OPT	A	LFT	A	BCP	A	LFT	A	BCP	A	BCP	A
SLK	A	OPT	AB	DCF	AB	BCP	A	LFT	AB	LFT	A
LFT	A	SLK	AB	OPT	AB	OPT	A	OPT	AB	OPT	A
DCF	A	BCP	B	LFT	AB	SLK	A	SLK	B	SLK	A
BCP	A	DCF	C	SLK	B	DCF	B	DCF	B	DCF	B
RSO	B	RSO	D	RSO	C	RSO	C	RSO	C	RSO	C
LSC	C	LSC	E	LSC	D	LSC	C	LSC	D	LSC	D
		FRW									
none		some	.003	none	.244	some	.000	none	.004	some	.000
A		LSC	A	RSO	A	LSC	A	BCP	A	RSO	A
L		RSO	A	LSC	AB	RSO	A	RSO	AB	LSC	A
L	E	LFT	A	BCP	AB	LFT	AB	SLK	AB	BCP	A
	Q	SLK	AB	LFT	AB	SLK	AB	LFT	AB	OPT	A
	U	OPT	AB	SLK	AB	OPT	BC	LSC	BC	LFT	A
	A	BCP	B	OPT	B	BCP	BC	OPT	BC	SLK	A
	L	DCF	B	DCF	B	DCF	C	DCF	C	DCF	B
		NRN									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
BCP	A	LFT	A	BCP	A	BCP	A	LFT	A	BCP	A
DCF	B	SLK	B	SLK	A	SLK	AB	BCP	A	LFT	A
LFT	B	BCP	B	LFT	A	LFT	AB	SLK	A	SLK	A
SLK	B	DCF	B	DCF	A	DCF	B	DCF	B	OPT	B
OPT	C	OPT	C	OPT	B	OPT	C	OPT	C	DCF	B
LSC	D	LSC	D	LSC	C	LSC	D	LSC	D	LSC	C
RSO	E	RSO	D	RSO	D	RSO	D	RSO	E	RSO	C
		NRW									
none		some	.006	none	.055	some	.000	none	.000	some	.000
A		LSC	A	RSO	A	LSC	A	RSO	A	RSO	A
L		RSO	AB	LFT	AB	RSO	A	LFT	AB	LFT	AB
L	E	LFT	ABC	LSC	AB	LFT	AB	SLK	AB	LSC	AB
	Q	SLK	BC	BCP	AB	SLK	BC	BCP	AB	SLK	B
	U	BCP	C	OPT	AB	OPT	C	LSC	B	BCP	B
	A	OPT	C	SLK	B	BCP	C	OPT	C	OPT	B
	L	DCF	C	DCF	B	DCF	C	DCF	C	DCF	C

Table G-11:
Scheduling Method Performance by Execution Method for POOR

POOR		FRN									
	NONE				FREQ				INFQ		
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
OPT	A	LFT	A	BCP	A	LFT	A	BCP	A	BCP	A
SLK	A	OPT	AB	DCF	AB	BCP	A	LFT	AB	LFT	A
LFT	A	SLK	AB	OPT	AB	OPT	A	OPT	AB	OPT	A
DCF	A	BCP	B	LFT	AB	SLK	A	SLK	B	SLK	A
BCP	A	DCF	C	SLK	B	DCF	B	DCF	B	DCF	B
RSO	B	RSO	D	RSO	C	RSO	C	RSO	C	RSO	C
LSC	C	LSC	E	LSC	D	LSC	C	LSC	D	LSC	D
		FRW									
none		some	.003	none	.245	some	.000	none	.004	some	.000
A		LSC	A	RSO	A	LSC	A	BCP	A	RSO	A
L		RSO	A	LSC	AB	RSO	A	RSO	AB	LSC	A
L	E	LFT	A	BCP	AB	LFT	AB	SLK	AB	BCP	A
	Q	SLK	AB	LFT	AB	SLK	AB	LFT	AB	OPT	A
	U	OPT	AB	SLK	AB	OPT	BC	LSC	BC	LFT	A
	A	BCP	B	OPT	B	BCP	BC	OPT	BC	SLK	A
	L	DCF	B	DCF	B	DCF	C	DCF	C	DCF	B
		NRN									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
BCP	A	LFT	A	BCP	A	BCP	A	LFT	A	BCP	A
DCF	B	SLK	B	SLK	A	SLK	AB	BCP	A	LFT	A
LFT	B	BCP	B	LFT	A	LFT	B	SLK	A	SLK	A
SLK	B	DCF	B	DCF	A	DCF	B	DCF	B	OPT	B
OPT	C	OPT	C	OPT	B	OPT	C	OPT	C	DCF	B
LSC	D	LSC	D	LSC	C	LSC	D	LSC	D	LSC	C
RSO	E	RSO	D	RSO	D	RSO	D	RSO	E	RSO	C
		NRW									
none		some	.006	none	.056	some	.000	none	.000	some	.000
A		LSC	A	RSO	A	LSC	A	RSO	A	RSO	A
L		RSO	AB	LFT	AB	RSO	A	LFT	AB	LFT	AB
L	E	LFT	ABC	LSC	AB	LFT	AB	SLK	AB	LSC	AB
	Q	SLK	BC	BCP	AB	SLK	BC	BCP	AB	SLK	B
	U	BCP	C	OPT	AB	OPT	C	LSC	B	BCP	B
	A	OPT	C	SLK	B	BCP	C	OPT	C	OPT	B
	L	DCF	C	DCF	B	DCF	C	DCF	C	DCF	C

Table G-12:
Execution Method Performance by Scheduling Method for ADUR

ADUR		OPT									
NONE				FREQ				INFQ			
none	.000	some	.000	none	.000	some	.000	none	.000	some	.074
FRN	A	FRN	A	FRN	A	FRN	A	FRW	A	FRN	A
FRW	A	NRN	B	FRW	B	FRW	B	FRN	AB	NRN	A
NRW	A	NRW	B	NRW	C	NRN	C	NRW	B	FRW	AB
NRN	B	FRW	C	NRN	D	NRW	C	NRN	C	NRW	B
		SLK									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRN	A	FRN	A	NRN	A	NRN	A	NRN	A
FRW	A	FRN	A	FRW	AB	FRN	A	NRW	B	NRW	B
NRW	A	NRW	B	NRN	B	FRW	B	FRW	B	FRN	BC
NRN	B	FRW	C	NRW	C	NRW	B	FRN	C	FRW	C
		LFT									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRN	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	FRN	B	FRW	B	NRN	A	NRW	B	FRN	B
NRW	A	NRW	C	NRN	B	FRW	B	FRW	BC	NRW	B
NRN	B	FRW	D	NRW	C	NRW	B	FRN	C	FRW	C
		RSO									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	FRN	A	FRN	A	FRN	A	FRN	A	NRN	A
FRW	A	NRN	B	FRW	B	FRW	B	NRW	AB	FRN	A
NRW	A	NRW	C	NRW	C	NRN	B	FRW	AB	NRW	B
NRN	B	FRW	D	NRN	D	NRW	B	NRN	B	FRW	B
		LSC									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	FRN	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	NRN	A	NRN	B	NRN	B	FRN	B	FRN	B
NRW	A	NRW	B	FRW	C	FRW	C	NRW	C	FRW	C
NRN	B	FRW	C	NRW	D	NRW	C	FRW	C	NRW	C
		DCF									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
NRN	A	NRN	A	NRN	A	NRN	A	NRN	A	NRN	A
FRN	B	FRN	B	FRN	B	FRN	B	NRW	B	NRW	B
FRW	B	NRW	C	FRW	C	NRW	C	FRW	C	FRN	C
NRW	B	FRW	D	NRW	D	FRW	C	FRN	C	FRW	D
		BCP									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRN	A	NRN	A	NRN	A	NRN	A	NRN	A
FRW	A	FRN	B	FRN	B	FRN	B	NRW	B	FRN	B
NRW	A	NRW	C	FRW	C	FRW	C	FRW	BC	NRW	BC
NRN	B	FRW	D	NRW	D	NRW	C	FRN	C	FRW	C

Table G-13:
Execution Method Performance by Scheduling Method for RDUR

RDUR		OPT									
	NONE			FREQ				INFQ			
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	FRN	A	FRN	A	FRN	A	FRW	A	FRN	A
FRW	A	NRN	B	FRW	A	FRW	B	FRN	AB	NRN	A
NRW	A	NRW	B	NRW	B	NRN	C	NRW	B	FRW	AB
NRN	B	FRW	C	NRN	C	NRW	C	NRN	C	NRW	B
		SLK									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRN	A	FRN	A	NRN	A	NRN	A	NRN	A
FRW	A	FRN	A	FRW	AB	FRN	A	NRW	B	NRW	B
NRW	A	NRW	B	NRN	B	FRW	B	FRW	B	FRN	BC
NRN	B	FRW	C	NRW	C	NRW	B	FRN	C	FRW	C
		LFT									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRN	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	FRN	B	FRW	B	NRN	A	NRW	B	FRN	B
NRW	A	NRW	C	NRN	B	FRW	B	FRW	BC	NRW	B
NRN	B	FRW	D	NRW	C	NRW	B	FRN	C	FRW	C
		RSO									
none	.000	some	.000	none	.000	some	.000	none	.197	some	.000
FRN	A	FRN	A	FRN	A	FRN	A	FRN	A	NRN	A
FRW	A	NRN	B	FRW	B	FRW	B	NRW	AB	FRN	A
NRW	A	NRW	C	NRW	C	NRN	B	FRW	AB	NRW	B
NRN	B	FRW	D	NRN	D	NRW	B	NRN	B	FRW	B
		LSC									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	FRN	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	NRN	A	NRN	B	NRN	B	FRN	B	FRN	B
NRW	A	NRW	B	FRW	C	FRW	C	NRW	C	FRW	C
NRN	B	FRW	C	NRW	D	NRW	C	FRW	C	NRW	C
		DCF									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
NRN	A	NRN	A	NRN	A	NRN	A	NRN	A	NRN	A
FRN	B	FRN	B	FRN	B	FRN	B	NRW	B	NRW	B
FRW	B	NRW	C	FRW	C	NRW	C	FRW	C	FRN	C
NRW	B	FRW	D	NRW	D	FRW	C	FRN	C	FRW	D
		BCP									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRN	A	NRN	A	NRN	A	NRN	A	NRN	A
FRW	A	FRN	B	FRN	B	FRN	B	NRW	B	FRN	B
NRW	A	NRW	C	FRW	C	FRW	C	FRW	BC	NRW	BC
NRN	B	FRW	D	NRW	D	NRW	C	FRN	C	FRW	C

Table G-14:
Execution Method Performance by Scheduling Method for ANPV

ANPV		OPT									
NONE				FREQ				INFQ			
none	.000	some	.016	none	.000	some	.070	none	.000	some	.005
FRN	A	NRW	A	FRN	A	NRW	A	FRW	A	NRN	A
FRW	A	NRN	A	FRW	A	NRN	A	FRN	AB	NRW	A
NRW	A	FRN	B	NRW	B	FRN	AB	NRW	B	FRW	B
NRN	B	FRW	B	NRN	C	FRW	B	NRN	C	FRN	B
		SLK									
none	.000	some	.006	none	.000	some	.027	none	.000	some	.002
FRN	A	NRN	A	FRN	A	NRN	A	NRN	A	NRN	A
FRW	A	NRW	A	FRW	A	NRW	AB	NRW	A	NRW	A
NRW	A	FRN	B	NRN	A	FRN	BC	FRW	B	FRW	B
NRN	B	FRW	B	NRW	B	FRW	C	FRN	C	FRN	B
		LFT									
none	.000	some	.007	none	.000	some	.030	none	.000	some	.001
FRN	A	NRN	A	FRN	A	NRN	A	NRN	A	NRN	A
FRW	A	NRW	AB	FRW	B	NRW	AB	NRW	B	NRW	A
NRW	A	FRN	BC	NRN	B	FRN	BC	FRW	B	FRW	B
NRN	B	FRW	C	NRW	C	FRW	C	FRN	C	FRN	B
		RSO									
none	.000	some	.017	none	.000	some	.069	none	.000	some	.006
FRW	A	NRW	A	FRW	A	NRW	A	NRW	A	NRN	A
NRW	A	NRN	A	FRN	B	NRN	AB	FRW	A	NRW	A
FRN	B	FRN	B	NRW	B	FRN	AB	FRN	B	FRW	B
NRN	C	FRW	B	NRN	C	FRW	B	NRN	C	FRN	B
		LSC									
none	.000	some	.010	none	.000	some	.042	none	.009	some	.003
FRW	A	NRN	A	FRW	A	NRN	A	NRN	A	NRN	A
NRW	A	NRW	A	FRN	B	NRW	AB	NRW	A	NRW	A
FRN	B	FRN	B	NRW	B	FRN	BC	FRW	A	FRW	B
NRN	C	FRW	B	NRN	C	FRW	C	FRN	B	FRN	B
		DCF									
none	.000	some	.003	none	.000	some	.016	none	.000	some	.002
NRN	A	NRN	A	NRN	A	NRN	A	NRN	A	NRN	A
FRN	B	NRW	AB	FRN	B	NRW	AB	NRW	B	NRW	A
FRW	B	FRN	BC	FRW	C	FRN	BC	FRW	C	FRN	B
NRW	B	FRW	C	NRW	D	FRW	C	FRN	C	FRW	B
		BCP									
none	.000	some	.005	none	.000	some	.026	none	.000	some	.001
FRN	A	NRN	A	NRN	A	NRN	A	NRN	A	NRN	A
FRW	A	NRW	A	FRN	B	NRW	AB	NRW	B	NRW	A
NRW	A	FRN	B	FRW	C	FRN	BC	FRW	BC	FRW	B
NRN	B	FRW	B	NRW	D	FRW	C	FRN	C	FRN	B

Table G-15:
Execution Method Performance by Scheduling Method for RNPV

RNPV		OPT									
	NONE			FREQ				INFQ			
none	**.000**	**some**	**.016**	**none**	**.000**	**some**	**.070**	**none**	**.000**	**some**	**.005**
FRN	A	NRN	A	FRN	A	NRW	A	FRW	A	NRN	A
FRW	A	NRW	A	FRW	A	NRN	AB	FRN	AB	NRW	A
NRW	A	FRN	AB	NRW	B	FRN	AB	NRW	B	FRW	B
NRN	B	FRW	B	NRN	C	FRW	B	NRN	C	FRN	B
		SLK									
none	**.000**	**some**	**.006**	**none**	**.000**	**some**	**.028**	**none**	**.000**	**some**	**.002**
FRN	A	NRN	A	FRN	A	NRN	A	NRN	A	NRN	A
FRW	A	NRW	AB	FRW	AB	NRW	AB	NRW	A	NRW	A
NRW	A	FRN	BC	NRN	B	FRN	BC	FRW	B	FRW	B
NRN	B	FRW	C	NRW	C	FRW	C	FRN	C	FRN	B
		LFT									
none	**.000**	**some**	**.007**	**none**	**.000**	**some**	**.029**	**none**	**.000**	**some**	**.001**
FRN	A	NRN	A	FRN	A	NRN	A	NRN	A	NRN	A
FRW	A	NRW	AB	FRW	B	NRW	AB	NRW	B	NRW	A
NRW	A	FRN	BC	NRN	B	FRN	BC	FRW	BC	FRN	B
NRN	B	FRW	C	NRW	C	FRW	C	FRN	C	FRW	B
		RSO									
none	**.000**	**some**	**.017**	**none**	**.000**	**some**	**.069**	**none**	**.000**	**some**	**.006**
FRW	A	NRW	A	FRW	A	NRW	A	NRW	A	NRN	A
NRW	A	NRN	A	FRN	B	NRN	AB	FRW	A	NRW	A
FRN	B	FRN	B	NRW	B	FRN	AB	FRN	B	FRW	B
NRN	C	FRW	B	NRN	C	FRW	B	NRN	C	FRN	B
		LSC									
none	**.000**	**some**	**.010**	**none**	**.000**	**some**	**.042**	**none**	**.015**	**some**	**.003**
FRW	A	NRN	A	FRW	A	NRN	A	NRN	A	NRN	A
NRW	A	NRW	A	FRN	B	NRW	AB	NRW	A	NRW	A
FRN	B	FRN	B	NRW	B	FRN	BC	FRW	A	FRW	B
NRN	C	FRW	B	NRN	C	FRW	C	FRN	B	FRN	B
		DCF									
none	**.000**	**some**	**.003**	**none**	**.000**	**some**	**.016**	**none**	**.000**	**some**	**.002**
NRN	A	NRN	A	NRN	A	NRN	A	NRN	A	NRN	A
FRN	B	NRW	AB	FRN	B	NRW	AB	NRW	B	NRW	A
FRW	B	FRN	BC	FRW	C	FRN	BC	FRW	C	FRN	B
NRW	B	FRW	C	NRW	D	FRW	C	FRN	C	FRW	B
		BCP									
none	**.000**	**some**	**.005**	**none**	**.000**	**some**	**.026**	**none**	**.000**	**some**	**.001**
FRN	A	NRN	A	NRN	A	NRN	A	NRN	A	NRN	A
FRW	A	NRW	A	FRN	B	NRW	AB	NRW	B	NRW	A
NRW	A	FRN	B	FRW	C	FRN	B	FRW	BC	FRW	B
NRN	B	FRW	B	NRW	D	FRW	B	FRN	C	FRN	B

Table G-16:
Execution Method Performance by Scheduling Method for WADL

WDL		OPT									
	NONE				FREQ				INFQ		
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.026**
FRN	A	FRN	A	FRN	A	FRN	A	FRW	A	FRN	A
FRW	A	NRN	B	FRW	B	FRW	B	FRN	AB	NRN	A
NRW	A	NRW	B	NRW	C	NRW	C	NRW	B	NRW	AB
NRN	B	FRW	C	NRN	D	NRN	D	NRN	C	FRW	B
		SLK									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.024**	**some**	**.000**
FRN	A	FRN	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	NRN	A	FRW	A	NRN	B	FRW	A	FRN	B
NRW	A	NRW	B	NRW	B	FRW	B	NRN	A	NRW	B
NRN	B	FRW	C	NRN	C	NRW	B	FRN	B	FRW	C
		LFT									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.127**	**some**	**.000**
FRN	A	NRN	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	FRN	A	FRW	B	FRW	B	NRW	AB	FRN	B
NRW	A	NRW	B	NRW	C	NRW	BC	FRW	AB	NRW	B
NRN	B	FRW	C	NRN	D	NRN	C	FRN	B	FRW	C
		RSO									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.001**	**some**	**.000**
FRN	A	FRN	A	FRN	A	FRN	A	FRN	A	NRN	A
FRW	A	NRN	B	FRW	B	FRW	B	NRW	AB	FRN	A
NRW	A	NRW	C	NRW	C	NRW	B	FRW	BC	NRW	B
NRN	B	FRW	D	NRN	D	NRN	C	NRN	C	FRW	C
		LSC									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRN	A	FRN	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	NRN	B	FRW	B	NRN	B	FRN	B	FRN	B
NRW	A	NRW	C	NRW	C	FRW	C	NRW	C	NRW	C
NRN	B	FRW	D	NRN	D	NRW	C	FRW	C	FRW	C
		DCF									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.868**	**some**	**.000**
FRN	A	NRN	A	FRN	A	FRN	A	FRW	A	NRN	A
FRW	A	FRN	B	FRW	B	NRN	B	NRN	A	FRN	B
NRW	A	NRW	C	NRW	C	FRW	BC	NRW	A	NRW	C
NRN	B	FRW	D	NRN	D	NRW	C	FRN	A	FRW	C
		BCP									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRN	A	NRN	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	FRN	B	FRW	B	NRN	B	NRW	B	FRN	B
NRW	A	NRW	C	NRW	C	FRW	C	FRW	B	NRW	B
NRN	B	FRW	D	NRN	D	NRW	C	FRN	B	FRW	C

Table G-17:
Execution Method Performance by Scheduling Method for WADE

WDE		OPT									
NONE				FREQ				INFQ			
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRN	A	FRW	A	FRW	A	FRW	A	FRW	A	FRW	A
FRW	A	NRW	A	NRW	A	NRW	A	NRW	A	NRW	A
NRW	A	FRN	B	FRN	A	FRN	B	FRN	A	FRN	B
NRN	B	NRN	C	NRN	B	NRN	C	NRN	B	NRN	C
		SLK									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRN	A	FRW	A	FRW	A	FRW	A	FRW	A	FRW	A
FRW	A	NRW	A	NRW	A	NRW	A	NRW	A	NRW	A
NRW	A	FRN	B	FRN	A	FRN	B	FRN	A	FRN	B
NRN	B	NRN	C	NRN	B	NRN	C	NRN	B	NRN	C
		LFT									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRN	A	FRW	A	FRW	A	FRW	A	FRW	A	FRW	A
FRW	A	NRW	A	NRW	A	NRW	A	NRW	A	NRW	A
NRW	A	FRN	B	FRN	A	FRN	B	FRN	A	FRN	B
NRN	B	NRN	C	NRN	B	NRN	C	NRN	B	NRN	C
		RSO									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRW	A	FRW	A	FRW	A	FRW	A	FRW	A	FRW	A
NRW	A	NRW	A	NRW	A	NRW	A	NRW	A	NRW	A
FRN	B	FRN	B	FRN	B	FRN	B	FRN	B	FRN	B
NRN	C	NRN	C	NRN	C	NRN	C	NRN	C	NRN	C
		LSC									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRW	A	FRW	A	FRW	A	FRW	A	FRW	A	FRW	A
NRW	A	NRW	A	NRW	A	NRW	A	NRW	A	NRW	A
FRN	B	FRN	B	FRN	B	FRN	B	FRN	B	FRN	B
NRN	C	NRN	C	NRN	C	NRN	C	NRN	C	NRN	C
		DCF									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRN	A	FRW	A	FRW	A	FRW	A	FRN	A	FRW	A
FRW	A	NRW	A	NRW	A	NRW	A	NRW	A	NRW	A
NRW	A	FRN	B	FRN	A	FRN	B	FRW	A	FRN	B
NRN	B	NRN	C	NRN	B	NRN	C	NRN	B	NRN	C
		BCP									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRN	A	FRW	A	FRW	A	FRW	A	FRW	A	FRW	A
FRW	A	NRW	A	NRW	A	NRW	A	NRW	A	NRW	A
NRW	A	FRN	B	FRN	A	FRN	B	FRN	A	FRN	B
NRN	B	NRN	C	NRN	B	NRN	C	NRN	B	NRN	C

Table G-18:
Execution Method Performance by Scheduling Method for WADC

WDC		OPT									
	NONE				FREQ				INFQ		
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	FRW	A	NRW	A
FRW	A	FRW	A	FRW	B	FRW	A	FRN	A	FRN	A
NRW	A	FRN	B	NRW	C	NRW	B	NRW	A	FRW	A
NRN	B	NRN	C	NRN	D	NRN	C	NRN	B	NRN	B
		SLK									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRW	A
FRW	A	FRW	B	FRW	A	FRW	A	FRW	A	FRN	B
NRW	A	FRN	C	NRW	B	NRW	A	FRN	B	FRW	B
NRN	B	NRN	D	NRN	C	NRN	B	NRN	C	NRN	C
		LFT									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRW	A
FRW	A	FRW	B	FRW	B	FRW	AB	FRW	A	FRN	B
NRW	A	FRN	C	NRW	C	NRW	B	FRN	A	FRW	B
NRN	B	NRN	D	NRN	D	NRN	C	NRN	B	NRN	B
		RSO									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRW	A	NRW	A	FRW	A	FRW	A	NRW	A	NRW	A
NRW	A	FRW	B	NRW	B	NRW	AB	FRW	A	FRW	B
FRN	B	FRN	C	FRN	C	FRN	B	FRN	B	FRN	C
NRN	C	NRN	D	NRN	D	NRN	C	NRN	C	NRN	D
		LSC									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRW	A	NRW	A	FRW	A	FRW	A	NRW	A	NRW	A
NRW	A	FRW	B	NRW	B	NRW	A	FRW	A	FRW	B
FRN	B	FRN	C	FRN	C	FRN	B	FRN	B	FRN	C
NRN	C	NRN	D	NRN	D	NRN	C	NRN	C	NRN	D
		DCF									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	FRW	A	NRW	A
FRW	A	FRW	B	FRW	B	FRW	A	NRW	A	FRW	A
NRW	A	FRN	C	NRW	C	NRW	A	FRN	A	FRN	A
NRN	B	NRN	D	NRN	D	NRN	B	NRN	B	NRN	B
		BCP									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRW	A
FRW	A	FRW	B	FRW	B	FRW	AB	FRW	A	FRN	B
NRW	A	FRN	C	NRW	C	NRW	B	FRN	A	FRW	B
NRN	B	NRN	D	NRN	D	NRN	C	NRN	B	NRN	C

Table G-19:
Execution Method Performance by Scheduling Method for POIC

POIC		OPT									
NONE				FREQ				INFQ			
none	.000	some	.000	none	.000	some	.000	none	.000	some	.086
FRN	A	FRN	A	FRN	A	FRN	A	NRW	A	NRW	A
FRW	A	NRW	A	FRW	A	FRW	B	FRW	AB	FRN	AB
NRW	A	FRW	B	NRW	B	NRW	C	FRN	B	NRN	B
NRN	B	NRN	C	NRN	C	NRN	D	NRN	C	FRW	B
		SLK									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	FRN	A	FRW	A	FRW	B	NRN	A	NRW	B
NRW	A	FRW	B	NRW	B	NRW	B	FRW	A	FRN	C
NRN	B	NRN	C	NRN	C	NRN	C	FRN	B	FRW	C
		LFT									
none	.000	some	.003	none	.000	some	.000	none	.000	some	.000
FRN	A	FRN	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	NRW	A	FRW	B	FRW	B	NRW	AB	NRW	B
NRW	A	NRN	B	NRW	B	NRW	B	FRW	BC	FRN	C
NRN	B	FRW	B	NRN	C	NRN	C	FRN	C	FRW	C
		RSO									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRW	A	NRW	A	FRW	A	FRW	A	NRW	A	NRW	A
NRW	A	FRW	B	NRW	B	NRW	A	FRW	B	FRW	B
FRN	B	FRN	C	FRN	C	FRN	B	FRN	C	FRN	C
NRN	C	NRN	D	NRN	D	NRN	C	NRN	D	NRN	C
		LSC									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRW	A	NRW	A	FRW	A	FRW	A	NRW	A	NRW	A
NRW	A	FRW	B	NRW	B	NRW	A	FRW	B	FRW	B
FRN	B	FRN	C	FRN	C	FRN	B	NRN	C	NRN	C
NRN	C	NRN	D	NRN	D	NRN	C	FRN	D	FRN	D
		DCF									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	FRN	B	FRW	B	FRW	B	NRN	AB	NRW	A
NRW	A	FRW	B	NRW	C	NRW	B	FRW	B	FRN	B
NRN	B	NRN	B	NRN	D	NRN	C	FRN	B	FRW	B
		BCP									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	FRN	AB	FRW	B	FRW	B	NRN	A	NRW	B
NRW	A	NRN	BC	NRW	C	NRW	BC	FRW	AB	FRN	B
NRN	B	FRW	C	NRN	D	NRN	C	FRN	B	FRW	C

Table G-20:
Execution Method Performance by Scheduling Method for POIR

POIR		OPT									
	NONE				FREQ				INFQ		
none	.000	some	.000	none	.000	some	.000	none	.000	some	.086
FRN	A	FRN	A	FRN	A	FRN	A	NRW	A	NRW	A
FRW	A	NRW	A	FRW	A	FRW	B	FRW	AB	FRN	AB
NRW	A	FRW	B	NRW	B	NRW	C	FRN	B	NRN	B
NRN	B	NRN	C	NRN	C	NRN	D	NRN	C	FRW	B
		SLK									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	FRN	A	FRW	A	FRW	B	NRN	A	NRW	B
NRW	A	FRW	B	NRW	B	NRW	B	FRW	A	FRN	C
NRN	B	NRN	C	NRN	C	NRN	C	FRN	B	FRW	C
		LFT									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRN	A	FRN	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	NRW	A	FRW	B	FRW	B	NRW	AB	NRW	B
NRW	A	NRN	B	NRW	B	NRW	B	FRW	BC	FRN	C
NRN	B	FRW	B	NRN	C	NRN	C	FRN	C	FRW	C
		RSO									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRW	A	NRW	A	FRW	A	FRW	A	NRW	A	NRW	A
NRW	A	FRW	B	NRW	B	NRW	A	FRW	B	FRW	B
FRN	B	FRN	C	FRN	C	FRN	B	FRN	C	FRN	C
NRN	C	NRN	D	NRN	D	NRN	C	NRN	D	NRN	C
		LSC									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRW	A	NRW	A	FRW	A	FRW	A	NRW	A	NRW	A
NRW	A	FRW	A	NRW	B	NRW	A	FRW	B	FRW	B
FRN	B	FRN	B	FRN	C	FRN	B	NRN	C	NRN	C
NRN	C	NRN	C	NRN	D	NRN	C	FRN	D	FRN	D
		DCF									
none	.000	some	.000	none	.000	some	.000	none	.021	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	FRN	B	FRW	B	FRW	B	NRN	AB	NRW	A
NRW	A	FRW	B	NRW	C	NRW	B	FRW	B	FRN	B
NRN	B	NRN	B	NRN	D	NRN	C	FRN	B	FRW	B
		BCP									
none	.000	some	.000	none	.000	some	.000	none	.059	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	FRN	AB	FRW	B	FRW	B	NRN	AB	NRW	B
NRW	A	NRN	BC	NRW	C	NRW	BC	FRW	AB	FRN	B
NRN	B	FRW	C	NRN	D	NRN	C	FRN	B	FRW	C

Table G-21:
Execution Method Performance by Scheduling Method for POOC

POOC		OPT									
	NONE			FREQ				INFQ			
none	.000	some	.000	none	.000	some	.000	none	.000	some	.008
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRW	A
FRW	A	FRN	B	FRW	A	NRW	B	FRW	AB	NRN	AB
NRW	A	FRW	B	NRW	B	FRW	B	FRN	B	FRN	B
NRN	B	NRN	C	NRN	C	NRN	C	NRN	C	FRW	B
		SLK									
none	.000	some	.000	none	.000	some	.001	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	FRN	B	FRW	A	NRW	AB	NRN	A	NRW	B
NRW	A	FRW	B	NRW	B	FRW	B	FRW	A	FRN	C
NRN	B	NRN	B	NRN	C	NRN	C	FRN	B	FRW	C
		LFT									
none	.000	some	.007	none	.000	some	.000	none	.000	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	FRN	B	FRW	B	NRW	B	NRW	AB	NRW	B
NRW	A	NRN	B	NRW	B	FRW	B	FRW	BC	FRN	C
NRN	B	FRW	B	NRN	C	NRN	C	FRN	C	FRW	C
		RSO									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRW	A	NRW	A	FRW	A	NRW	A	NRW	A	NRW	A
NRW	A	FRW	B	NRW	B	FRW	A	FRW	B	FRW	B
FRN	A	FRN	C	FRN	C	FRN	B	FRN	C	NRN	C
NRN	B	NRN	D	NRN	D	NRN	C	NRN	D	FRN	C
		LSC									
none	.000	some	.000	none	.000	some	.000	none	.000	some	.000
FRW	A	NRW	A	FRW	A	NRW	A	NRW	A	NRW	A
NRW	A	FRW	B	NRW	B	FRW	A	FRW	B	FRW	B
FRN	B	FRN	C	FRN	C	FRN	B	NRN	C	NRN	C
NRN	C	NRN	D	NRN	D	NRN	C	FRN	D	FRN	D
		DCF									
none	.000	some	.000	none	.000	some	.004	none	.021	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	FRW	B	FRW	B	NRW	A	NRN	AB	NRW	A
NRW	A	NRN	B	NRW	C	FRW	AB	FRW	B	FRN	B
NRN	B	FRN	B	NRN	D	NRN	B	FRN	B	FRW	B
		BCP									
none	.000	some	.000	none	.000	some	.000	none	.060	some	.000
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	NRN	B	FRW	B	NRW	B	NRN	A	NRW	B
NRW	A	FRN	B	NRW	C	FRW	B	FRW	AB	FRN	BC
NRN	B	FRW	B	NRN	D	NRN	B	FRN	B	FRW	C

Table G-22:
Execution Method Performance by Scheduling Method for POOR

POOR		**OPT**									
	NONE					**FREQ**				**INFQ**	
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.008**
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRW	A
FRW	A	FRN	B	FRW	A	NRW	B	FRW	AB	NRN	AB
NRW	A	FRW	B	NRW	B	FRW	B	FRN	B	FRN	B
NRN	B	NRN	C	NRN	C	NRN	C	NRN	C	FRW	B
		SLK									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	FRN	B	FRW	A	NRW	AB	NRN	A	NRW	B
NRW	A	FRW	B	NRW	B	FRW	B	FRW	A	FRN	C
NRN	B	NRN	B	NRN	C	NRN	C	FRN	B	FRW	C
		LFT									
none	**.000**	**some**	**.007**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRN	A	NRW	A	FRN	A	FRN	A	NRN	A	NRN	A
FRW	A	FRN	B	FRW	B	NRW	B	NRW	AB	NRW	B
NRW	A	NRN	B	NRW	B	FRW	B	FRW	BC	FRN	C
NRN	B	FRW	B	NRN	C	NRN	C	FRN	C	FRW	C
		RSO									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRW	A	NRW	A	FRW	A	NRW	A	NRW	A	NRW	A
NRW	A	FRW	B	NRW	B	FRW	A	FRW	B	FRW	B
FRN	B	FRN	C	FRN	C	FRN	B	FRN	C	NRN	C
NRN	C	NRN	D	NRN	D	NRN	C	NRN	D	FRN	C
		LSC									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**
FRW	A	NRW	A	FRW	A	NRW	A	NRW	A	NRW	A
NRW	A	FRW	B	NRW	B	FRW	A	FRW	B	FRW	B
FRN	B	FRN	C	FRN	C	FRN	B	NRN	C	NRN	C
NRN	C	NRN	D	NRN	D	NRN	C	FRN	D	FRN	D
		DCF									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.004**	**none**	**.021**	**some**	**.000**
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	FRW	B	FRW	A	NRW	A	NRN	AB	NRW	A
NRW	A	NRN	B	NRW	B	FRW	AB	FRW	B	FRN	B
NRN	B	FRN	B	NRN	C	NRN	B	FRN	B	FRW	B
		BCP									
none	**.000**	**some**	**.000**	**none**	**.000**	**some**	**.000**	**none**	**.059**	**some**	**.000**
FRN	A	NRW	A	FRN	A	FRN	A	NRW	A	NRN	A
FRW	A	NRN	B	FRW	B	NRW	B	NRN	A	NRW	B
NRW	A	FRN	B	NRW	C	FRW	B	FRW	AB	FRN	BC
NRN	B	FRW	B	NRN	D	NRN	B	FRN	B	FRW	C

APPENDIX H

DIFFERENCES IN RANKED PERFORMANCE

Table H-1:
Tally of Differences in Ranks: Scheduling by Execution (Traditional)

		NONE	FREQ	INFQ	NONE	SOME
ADUR	FRN	-	-	-	-	-
	FRW	-	-	-	-	-
	NRN	+	+	-	+	-
	NRW	-	-	-	-	+
RDUR	FRN	-	+	-	-	-
	FRW	-	+	+	-	-
	NRN	-	-	-	+	-
	NRW	-	+	-	+	-
ANPV	FRN	-	-	-	+	-
	FRW	-	-	-	+	-
	NRN	-	-	-	+	-
	NRW	-	-	-	+	-
RNPV	FRN	-	-	-	+	-
	FRW	-	-	-	+	-
	NRN	-	-	-	+	-
	NRW	-	-	-	-	-

Table H-2:
Tally of Differences in Ranks: Scheduling by Execution (Stability)

		NONE	FREQ	INFQ	NONE	SOME
WADE	FRN	-	+	-	-	+
	FRW	-	-	-	-	-
	NRN	+	-	-	+	+
	NRW	-	-	-	-	-
WADL	FRN	-	+	+	-	+
	FRW	-	+	+	+	+
	NRN	+	-	-	+	+
	NRW	-	+	+	+	-
WADC	FRN	-	-	-	-	-
	FRW	-	+	+	+	-
	NRN	+	-	-	+	-
	NRW	-	+	+	+	+
POIC	FRN	-	+	-	+	+
	FRW	-	+	+	+	+
	NRN	+	-	-	-	+
	NRW	-	+	+	+	+
POIR	FRN	-	+	-	+	+
	FRW	-	+	+	+	+
	NRN	+	-	-	-	+
	NRW	-	+	+	+	+
POOC	FRN	-	+	-	+	-
	FRW	-	+	-	+	-
	NRN	+	-	-	+	+
	NRW	-	+	+	+	+
POOR	FRN	-	+	-	+	-
	FRW	-	+	-	+	-
	NRN	+	-	-	+	+
	NRW	-	+	+	+	+

Table H-3:
Tally of Differences in Ranks: Execution by Scheduling (Traditional)

		NONE	FREQ	INFQ	NONE	SOME
WADE	FRN	-	+	-	-	+
	FRW	-	-	-	-	-
	NRN	+	-	-	+	+
	NRW	-	-	-	-	-
WADL	FRN	-	+	+	-	+
	FRW	-	+	+	+	+
	NRN	+	-	-	+	+
	NRW	-	+	+	+	-
WADC	FRN	-	-	-	-	-
	FRW	-	+	+	+	-
	NRN	+	-	-	+	-
	NRW	-	+	+	+	+
POIC	FRN	-	+	-	+	+
	FRW	-	+	+	+	+
	NRN	+	-	-	-	+
	NRW	-	+	+	+	+
POIR	FRN	-	+	-	+	+
	FRW	-	+	+	+	+
	NRN	+	-	-	-	+
	NRW	-	+	+	+	+
POOC	FRN	-	+	-	+	-
	FRW	-	+	-	+	-
	NRN	+	-	-	+	+
	NRW	-	+	+	+	+
POOR	FRN	-	+	-	+	-
	FRW	-	+	-	+	-
	NRN	+	-	-	+	+
	NRW	-	+	+	+	+

Table H-4:
Tally of Differences in Ranks: Execution by Scheduling (Stability)

		NONE	FREQ	INFQ	NONE	SOME
WADE	OPT	-	-	-	-	-
	SLK	-	-	-	-	-
	LFT	-	-	-	-	-
	RSO	-	-	-	-	-
	LSC	-	-	-	-	-
	DCF	-	-	-	-	-
	BCP	-	-	-	-	-
WADL	OPT	+	-	+	+	+
	SLK	+	+	+	+	+
	LFT	+	-	+	+	+
	RSO	+	-	+	-	+
	LSC	+	+	-	+	+
	DCF	+	+	-	-	+
	BCP	+	+	-	+	+
WADC	OPT	-	-	-	-	+
	SLK	-	-	-	+	-
	LFT	-	-	-	-	+
	RSO	-	-	-	-	+
	LSC	-	-	-	-	-
	DCF	-	-	-	-	-
	BCP	-	-	-	-	+
POIC	OPT	-	-	+	+	+
	SLK	-	-	-	+	+
	LFT	-	-	-	+	+
	RSO	-	-	-	+	-
	LSC	-	-	-	+	+
	DCF	-	-	-	+	+
	BCP	+	-	+	+	+
POIR	OPT	-	-	+	+	+
	SLK	-	-	-	+	+
	LFT	-	-	-	+	+
	RSO	-	-	-	+	-
	LSC	-	-	-	+	+
	DCF	-	-	-	+	+
	BCP	+	-	+	+	+
POOC	OPT	-	-	+	+	+
	SLK	-	+	-	+	+
	LFT	-	-	-	+	+
	RSO	-	-	-	+	-
	LSC	-	-	-	+	+
	DCF	-	+	-	+	+
	BCP	-	-	+	+	+
POOR	OPT	-	-	+	+	+
	SLK	-	+	-	+	+
	LFT	-	-	-	+	+
	RSO	-	-	-	+	-
	LSC	-	-	-	+	+
	DCF	-	+	-	+	+
	BCP	-	-	+	+	+

APPENDIX I

PROJECT PROBLEM NETWORKS

Figure I-3: Heur056

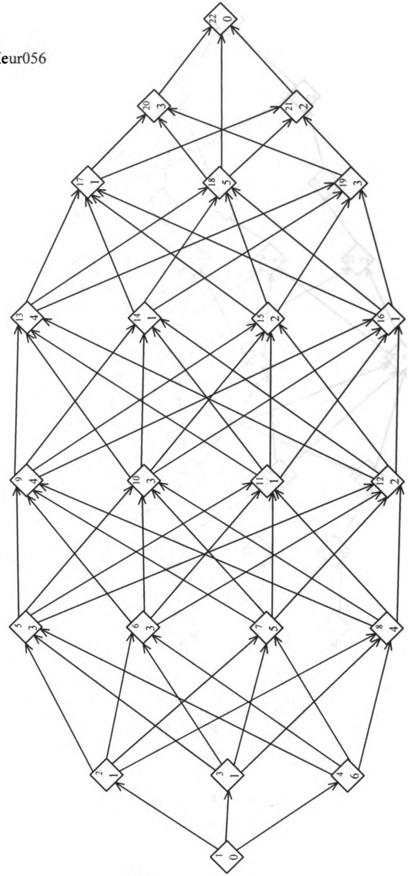


Figure I-5: Heur015

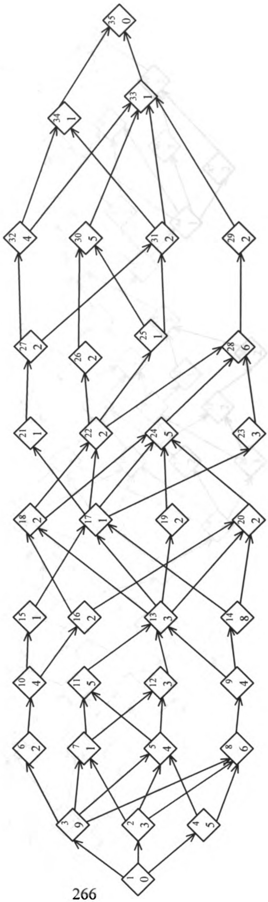


Figure I-6: Heur105

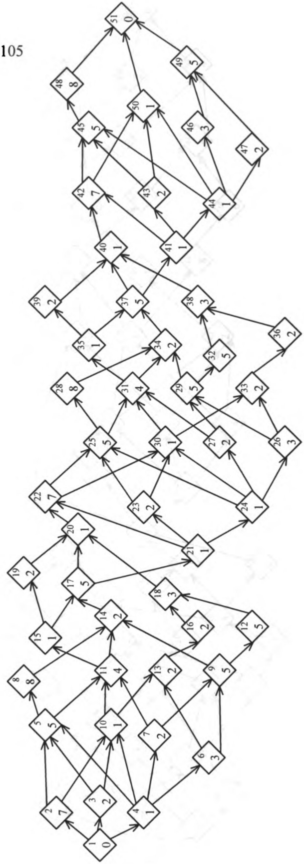


Figure I-7: Heur107

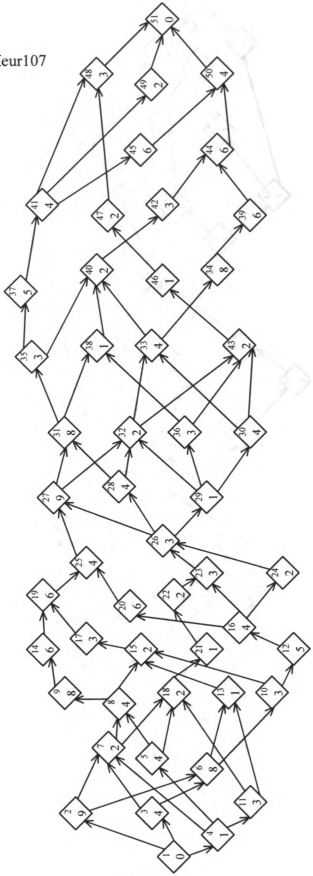
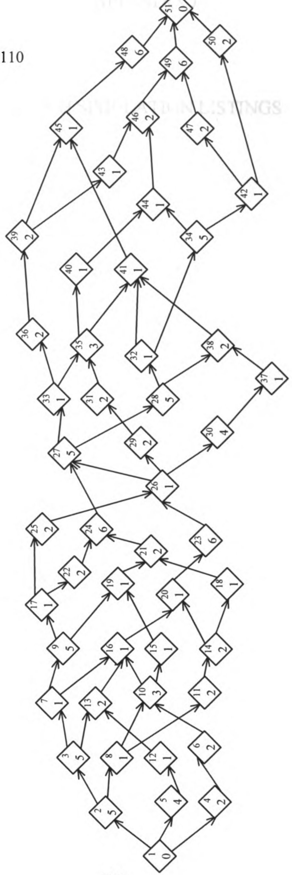


Figure I-8: Heur110



APPENDIX J

GPSS/H SIMULATION LISTINGS

```
******************************************************************************
*                     PRO1.GPS - A Project Simulator                         *
*                                                                            *
* Planning:   Per schedule from POLB (priority based on SST)                 *
* Execution:  Full Reservation (tech feas act's lock resources when avail)   *
*             No Waiting (act's advance when feas, even if SST not expired)  *
*                                                                            *
* >PRO1: Full Reservation-Wait (lock partial resources/wait till schedule)   *
*  PRO2: Full Reservation-No Wait (lock partial resources/go when feasible)  *
*  PRO3: No Reservation-Wait (lock iff fully avail/wait till schedule)       *
*  PRO4: No Reservation-No Wait (lock iff fully avail/go when feasible)      *
*                                                                            *
* POLB: file containing problem data sets                                    *
* SIMPOL1:  file written to with simulation results                          *
*                                                                            *
* MH$DAT1: matrix containing problem data from POLB                          *
* MB$DAT2: sparse matrix representing activity feasibility                   *
* ML$DAT3: matrix containing simulation output to write to SIMPOL1           *
* ML$DT:   matrix accumulating downtime (total time) of resource 1, 2 or 3   *
*                                                                            *
* RN(1): reserved                                                            *
* RN(2): up time of storages as sampled by ADVANCE (rvexpo) block            *
* RN(3): duration of activities as sampled by BETA function                  *
* RN(4): down time of activities as sampled by ADVANCE (rvexpo) block        *
*                                                                            *
* &SPD: variability (spread) ratio of activity durations                     *
* &DIS: number of expected disruptions to each resource during project       *
*                                                                            *
* &L:   number of individual problems read from the POLB data file           *
* &M:   number of simulation repetitions of each individual problem          *
*                                                                            *
* TECH: chain holding technical/time infeasible activities (first stage)     *
* RESO: chain holding resource infeasible activities (second stage)          *
*                                                                            *
* PB$ANUM: activity number (per problem data matrix)                         *
* PB$RESx: number of resources (storage) remaining for activity start        *
* PB$FEZ:  number of precedence activities remaining for activity start      *
* PB$TOT:  "tote" counter for looping and xact management                    *
* PH$SST:  scheduled start time from POLB (used for chain order)             *
* PL$DUR:  activity duration from beta distributed around POLB  duration     *
*                                                                            *
******************************************************************************
*
        SIMULATE
        REALLOCATE  FMS,0
        REALLOCATE  FSV,0
        REALLOCATE  GRP,0
        REALLOCATE  HSV,0
        REALLOCATE  LOG,0
        REALLOCATE  QUE,0
        REALLOCATE  TAB,0
        REALLOCATE  COM,25008
*
        INTEGER     &I,&J,&K,&L,&M,&SPD1,&DIS1,&PREC,&NACT,&NRES
        INTEGER     &D4,&R1,&R2,&R3,&NTR1,&NTR2,&NTR3
        REAL        &DUR,&SPD,&MRK,&SFT,&D,&D5,&DIS,&TMR
        CHAR*8      &D2,&D3
*
BETA    FUNCTION    RN(3),C8
0,0/0.02,0.03/0.14,0.11/0.67,0.41/0.85,0.56/0.94,0.68/0.99,0.81/1,1
```

```
*
****************************************
* technical/time feasibility
*
RELT   BVARIABLE   ((PB$FEZ)'E'(0))
*
****************************************
* resource (storage) feasibility
*
RELR   BVARIABLE   ((PB$RES1)'E'(0))*((PB$RES2)'E'(0))*((PB$RES3)'E'(0))
*
****************************************************************************
*                  Dynamic Program Code                                    *
****************************************************************************
*
       GENERATE    ,,,&NACT,,0PF,1PH,6PB,1PL
*
****************************************
* assign actnum, resource requirements,
* schedstart, and duration
*
       BLET        &K=&K-1
       ASSIGN      ANUM,&K,PB
*
       ASSIGN      RES1,MH$DAT1(PB$ANUM,9),PB
       ASSIGN      RES2,MH$DAT1(PB$ANUM,10),PB
       ASSIGN      RES3,MH$DAT1(PB$ANUM,11),PB
*
       ASSIGN      SST,MH$DAT1(PB$ANUM,2),PH
*
       BLET        &DUR=MH$DAT1(PB$ANUM,3)*(1-(&SPD/3)+&SPD*FN(BETA))
       ASSIGN      LGT,&DUR,PL
*
       TEST G      PB$ANUM,1,WRIT      * start node skip to end (writ)
*
       BLET        &TMR=FLT(PH$SST)
       TEST G      &TMR,AC1,CKFZ       * if SST<=AC1, skip next else
       ADVANCE     &TMR-AC1            * wait until SST=AC1 then
*
****************************************
****************************************
* update technical feasibility
* sum undone prec activities for self
*
CKFZ   ASSIGN      TOT,&NACT,PB
       BLET        &PREC=0
CKPR   BLET        &PREC=&PREC+MB$DAT2(PB$TOT,PB$ANUM)
       LOOP        TOT$PB,CKPR
       ASSIGN      FEZ,&PREC,PB
*
****************************************
****************************************
* update resource feasibility and start
* this activity if all feas satisfied
*
       TEST GE     R1,PB$RES1,ELS1
       BLET        &NTR1=PB$RES1
       TRANSFER    ,ELS2
ELS1   BLET        &NTR1=R1
*
```

```
ELS2    TEST GE      R2,PB$RES2,ELS3
        BLET         &NTR2=PB$RES2
        TRANSFER     ,ELS4
ELS3    BLET         &NTR2=R2
*
ELS4    TEST GE      R3,PB$RES3,ELS5
        BLET         &NTR3=PB$RES3
        TRANSFER     ,ELS6
ELS5    BLET         &NTR3=R3
*
ELS6    ASSIGN       RES1-,&NTR1,PB
        ASSIGN       RES2-,&NTR2,PB
        ASSIGN       RES3-,&NTR3,PB
*
        ENTER        1,&NTR1
        ENTER        2,&NTR2
        ENTER        3,&NTR3
*
        TEST E       BV$RELT,0,CKRS
LWAT    LINK         WAIT,SST$PH
CKRS    TEST E       BV$RELR,1,LWAT
*
        MARK
*
        TEST E       &SPD,&DIS,RESU1
        ADVANCE      PL$LGT-(AC1-(FIX(AC1)))
        TRANSFER     ,RESU2
*
RESU1   ADVANCE      PL$LGT
RESU2   LEAVE        1,MH$DAT1(PB$ANUM,9)
        LEAVE        2,MH$DAT1(PB$ANUM,10)
        LEAVE        3,MH$DAT1(PB$ANUM,11)
*
*****************************************
*****************************************
* write activity information to raw matrix
*
WRIT    BLET         &MRK=AC1-M1
        BLET         &SFT=MH$DAT1(PB$ANUM,2)+MH$DAT1(PB$ANUM,3)
        MSAVEVALUE   DAT3,PB$ANUM,1,PB$ANUM,ML
        MSAVEVALUE   DAT3,PB$ANUM,2,PH$SST,ML
        MSAVEVALUE   DAT3,PB$ANUM,3,&MRK,ML
        MSAVEVALUE   DAT3,PB$ANUM,4,&SFT,ML
        MSAVEVALUE   DAT3,PB$ANUM,5,AC1,ML
        MSAVEVALUE   DAT3,PB$ANUM,6,MH$DAT1(PB$ANUM,3),ML
        MSAVEVALUE   DAT3,PB$ANUM,7,PL$LGT,ML
        MSAVEVALUE   DAT3,PB$ANUM,8,MH$DAT1(PB$ANUM,9),ML
        MSAVEVALUE   DAT3,PB$ANUM,9,MH$DAT1(PB$ANUM,10),ML
        MSAVEVALUE   DAT3,PB$ANUM,10,MH$DAT1(PB$ANUM,11),ML
*
*****************************************
*****************************************
* update prec feas matrix for followers
*
        ASSIGN       TOT,&NACT,PB
ZERO    MSAVEVALUE   DAT2,PB$ANUM,PB$TOT,0,MB
        LOOP         TOT$PB,ZERO
*
*****************************************
* kick all activities to tech/resource
```

```
* (& start if qual)
*
       UNLINK      WAIT,CKFZ,ALL
*
       ADVANCE     0.0001
*
****************************************
* act 1 goes to clone for disruptions
*
       TEST G      PB$ANUM,1,DRUP
DIE    TERMINATE   1
*
****************************************
****************************************
* dummy start activity (and clones) now
* generate some disruptions
*
DRUP   SPLIT       &R1-1,NEXT1,ANUM$PB
       SPLIT       &R2,NEXT2,ANUM$PB
       SPLIT       &R3,NEXT3,ANUM$PB
       TRANSFER    ,NEXT1
*
NEXT3  ASSIGN      ANUM,3,PB
       TRANSFER    ,NEXT
NEXT2  ASSIGN      ANUM,2,PB
       TRANSFER    ,NEXT
NEXT1  ASSIGN      ANUM,1,PB
*
NEXT   PRIORITY    1
*
CYCL   UNLINK      WAIT,CKFZ,ALL
       ADVANCE     0.0001
*
       TEST E      &DIS,0,CYCL2
       TERMINATE   0
*
CYCL2  ADVANCE     RVEXPO(2,&D)        * uptime (huge, 15, 5)
       TEST GE     R(PB$ANUM),1,CYCL2
       ENTER       PB$ANUM,1
       MARK
       ADVANCE     RVEXPO(4,3/(&DIS+0.0001))     * downtime (huge, 3, 1)
       LEAVE       PB$ANUM,1
       MSAVEVALUE  DT+,1,PB$ANUM,M1,ML
       TEST GE     N$DIE,&NACT-1,CYCL
       TRANSFER    ,DIE
*
****************************************************************************
*             Program Execution & Control                                  *
****************************************************************************
*
       DO          &L=1,18             * number of problems read from POLB
*
****************************************
* read input file, set feas & out matrix
*
       GETLIST     FILE=POLB,&NACT,&NRES,&D2
DAT1   MATRIX      MH,&NACT,11                  * input matrix
DAT2   MATRIX      MB,&NACT,&NACT               * feasibility matrix
DAT3   MATRIX      ML,&NACT,10                  * raw output matrix
DT     MATRIX      ML,1,3                       * resource downtime matrix
```

```
*
       GETLIST      FILE=POLB,&D3,&R1,&R2,&R3,&D4,&D5
       GETLIST      FILE=POLB,(((MH$DAT1(&I,&J),&J=1,11),&I=1,&NACT))
*
*****************************************
* set multiple runs over the multiple
* values of variability and disruption
*
       DO           &SPD1=0,1,1          * set multiple values of spread
       LET          &SPD=&SPD1*0.6       * adjust to 0, .6 (10-2+4)
*
       DO           &DIS1=0,2,1          * set multiple values of disruption
       IF           &DIS1=2              * factor to be 0, 1, 3
       LET          &DIS1=&DIS1+1
       ENDIF
       LET          &DIS=&DIS1*1.0       * format &DIS1 to real &DIS
       LET          &D=15/(&DIS+0.0001) * dis factor (0, 1, 3)->(M, 15, 5)
*
       DO           &M=1,35              * number of reps for each problem
*
*****************************************
* initialize feasibility matrix
*
       DO           &I=1,&NACT
       DO           &J=4,8
       IF           (MH$DAT1(&I,&J))'G'(0)
       INITIAL      MB$DAT2(&I,MH$DAT1(&I,&J)),1
       ELSE
       ENDIF
       ENDDO
       ENDDO
*
*****************************************
* set initial run conditions
*
       STORAGE      S1,&R1/S2,&R2/S3,&R3
*
       LET          &K=&NACT+1
*
       START        &NACT-1
*
*****************************************
* end of run file writing
*
       PUTPIC       FILE=SIMPOL1,&D2,&SPD,&DIS,ML$DT(1,1),ML$DT(1,2),ML$DT(1,3)
********  *.*  **     ****.**  ****.**  ****.**
*
       DO           &I=1,&NACT
       PUTPIC       FILE=SIMPOL1,ML$DAT3(&I,1),ML$DAT3(&I,2),ML$DAT3(&I,3),_
ML$DAT3(&I,4),ML$DAT3(&I,5),ML$DAT3(&I,6),ML$DAT3(&I,7),ML$DAT3(&I,8),_
ML$DAT3(&I,9),ML$DAT3(&I,10)
***  ***  ***.**  ***  ***.**  **  **.**  **  **  **
       ENDDO
*
       PUTSTRING    FILE=SIMPOL1,('')
*
       RMULT        &M*124,&M*124,&M*124,&M*124
       CLEAR        MH$DAT1
*
*****************************************
```

```
* boundaries of multiple runs
*
      ENDDO                        * &M; number of reps of each problem
*
      ENDDO                        * &DIS; disruption level
*
      ENDDO                        * &SPD; variability (spread) level
*
      ENDDO                        * &L; number of problems read
*
      END




*****************************************************************************
*                       PRO2.GPS - A Project Simulator                      *
*                                                                           *
* Planning:   Per schedule from POL (priority based on SST)                 *
* Execution:  Full Reservation (tech feas act's lock resources when avail)  *
*             No Waiting (act's advance when feas, even if SST not expired) *
*                                                                           *
*  PRO1: Full Reservation-Wait (lock partial resources/wait till schedule)  *
* >PRO2: Full Reservation-No Wait (lock partial resources/go when feasible) *
*  PRO3: No Reservation-Wait (lock iff fully avail/wait till schedule)      *
*  PRO4: No Reservation-No Wait (lock iff fully avail/go when feasible)     *
*                                                                           *
* POLB: file containing problem data sets                                   *
* SIMPOL2:  file written to with simulation results                         *
*                                                                           *
* MH$DAT1: matrix containing problem data from POL                          *
* MB$DAT2: sparse matrix representing activity feasibility                  *
* ML$DAT3: matrix containing simulation output to write to SIMPOL2          *
* ML$DT:   matrix accumulating downtime (total time) of resource 1, 2 or 3  *
*                                                                           *
* RN(1): reserved                                                           *
* RN(2): up time of storages as sampled by ADVANCE (rvexpo) block           *
* RN(3): duration of activities as sampled by BETA function                 *
* RN(4): downtime of storages as sampled by ADVANCE (rvexpo) block          *
*                                                                           *
* &SPD: variability (spread) ratio of activity durations                    *
* &DIS: number of expected disruptions to each resource during project      *
*                                                                           *
* &L:   number of individual problems read from the POLB data file          *
* &M:   number of simulation repetitions of each individual problem         *
*                                                                           *
* TECH: chain holding technical/time infeasible activities (first stage)    *
* RESO: chain holding resource infeasible activities (second stage)         *
*                                                                           *
* PB$ANUM: activity number (per problem data matrix)                        *
* PB$RESx: number of resources (storage) remaining for activity start       *
* PB$FEZ:  number of precedence activities remaining for activity start     *
* PB$TOT:  "tote" counter for looping and xact management                   *
* PH$SST:  scheduled start time from POL (used for chain order)             *
* PL$DUR:  activity duration from beta distributed around POLB duration     *
*                                                                           *
*****************************************************************************
*
      SIMULATE
```

```
        REALLOCATE  FMS,0
        REALLOCATE  FSV,0
        REALLOCATE  GRP,0
        REALLOCATE  HSV,0
        REALLOCATE  LOG,0
        REALLOCATE  QUE,0
        REALLOCATE  TAB,0
        REALLOCATE  COM,25008
*
        INTEGER     &I,&J,&K,&L,&M,&SPD1,&DIS1,&PREC,&NACT,&NRES
        INTEGER     &D4,&R1,&R2,&R3,&NTR1,&NTR2,&NTR3
        REAL        &DUR,&SPD,&MRK,&SFT,&D,&D5,&DIS
        CHAR*8      &D2,&D3
*
BETA    FUNCTION    RN(3),C8
0,0/0.02,0.03/0.14,0.11/0.67,0.41/0.85,0.56/0.94,0.68/0.99,0.81/1,1
*
****************************************
* technical/time feasibility
*
RELT    BVARIABLE   ((PB$FEZ)'E'(0))
*
****************************************
* resource (storage) feasibility
*
RELR    BVARIABLE   ((PB$RES1)'E'(0))*((PB$RES2)'E'(0))*((PB$RES3)'E'(0))
*
*************************************************************************
*                   Dynamic Program Code                                *
*************************************************************************
*
        GENERATE    ,,,&NACT,,0PF,1PH,6PB,1PL
*
****************************************
* assign actnum, resource requirements,
* schedstart, and duration
*
        BLET        &K=&K-1
        ASSIGN      ANUM,&K,PB
*
        ASSIGN      RES1,MH$DAT1(PB$ANUM,9),PB
        ASSIGN      RES2,MH$DAT1(PB$ANUM,10),PB
        ASSIGN      RES3,MH$DAT1(PB$ANUM,11),PB
*
        ASSIGN      SST,MH$DAT1(PB$ANUM,2),PH
*
        BLET        &DUR=MH$DAT1(PB$ANUM,3)*(1-(&SPD/3)+&SPD*FN(BETA))
        ASSIGN      LGT,&DUR,PL
*
        TEST G      PB$ANUM,1,WRIT      * start node skip to end (writ)
        LINK        WAIT,SST$PH
*
****************************************
****************************************
* update technical feasibility
* sum undone prec activities for self
*
CKFZ    ASSIGN      TOT,&NACT,PB
        BLET        &PREC=0
CKPR    BLET        &PREC=&PREC+MB$DAT2(PB$TOT,PB$ANUM)
```

```
        LOOP         TOT$PB,CKPR
        ASSIGN       FEZ,&PREC,PB
*
*****************************************
*****************************************
* update resource feasibility and start
* this activity if all feas satisfied
*
        TEST GE      R1,PB$RES1,ELS1
        BLET         &NTR1=PB$RES1
        TRANSFER     ,ELS2
ELS1    BLET         &NTR1=R1
*
ELS2    TEST GE      R2,PB$RES2,ELS3
        BLET         &NTR2=PB$RES2
        TRANSFER     ,ELS4
ELS3    BLET         &NTR2=R2
*
ELS4    TEST GE      R3,PB$RES3,ELS5
        BLET         &NTR3=PB$RES3
        TRANSFER     ,ELS6
ELS5    BLET         &NTR3=R3
*
ELS6    ASSIGN       RES1-,&NTR1,PB
        ASSIGN       RES2-,&NTR2,PB
        ASSIGN       RES3-,&NTR3,PB
*
        ENTER        1,&NTR1
        ENTER        2,&NTR2
        ENTER        3,&NTR3
*
        TEST E       BV$RELT,0,CKRS
LWAT    LINK         WAIT,SST$PH
CKRS    TEST E       BV$RELR,1,LWAT
*
        MARK
        ADVANCE      PL$LGT
        LEAVE        1,MH$DAT1(PB$ANUM,9)
        LEAVE        2,MH$DAT1(PB$ANUM,10)
        LEAVE        3,MH$DAT1(PB$ANUM,11)
*
*****************************************
*****************************************
* write activity information to raw matrix
*
WRIT    BLET         &MRK=AC1-M1
        BLET         &SFT=MH$DAT1(PB$ANUM,2)+MH$DAT1(PB$ANUM,3)
        MSAVEVALUE   DAT3,PB$ANUM,1,PB$ANUM,ML
        MSAVEVALUE   DAT3,PB$ANUM,2,PH$SST,ML
        MSAVEVALUE   DAT3,PB$ANUM,3,&MRK,ML
        MSAVEVALUE   DAT3,PB$ANUM,4,&SFT,ML
        MSAVEVALUE   DAT3,PB$ANUM,5,AC1,ML
        MSAVEVALUE   DAT3,PB$ANUM,6,MH$DAT1(PB$ANUM,3),ML
        MSAVEVALUE   DAT3,PB$ANUM,7,PL$LGT,ML
        MSAVEVALUE   DAT3,PB$ANUM,8,MH$DAT1(PB$ANUM,9),ML
        MSAVEVALUE   DAT3,PB$ANUM,9,MH$DAT1(PB$ANUM,10),ML
        MSAVEVALUE   DAT3,PB$ANUM,10,MH$DAT1(PB$ANUM,11),ML
*
*****************************************
*****************************************
```

```
* update prec feas matrix for followers
*
       ASSIGN      TOT,&NACT,PB
ZERO   MSAVEVALUE  DAT2,PB$ANUM,PB$TOT,0,MB
       LOOP        TOT$PB,ZERO
*
****************************************
* kick all activities to tech/resource
* (& start if qual)
*
       UNLINK      WAIT,CKFZ,ALL
*
       ADVANCE     0.0001
*
****************************************
* act 1 goes to clone for disruptions
*
       TEST G      PB$ANUM,1,DRUP
DIE    TERMINATE   1
*
****************************************
****************************************
* dummy start activity (and clones) now
* generate some disruptions
*
DRUP   SPLIT       &R1-1,NEXT1,ANUM$PB
       SPLIT       &R2,NEXT2,ANUM$PB
       SPLIT       &R3,NEXT3,ANUM$PB
       TRANSFER    ,NEXT1
*
NEXT3  ASSIGN      ANUM,3,PB
       TRANSFER    ,NEXT
NEXT2  ASSIGN      ANUM,2,PB
       TRANSFER    ,NEXT
NEXT1  ASSIGN      ANUM,1,PB
*
NEXT   PRIORITY    1
*
CYCL   UNLINK      WAIT,CKFZ,ALL
       ADVANCE     0.0001
*
       TEST E      &DIS,0,CYCL2
       TERMINATE   0
*
CYCL2  ADVANCE     RVEXPO(2,&D)        * uptime (huge, 15, 5)
       TEST GE     R(PB$ANUM),1,CYCL2
       ENTER       PB$ANUM,1
       MARK
       ADVANCE     RVEXPO(4,3/(&DIS+0.0001))     * downtime (huge, 3, 1)
       LEAVE       PB$ANUM,1
       MSAVEVALUE  DT+,1,PB$ANUM,M1,ML
       TEST GE     N$DIE,&NACT-1,CYCL
       TRANSFER    ,DIE
*
**************************************************************
*            Program Execution & Control                     *
**************************************************************
*
       DO          &L=1,18             * number of problems read from POL
*
```

```
*****************************************
* read input file, set feas & out matrix
*
       GETLIST      FILE=POLB,&NACT,&NRES,&D2
DAT1   MATRIX       MH,&NACT,11                   * input matrix
DAT2   MATRIX       MB,&NACT,&NACT                * feasibility matrix
DAT3   MATRIX       ML,&NACT,10                   * raw output matrix
DT     MATRIX       ML,1,3                        * resource downtime matrix
*
       GETLIST      FILE=POLB,&D3,&R1,&R2,&R3,&D4,&D5
       GETLIST      FILE=POLB,(((MH$DAT1(&I,&J),&J=1,11),&I=1,&NACT))
*
*****************************************
* set multiple runs over the multiple
* values of variability and disruption
*
       DO           &SPD1=0,1,1         * set multiple values of spread
       LET          &SPD=&SPD1*0.6      * adjust to 0, .6
*
       DO           &DIS1=0,2,1         * set multiple values of disruption
       IF           &DIS1=2             * factor to be 0, 1, 3
       LET          &DIS1=&DIS1+1
       ENDIF
       LET          &DIS=&DIS1*1.0      * format &DIS1 to real &DIS
       LET          &D=15/(&DIS+0.0001) * dis factor (0, 1, 3)->(M, 15, 5)
*
       DO           &M=1,35             * number of reps for each problem
*
*****************************************
* initialize feasibility matrix
*
       DO           &I=1,&NACT
       DO           &J=4,8
       IF           (MH$DAT1(&I,&J))'G'(0)
       INITIAL      MB$DAT2(&I,MH$DAT1(&I,&J)),1
       ELSE
       ENDIF
       ENDDO
       ENDDO
*
*****************************************
* set initial run conditions
*
       STORAGE      S1,&R1/S2,&R2/S3,&R3
*
       LET          &K=&NACT+1
*
       START        &NACT-1
*
*****************************************
* end of run file writing
*
       PUTPIC       FILE=SIMPOL2,&D2,&SPD,&DIS,ML$DT(1,1),ML$DT(1,2),ML$DT(1,3)
********  *.*  **      ****.**  ****.**  ****.**
*
       DO           &I=1,&NACT
       PUTPIC       FILE=SIMPOL2,ML$DAT3(&I,1),ML$DAT3(&I,2),ML$DAT3(&I,3),_
ML$DAT3(&I,4),ML$DAT3(&I,5),ML$DAT3(&I,6),ML$DAT3(&I,7),ML$DAT3(&I,8),_
ML$DAT3(&I,9),ML$DAT3(&I,10)
***  ***  ***.**  ***  ***.**  **  **.**  **  **  **
```

```
      ENDDO
*
      PUTSTRING   FILE=SIMPOL2,('')
*
      RMULT       &M*124,&M*124,&M*124,&M*124
      CLEAR       MH$DAT1
*
****************************************
* boundaries of multiple runs
*
      ENDDO                           * &M; number of reps of each problem
*
      ENDDO                           * &DIS; disruption level
*
      ENDDO                           * &SPD; variability (spread) level
*
      ENDDO                           * &L; number of problems read
*
      END
```

```
******************************************************************************
*                       PRO3.GPS - A Project Simulator                       *
*                                                                            *
* Planning:   Per schedule from POL (priority based on SST)                  *
* Execution:  No Reservation (FCFS, by priority, of tech feasible act's)     *
*             Waiting (act's advance iff BOTH tech and SST conditions met)   *
*                                                                            *
*  PRO1: Full Reservation-Wait (lock partial resources/wait till schedule)   *
*  PRO2: Full Reservation-No Wait (lock partial resources/go when feasible)  *
* >PRO3: No Reservation-Wait (lock iff fully avail/wait till schedule)       *
*  PRO4: No Reservation-No Wait (lock iff fully avail/go when feasible)      *
*                                                                            *
* POLB: file containing problem data sets                                    *
* SIMPOL3:  file written to with simulation results                          *
*                                                                            *
* MH$DAT1: matrix containing problem data from POLB                          *
* MB$DAT2: sparse matrix representing activity feasibility                   *
* ML$DAT3: matrix containing simulation output to write to SIMPOL3           *
* ML$DT:   matrix accumulating downtime (total time) of resource 1, 2 or 3   *
*                                                                            *
* RN(1): reserved                                                            *
* RN(2): up time of storages as sampled by ADVANCE (rvexpo) block            *
* RN(3): duration of activities as sampled by BETA function                  *
* RN(4): down time of storages as sampled by ADVANCE (rvexpo) block          *
*                                                                            *
* &SPD: variability (spread) ratio of activity durations                     *
* &DIS: number of expected disruptions to each resource during project       *
*                                                                            *
* &L:   number of individual problems read from the POLB data file           *
* &M:   number of simulation repetitions of each individual problem          *
*                                                                            *
* TECH: chain holding technical/time infeasible activities (first stage)     *
* RESO: chain holding resource infeasible activities (second stage)          *
*                                                                            *
* PB$ANUM: activity number (per problem data matrix)                         *
* PB$RESx: number of resources (storage) remaining for activity start        *
```

```
* PB$FEZ:  number of precedence activities remaining for activity start    *
* PB$TOT:  "tote" counter for looping and xact management                  *
* PH$SST:  scheduled start time from POL (used for chain order)            *
* PL$DUR:  activity duration from beta distributed around POLB duration    *
*                                                                          *
****************************************************************************
*
       SIMULATE
       REALLOCATE  FMS,0
       REALLOCATE  FSV,0
       REALLOCATE  GRP,0
       REALLOCATE  HSV,0
       REALLOCATE  LOG,0
       REALLOCATE  QUE,0
       REALLOCATE  TAB,0
       REALLOCATE  COM,25008
*
       INTEGER     &I,&J,&K,&L,&M,&SPD1,&DIS1,&PREC,&NACT,&NRES
       INTEGER     &D4,&R1,&R2,&R3
       REAL        &DUR,&SPD,&MRK,&SFT,&D,&D5,&DIS,&TMR
       CHAR*8      &D2,&D3
*
BETA   FUNCTION    RN(3),C8
0,0/0.02,0.03/0.14,0.11/0.67,0.41/0.85,0.56/0.94,0.68/0.99,0.81/1,1
*
****************************************
* technical feasibility
*
RELT   BVARIABLE   ((PB$FEZ)'E'(0))
*
****************************************
* resource (storage) feasibility
*
RELR   BVARIABLE   ((PB$RES1)'E'(0))*((PB$RES2)'E'(0))*((PB$RES3)'E'(0))
*
****************************************************************************
*                  Dynamic Program Code                                    *
****************************************************************************
*
       GENERATE    ,,,&NACT,,0PF,1PH,6PB,1PL
*
****************************************
* assign actnum, resource requirements,
* schedstart, and duration
*
       BLET        &K=&K-1
       ASSIGN      ANUM,&K,PB
*
       ASSIGN      RES1,MH$DAT1(PB$ANUM,9),PB
       ASSIGN      RES2,MH$DAT1(PB$ANUM,10),PB
       ASSIGN      RES3,MH$DAT1(PB$ANUM,11),PB
*
       ASSIGN      SST,MH$DAT1(PB$ANUM,2),PH
*
       BLET        &DUR=MH$DAT1(PB$ANUM,3)*(1-(&SPD/3)+&SPD*FN(BETA))
       ASSIGN      LGT,&DUR,PL
*
       TEST G      PB$ANUM,1,WRIT      * start node skip to end (writ)
*
****************************************
```

```
****************************************
* sum undone prec activities for self
*
CKFZ   ASSIGN      TOT,&NACT,PB
       BLET        &PREC=0
CKPR   BLET        &PREC=&PREC+MB$DAT2(PB$TOT,PB$ANUM)
       LOOP        TOT$PB,CKPR
       ASSIGN      FEZ,&PREC,PB
*
****************************************
* if tech & time feas, wait on reso chain
* else go back to tech chain
*
       TEST E      BV$RELT,1,NYET       * if not yet tech feas, back to TECH
       BLET        &TMR=FLT(PH$SST)
       TEST G      &TMR,AC1,CKRS        * if SST > AC1, then
       ADVANCE     &TMR-AC1             *   wait here until SST = AC1, then
       TRANSFER    ,CKRS                *   go to check resources
LRES   LINK        RESO,SST$PH          * tech/time feas go to reso
NYET   LINK        TECH,SST$PH          * not yet tech/time feas back to TECH
*
****************************************
****************************************
* update resource feasibility and start
* this activity if all resources avail
*
CKRS   TEST GE     R1,MH$DAT1(PB$ANUM,9),LRES
       TEST GE     R2,MH$DAT1(PB$ANUM,10),LRES
       TEST GE     R3,MH$DAT1(PB$ANUM,11),LRES
*
       ASSIGN      RES1,0,PB
       ASSIGN      RES2,0,PB
       ASSIGN      RES3,0,PB
*
       ENTER       1,MH$DAT1(PB$ANUM,9)
       ENTER       2,MH$DAT1(PB$ANUM,10)
       ENTER       3,MH$DAT1(PB$ANUM,11)
*
       TEST E      BV$RELR,1,LRES
*
       MARK
       ADVANCE     PL$LGT
       LEAVE       1,MH$DAT1(PB$ANUM,9)
       LEAVE       2,MH$DAT1(PB$ANUM,10)
       LEAVE       3,MH$DAT1(PB$ANUM,11)
*
****************************************
****************************************
* write activity information to raw matrix
*
WRIT   BLET        &MRK=AC1-M1
       BLET        &SFT=MH$DAT1(PB$ANUM,2)+MH$DAT1(PB$ANUM,3)
       MSAVEVALUE  DAT3,PB$ANUM,1,PB$ANUM,ML
       MSAVEVALUE  DAT3,PB$ANUM,2,PH$SST,ML
       MSAVEVALUE  DAT3,PB$ANUM,3,&MRK,ML
       MSAVEVALUE  DAT3,PB$ANUM,4,&SFT,ML
       MSAVEVALUE  DAT3,PB$ANUM,5,AC1,ML
       MSAVEVALUE  DAT3,PB$ANUM,6,MH$DAT1(PB$ANUM,3),ML
       MSAVEVALUE  DAT3,PB$ANUM,7,PL$LGT,ML
       MSAVEVALUE  DAT3,PB$ANUM,8,MH$DAT1(PB$ANUM,9),ML
```

```
       MSAVEVALUE  DAT3,PB$ANUM,9,MH$DAT1(PB$ANUM,10),ML
       MSAVEVALUE  DAT3,PB$ANUM,10,MH$DAT1(PB$ANUM,11),ML
*
****************************************
****************************************
* update prec feas matrix for followers
*
       ASSIGN      TOT,&NACT,PB
ZERO   MSAVEVALUE  DAT2,PB$ANUM,PB$TOT,0,MB
       LOOP        TOT$PB,ZERO
*
****************************************
* kick all tech/time feas activities to
* resource update (& start if qual)
*
       UNLINK      RESO,CKRS,ALL
*
       ADVANCE     0.00001
*
****************************************
* trigger feas update of all waiting on
* tech chain (& send to reso if qual)
*
       UNLINK      TECH,CKFZ,ALL
*
       ADVANCE     0.00001
*
       TEST G      PB$ANUM,1,DRUP
DIE    TERMINATE   1
*
****************************************
****************************************
* dummy start activity (and clones) now
* generate some disruptions
*
DRUP   SPLIT       &R1-1,NEXT1,ANUM$PB
       SPLIT       &R2,NEXT2,ANUM$PB
       SPLIT       &R3,NEXT3,ANUM$PB
       TRANSFER    ,NEXT1
*
NEXT3  ASSIGN      ANUM,3,PB
       TRANSFER    ,NEXT
NEXT2  ASSIGN      ANUM,2,PB
       TRANSFER    ,NEXT
NEXT1  ASSIGN      ANUM,1,PB
*
NEXT   PRIORITY    1
*
CYCL   UNLINK      WAIT,CKFZ,ALL
       ADVANCE     0.0001
       UNLINK      RESO,CKRS,ALL
       ADVANCE     0.0001

*
       TEST E      &DIS,0,CYCL2
       TERMINATE   0
*
CYCL2  ADVANCE     RVEXPO(2,&D)        * uptime (huge, 15, 5)
       TEST GE     R(PB$ANUM),1,CYCL2
       ENTER       PB$ANUM,1
```

```
      MARK
      ADVANCE     RVEXPO(4,3/(&DIS+0.0001))    * downtime (huge, 3, 1)
      LEAVE       PB$ANUM,1
      MSAVEVALUE  DT+,1,PB$ANUM,M1,ML
      TEST GE     N$DIE,&NACT-1,CYCL
      TRANSFER    ,DIE
*
****************************************************************************
*           Program Execution & Control                                    *
****************************************************************************
*
      DO          &L=1,18            * number of problems read from POL
*
****************************************
* read input file, set feas & out matrix
*
      GETLIST     FILE=POLB,&NACT,&NRES,&D2
DAT1  MATRIX      MH,&NACT,11                * input matrix
DAT2  MATRIX      MB,&NACT,&NACT             * feasibility matrix
DAT3  MATRIX      ML,&NACT,10                * raw output matrix
DT    MATRIX      ML,1,3                     * resource downtime matrix
*
      GETLIST     FILE=POLB,&D3,&R1,&R2,&R3,&D4,&D5
      GETLIST     FILE=POLB,(((MH$DAT1(&I,&J),&J=1,11),&I=1,&NACT))
*
****************************************
* set multiple runs over the multiple
* values of variability and disruption
*
      DO          &SPD1=0,1,1        * set multiple values of spread
      LET         &SPD=&SPD1*0.6     * adjust to 0, .6
*
      DO          &DIS1=0,2,1        * set multiple values of disruption
      IF          &DIS1=2            * factor to be 0, 1, 3
      LET         &DIS1=&DIS1+1
      ENDIF
      LET         &DIS=&DIS1*1.0     * convert to real
      LET         &D=15/(&DIS+0.0001) * dis factor (0, 1, 3)->(M, 15, 5)
*
      DO          &M=1,35            * number of reps for each problem
*
****************************************
* initialize feasibility matrix
*
      DO          &I=1,&NACT
      DO          &J=4,8
      IF          (MH$DAT1(&I,&J))'G'(0)
      INITIAL     MB$DAT2(&I,MH$DAT1(&I,&J)),1
      ELSE
      ENDIF
      ENDDO
      ENDDO
*
****************************************
* set initial run conditions
*
      STORAGE     S1,&R1/S2,&R2/S3,&R3
*
      LET         &K=&NACT+1
*
```

```
      START       &NACT-1
*
****************************************
* end of run file writing
*
      PUTPIC      FILE=SIMPOL3,&D2,&SPD,&DIS,ML$DT(1,1),ML$DT(1,2),ML$DT(1,3)
********  *.*  **     ****.**  ****.**  ****.**
*
      DO          &I=1,&NACT
      PUTPIC      FILE=SIMPOL3,ML$DAT3(&I,1),ML$DAT3(&I,2),ML$DAT3(&I,3),_
ML$DAT3(&I,4),ML$DAT3(&I,5),ML$DAT3(&I,6),ML$DAT3(&I,7),ML$DAT3(&I,8),_
ML$DAT3(&I,9),ML$DAT3(&I,10)
***  ***  ***.**  ***  ***.**  **  **.**  **  **  **
      ENDDO
*
      PUTSTRING   FILE=SIMPOL3,('')
*
      RMULT       &M*124,&M*124,&M*124,&M*124
      CLEAR       MH$DAT1
*
****************************************
* boundaries of multiple runs
*
      ENDDO                          * &M; number of reps of each problem
*
      ENDDO                          * &DIS; disruption level
*
      ENDDO                          * &SPD; variability (spread) level
*
      ENDDO                          * &L; number of problems read
*
      END



****************************************************************************
*                      PRO4.GPS - A Project Simulator                      *
*                                                                          *
* Planning:   Per schedule from POLB (priority based on SST)               *
* Execution:  No Reservation (FCFS, by priority, of tech feasible act's)   *
*             No Waiting (act's advance when feas, even if SST not expired) *
*                                                                          *
*  PRO1: Full Reservation-Wait (lock partial resources/wait till schedule)  *
*  PRO2: Full Reservation-No Wait (lock partial resources/go when feasible) *
*  PRO3: No Reservation-Wait (lock iff fully avail/wait till schedule)      *
* >PRO4: No Reservation-No Wait (lock iff fully avail/go when feasible)    *
*                                                                          *
* POLB: file containing problem data sets                                  *
* SIMPOL4:  file written to with simulation results                        *
*                                                                          *
* MH$DAT1: matrix containing problem data from POLB                        *
* MB$DAT2: sparse matrix representing activity feasibility                 *
* ML$DAT3: matrix containing simulation output to write to SIMPOL4         *
* ML$DT:   matrix accumulating downtime (total time) of resource 1, 2 or 3  *
*                                                                          *
* RN(1): reserved                                                          *
* RN(2): up time of storages as sampled by ADVANCE (rvexpo) block          *
* RN(3): duration of activities as sampled by BETA function                *
```

```
* RN(4): down time of storages as sampled by ADVANCE (rvexpo) block        *
*                                                                          *
* &SPD: variability (spread) ratio of activity durations                   *
* &DIS: number of expected disruptions to each resource during project     *
*                                                                          *
* &L:   number of individual problems read from the POLB data file         *
* &M:   number of simulation repetitions of each individual problem        *
*                                                                          *
* TECH: chain holding technical/time infeasible activities (first stage)   *
* RESO: chain holding resource infeasible activities (second stage)        *
*                                                                          *
* PB$ANUM: activity number (per problem data matrix)                       *
* PB$RESx: number of resources (storage) remaining for activity start      *
* PB$FEZ:  number of precedence activities remaining for activity start    *
* PB$TOT:  "tote" counter for looping and xact management                  *
* PH$SST:  scheduled start time from POLB (used for chain order)           *
* PL$DUR:  activity duration from beta distributed around POLB duration    *
*                                                                          *
****************************************************************************
*
       SIMULATE
       REALLOCATE  FMS,0
       REALLOCATE  FSV,0
       REALLOCATE  GRP,0
       REALLOCATE  HSV,0
       REALLOCATE  LOG,0
       REALLOCATE  QUE,0
       REALLOCATE  TAB,0
       REALLOCATE  COM,25008
*
       INTEGER     &I,&J,&K,&L,&M,&SPD1,&DIS1,&PREC,&NACT,&NRES
       INTEGER     &D4,&R1,&R2,&R3
       REAL        &DUR,&SPD,&MRK,&SFT,&D,&D5,&DIS
       CHAR*8      &D2,&D3
*
BETA   FUNCTION    RN(3),C8
0,0/0.02,0.03/0.14,0.11/0.67,0.41/0.85,0.56/0.94,0.68/0.99,0.81/1,1
*
****************************************
* technical/time feasibility
*
RELT   BVARIABLE   ((PB$FEZ)'E'(0))
*
****************************************
* resource (storage) feasibility
*
RELR   BVARIABLE   ((PB$RES1)'E'(0))*((PB$RES2)'E'(0))*((PB$RES3)'E'(0))
*
****************************************************************************
*                      Dynamic Program Code                                *
****************************************************************************
*
       GENERATE    ,,,&NACT,,0PF,1PH,6PB,1PL
*
****************************************
* assign actnum, resource requirements,
* schedstart, and duration
*
       BLET        &K=&K-1
       ASSIGN      ANUM,&K,PB
```

```
*
       ASSIGN      RES1,MH$DAT1(PB$ANUM,9),PB
       ASSIGN      RES2,MH$DAT1(PB$ANUM,10),PB
       ASSIGN      RES3,MH$DAT1(PB$ANUM,11),PB
*
       ASSIGN      SST,MH$DAT1(PB$ANUM,2),PH
*
       BLET        &DUR=MH$DAT1(PB$ANUM,3)*(1-(&SPD/3)+&SPD*FN(BETA))
       ASSIGN      LGT,&DUR,PL
*
       TEST G      PB$ANUM,1,WRIT      * start node skip to end (writ)
*
****************************************
****************************************
* sum undone prec activities for self
*
CKFZ   ASSIGN      TOT,&NACT,PB
       BLET        &PREC=0
CKPR   BLET        &PREC=&PREC+MB$DAT2(PB$TOT,PB$ANUM)
       LOOP        TOT$PB,CKPR
       ASSIGN      FEZ,&PREC,PB
*
****************************************
* if tech/time feas, wait on reso chain
* else go back to tech chain
*
       TEST E      BV$RELT,1,NYET
LRES   LINK        RESO,SST$PH         * tech/time feas go to reso
NYET   LINK        TECH,SST$PH         * not yet tech/time feas back to tech
*
****************************************
****************************************
* update resource feasibility and start
* this activity if all resources avail
*
CKRS   TEST GE     R1,MH$DAT1(PB$ANUM,9),LRES
       TEST GE     R2,MH$DAT1(PB$ANUM,10),LRES
       TEST GE     R3,MH$DAT1(PB$ANUM,11),LRES
*
       ASSIGN      RES1,0,PB
       ASSIGN      RES2,0,PB
       ASSIGN      RES3,0,PB
*
       ENTER       1,MH$DAT1(PB$ANUM,9)
       ENTER       2,MH$DAT1(PB$ANUM,10)
       ENTER       3,MH$DAT1(PB$ANUM,11)
*
       TEST E      BV$RELR,1,LRES
*
       MARK
       ADVANCE     PL$LGT
       LEAVE       1,MH$DAT1(PB$ANUM,9)
       LEAVE       2,MH$DAT1(PB$ANUM,10)
       LEAVE       3,MH$DAT1(PB$ANUM,11)
*
****************************************
****************************************
* write activity information to raw matrix
*
WRIT   BLET        &MRK=AC1-M1
```

```
       BLET          &SFT=MH$DAT1(PB$ANUM,2)+MH$DAT1(PB$ANUM,3)
       MSAVEVALUE    DAT3,PB$ANUM,1,PB$ANUM,ML
       MSAVEVALUE    DAT3,PB$ANUM,2,PH$SST,ML
       MSAVEVALUE    DAT3,PB$ANUM,3,&MRK,ML
       MSAVEVALUE    DAT3,PB$ANUM,4,&SFT,ML
       MSAVEVALUE    DAT3,PB$ANUM,5,AC1,ML
       MSAVEVALUE    DAT3,PB$ANUM,6,MH$DAT1(PB$ANUM,3),ML
       MSAVEVALUE    DAT3,PB$ANUM,7,PL$LGT,ML
       MSAVEVALUE    DAT3,PB$ANUM,8,MH$DAT1(PB$ANUM,9),ML
       MSAVEVALUE    DAT3,PB$ANUM,9,MH$DAT1(PB$ANUM,10),ML
       MSAVEVALUE    DAT3,PB$ANUM,10,MH$DAT1(PB$ANUM,11),ML
*
****************************************
****************************************
* update prec feas matrix for followers
*
       ASSIGN        TOT,&NACT,PB
ZERO   MSAVEVALUE    DAT2,PB$ANUM,PB$TOT,0,MB
       LOOP          TOT$PB,ZERO
*
****************************************
* trigger feas update of all waiting on
* tech chain (& send to reso if qual)
*
       UNLINK        TECH,CKFZ,ALL
       ADVANCE       0.00001
*
****************************************
* kick all tech/time feas activities to
* resource update (& start if qual)
*
       UNLINK        RESO,CKRS,ALL
*
       ADVANCE       0.00001
*
       TEST G        PB$ANUM,1,DRUP
DIE    TERMINATE     1
*
****************************************
****************************************
* dummy start activity (and clones) now
* generate some disruptions
*
DRUP   SPLIT         &R1-1,NEXT1,ANUM$PB
       SPLIT         &R2,NEXT2,ANUM$PB
       SPLIT         &R3,NEXT3,ANUM$PB
       TRANSFER      ,NEXT1
*
NEXT3  ASSIGN        ANUM,3,PB
       TRANSFER      ,NEXT
NEXT2  ASSIGN        ANUM,2,PB
       TRANSFER      ,NEXT
NEXT1  ASSIGN        ANUM,1,PB
*
NEXT   PRIORITY      1
*
CYCL   UNLINK        WAIT,CKFZ,ALL
       ADVANCE       0.0001
       UNLINK        RESO,CKRS,ALL
       ADVANCE       0.0001
```

```
*
       TEST E       &DIS,0,CYCL2
       TERMINATE    0
*
CYCL2  ADVANCE      RVEXPO(2,&D)          * uptime (huge, 15, 5)
       TEST GE      R(PB$ANUM),1,CYCL2
       ENTER        PB$ANUM,1
       MARK
       ADVANCE      RVEXPO(4,3/(&DIS+0.0001))     * downtime (huge, 3, 1)
       LEAVE        PB$ANUM,1
       MSAVEVALUE   DT+,1,PB$ANUM,M1,ML
       TEST GE      N$DIE,&NACT-1,CYCL
       TRANSFER     ,DIE
*
******************************************************************************
*            Program Execution & Control                                     *
******************************************************************************
*
       DO           &L=1,18               * number of problems read from POLB
*
****************************************
* read input file, set feas & out matrix
*
       GETLIST      FILE=POLB,&NACT,&NRES,&D2
DAT1   MATRIX       MH,&NACT,11                   * input matrix
DAT2   MATRIX       MB,&NACT,&NACT                * feasibility matrix
DAT3   MATRIX       ML,&NACT,10                   * raw output matrix
DT     MATRIX       ML,1,3                        * resource downtime matrix
*
       GETLIST      FILE=POLB,&D3,&R1,&R2,&R3,&D4,&D5
       GETLIST      FILE=POLB,(((MH$DAT1(&I,&J),&J=1,11),&I=1,&NACT))
*
****************************************
* set multiple runs over the multiple
* values of variability and disruption
*
       DO           &SPD1=0,1,1           * set multiple values of spread
       LET          &SPD=&SPD1*0.6        * adjust to 0, .6
*
       DO           &DIS1=0,2,1           * set multiple values of disruption
       IF           &DIS1=2               * factor to be (0, 1, 3)
       LET          &DIS1=&DIS1+1
       ENDIF
       LET          &DIS=&DIS1*1.0        * convert to real
       LET          &D=15/(&DIS+0.0001) * dis factor (0, 1, 3)->(M, 15, 5)
*
       DO           &M=1,35               * number of reps for each problem
*
****************************************
* initialize feasibility matrix
*
       DO           &I=1,&NACT
       DO           &J=4,8
       IF           (MH$DAT1(&I,&J))'G'(0)
       INITIAL      MB$DAT2(&I,MH$DAT1(&I,&J)),1
       ELSE
       ENDIF
       ENDDO
       ENDDO
*
```

```
*****************************************
* set initial run conditions
*
       STORAGE      S1,&R1/S2,&R2/S3,&R3
*
       LET          &K=&NACT+1
*
       START        &NACT-1
*
*****************************************
* end of run file writing
*
       PUTPIC       FILE=SIMPOL4,&D2,&SPD,&DIS,ML$DT(1,1),ML$DT(1,2),ML$DT(1,3)
********  *.*  **      ****.**  ****.**  ****.**
*
       DO           &I=1,&NACT
       PUTPIC       FILE=SIMPOL4,ML$DAT3(&I,1),ML$DAT3(&I,2),ML$DAT3(&I,3),_
ML$DAT3(&I,4),ML$DAT3(&I,5),ML$DAT3(&I,6),ML$DAT3(&I,7),ML$DAT3(&I,8),_
ML$DAT3(&I,9),ML$DAT3(&I,10)
***  ***  ***.**  ***  ***.**  **  **.**  **  **  **
       ENDDO
*
       PUTSTRING    FILE=SIMPOL4,('')
*
       RMULT        &M*124,&M*124,&M*124,&M*124
       CLEAR        MH$DAT1
*
*****************************************
* boundaries of multiple runs
*
       ENDDO                              * &M; number of reps of each problem
*
       ENDDO                              * &DIS; disruption level
*
       ENDDO                              * &SPD; variability (spread) level
*
       ENDDO                              * &L; number of problems read
*
       END
```

APPENDIX K

PASCAL LISTINGS

```
{***************************************************************************}
{                                                                           }
{                                CONTST.PAS                                 }
{                                                                           }
{  File1:  Input file; problem schedule data                               }
{  File2:  Input file; simulation output data 30 reps x 6 factor combos    }
{  File3:  Input file; problem characteristics from Demographics file      }
{  File4:  Output file; the calculated results of this conversion program  }
{                                                                           }
{  ArIn1:  Array (60x11) problem schedule characteristics from File1       }
{  ArIn2:  Array (60x10) simulation output data from File2 (reps x factors) }
{                                                                           }
{                                                                           }
{                                                                           }
{***************************************************************************}
program Convert;

const
  Cost1 = 25;
  Cost2 = 25;
  Cost3 = 25;
  R = -0.15/365;

var

  Done: Boolean;

  File1, File2, File3, File4: Text;

  NAct, NRes, Dis, Dum2, OCPL, I, J, K, L, M, N:  Integer;

  ArIn1:  array[1..51, 1..11] of Real;
  ArIn2:  array[1..51, 1..10] of Real;
  Ar1, Ar2:  array[1..102, 1..4] of Real;

  Res1, Res2, Res3, DT1, DT2, DT3, Lod1, Lod2, Lod3, Cap1, Cap2, Cap3:  Real;
  ADur, PDur, RDur, Spd, AARU, RARU, AMRU, RMRU, SNPV, ANPV, RNPV:  Real;
  Den, S1L, S1E, S1, S2I, S2O, S2, S3I, S3O, ResLod, Tmp1, Tmp2: Real;
  PMT, EPMT, APMT, ARU, MRU, Num1, Num2, Dum, TLast:  Real;

  Filename,A1,A2,A3,A4,B1,B2,B3,B4,B5,B6,B7,B8,B9,B10:  String;
  C1,C2,C3,C4,C5,C6,C7,C8,C9:  String;

  Name:  String[12];
  NAc:  String[4];
  MDF, NDR, NCR, ARC, MRC: String[9];
  Nam1, Nam2, Dum1:  String[12];
  Sked, Exec:  String[3];

{***************************************************************************}

begin

  Write('Please enter schedule data input filename:  ');
    ReadLn(FileName);
    Assign(File1, FileName);

  Write('Please enter simulation data input filename:  ');
    ReadLn(FileName);
    Assign(File2, FileName);
```

```
  Write('Please enter problem demographic data input filename:  ');
    ReadLn(FileName);
    Assign(File3, FileName);

  Write('Please enter conversion data output filename:  ');
    ReadLn(Filename);
    Assign(File4, FileName);

  Write('Please enter scheduling method used (3 char):  ');
    ReadLn(Sked);

  Write('Please enter execution method used (3 char):  ');
    ReadLn(Exec);

  Reset(File1);
  Reset(File2);
  Reset(File3);
  ReWrite(File4);

{*****************************************************************}
{* initialize ArIn1 & ArIn2 matrices containing problem data      }

for I:=1 to 18 do                        {* number of problems     }

begin

  ReadLn(File1, NAct, NRes, Nam1);
  ReadLn(File1, Dum1, Res1, Res2, Res3, Dum2, OCPL);

  for K:=1 to NAct do
    begin
      for L:=1 to 11 do
        Read(File1, ArIn1[K, L]);
    end;

  ReadLn(File1);                         {* skip the blank line    }


  ReadLn(File3, Name, NAc, PDur, MDF, NDR, NCR, ARC, MRC, ARU, MRU);


{*****************************************************************}
{* initialize ArIn2 matrix containing 35 reps x 6 factors sim data}

for J:=1 to 210 do                       {* number of reps in File2}
                                         {  for each problem       }
begin

  ReadLn(File2, Nam2, Spd, Dis, DT1, DT2, DT3);

  for K:=1 to NAct do
    begin
      for L:=1 to 10 do
        Read(File2, ArIn2[K, L]);
    end;

    ReadLn(File2);                       {* skip the blank line    }
```

```
{*******************************************************}
{*  assign actual project duration ADur                }

  ADur:=ArIn2[NAct, 5];

{*******************************************************}
{* calculate percent project duration over sched PDur   }

  RDur:=ADur/PDur;

{*******************************************************}
{* calculate Actual Average Resource Utilization AARU   }

  Lod1:=0;
  Lod2:=0;
  Lod3:=0;

  Cap1:=ADur*Res1;
  Cap2:=ADur*Res2;
  Cap3:=ADur*Res3;

  for K:=1 to NAct do
  begin
    Lod1:=Lod1+ArIn2[K,8]*ArIn2[K,7];
    Lod2:=Lod2+ArIn2[K,9]*ArIn2[K,7];
    Lod3:=Lod3+ArIn2[K,10]*ArIn2[K,7];
  end;

  AARU:=(Lod1+Lod2+Lod3)/(Cap1+Cap2+Cap3);

  RARU:=AARU/ARU;

{*******************************************************}
{* calculate Actual Maximum Resource Utilization AMRU   }

  if (Lod1/Cap1) > (Lod2/Cap2)
    then AMRU:=(Lod1/Cap1)
    else AMRU:=(Lod2/Cap2);

  if (Lod3/Cap3) > AMRU
    then AMRU:=(Lod3/Cap3)
    else;

  RMRU:=AMRU/MRU;

{*******************************************************}
{* calculate project Net Present Values A/S/RNPV        }

  SNPV:=0;
  ANPV:=0;
  PMT:=0;

  for K:=1 to NAct do
  begin
    SNPV:=SNPV+((Cost1*ArIn2[K,8]*ArIn2[K,6])*(exp(R*ArIn2[K,4])));
    SNPV:=SNPV+((Cost2*ArIn2[K,9]*ArIn2[K,6])*(exp(R*ArIn2[K,4])));
    SNPV:=SNPV+((Cost3*ArIn2[K,10]*ArIn2[K,6])*(exp(R*ArIn2[K,4])));
    ANPV:=ANPV+((Cost1*ArIn2[K,8]*ArIn2[K,7])*(exp(R*ArIn2[K,5])));
    ANPV:=ANPV+((Cost2*ArIn2[K,9]*ArIn2[K,7])*(exp(R*ArIn2[K,5])));
    ANPV:=ANPV+((Cost3*ArIn2[K,10]*ArIn2[K,7])*(exp(R*ArIn2[K,5])));
```

```
  end;

  PMT:=1.5*(SNPV/(exp(R*ArIn2[NAct,4])));  {* what the firm will charge }

  EPMT:=PMT*(exp(R*ArIn2[NAct,4]));        {* Expected NPV of the payment }
  APMT:=PMT*(exp(R*ArIn2[NAct,5]));        {* Actual NPV of the payment }

  SNPV:=EPMT-SNPV;                         {* Firm's expected total NPV }
  ANPV:=APMT-ANPV;                         {* Firm's actual total NPV }
  RNPV:=ANPV/SNPV;                         {* Ratio of actual/expected }

{*****************************************************}
{* calculate Stability S1/L/E (Weighted Act Deviation)  }

  Num1:=0;
  Num2:=0;
  Den:=0;

  for K:=1 to NAct do
  begin
    if ArIn2[K,3] > ArIn2[K,2]               {* if late start }
      then Num1:=Num1+ArIn2[K,3]-ArIn2[K,2]  {* add lateness to N1 }
      else;
    if ArIn2[K,3] < ArIn2[K,2]               {* if early start }
      then Num2:=Num2+ArIn2[K,2]-ArIn2[K,3]  {* add earliness to N2 }
      else;
    Den:=Den+ArIn2[K,6];                     {* sum scheduled durations }
  end;

  Den:=Den/Nact;                             {* calc avg sched act dur }

  S1L:=Num1/(NAct*Den);
  S1E:=Num2/(NAct*Den);
  S1:=(Num1+Num2)/(NAct*Den);

{*****************************************************}
{* calculate Stability S2/I/O (Res-Weighted Dis)       }

  Num1:=0;
  Num2:=0;

  Den:=ArIn2[NAct,5]*Res1;
  Den:=Den+ArIn2[NAct,5]*Res2;
  Den:=Den+ArIn2[NAct,5]*Res3;


  for K:=1 to NAct do
  begin
    if ArIn2[K,3]-ArIn2[K,2]>0                 {* AST>SST (idle)   }
      then Num1:=Num1+ArIn2[K,3]-ArIn2[K,2]    {* add to Num1      }
      else;
    if ArIn2[K,4]-ArIn2[K,5]>0                 {* SFT>AFT (idle)   }
      then Num1:=Num1+ArIn2[K,4]-ArIn2[K,5]    {* add to Num1      }
      else;
    if ArIn2[K,2]-ArIn2[K,3]>0                 {* SST>AST (over)   }
      then Num2:=Num2+ArIn2[K,2]-ArIn2[K,3]    {* add to Num2      }
      else;
    if ArIn2[K,5]-ArIn2[K,4]>0                 {* AFT>SFT (over)   }
      then Num2:=Num2+ArIn2[K,5]-ArIn2[K,4]    {* add to Num2      }
      else;
```

```
  end;

  S2I:=1-(Num1/Den);
  S2O:=1-(Num2/Den);
  S2:=S2I+S2O-1;

{*******************************************************}
{* calculate Stability S3/I/O  (res profile mismatch)    }

{* initialize matrices Ar1 & Ar2 }

  for K:=1 to 102 do
    for L:=1 to 4 do
      begin
        Ar1[K,L]:=0;
        Ar2[K,L]:=0;
      end;

  for K:=1 to NAct do
    for L:=1 to 2 do
      begin
        Ar1[K,L]:=ArIn2[K,L+1];
        Ar1[K,L+2]:=ArIn2[K,8]+ArIn2[K,9]+ArIn2[K,10];
        Ar1[K+NAct,L]:=ArIn2[K,L+3];
        Ar1[K+NAct,L+2]:=-1*(ArIn2[K,8]+ArIn2[K,9]+ArIn2[K,10]);
      end;


{* chronologic sort matrix Ar1 scheduled (1,3) and actual (2,4) columns }

  for K:=1 to 2 do
    for L:=1 to 2*NAct do

      begin
        Tmp1:=Ar1[L,K];
        Tmp2:=Ar1[L,K+2];

        for M:=L+1 to 2*NAct do
        begin
          if Tmp1>Ar1[M,K] then
            begin
              Ar1[L,K]:=Ar1[M,K];
              Ar1[L,K+2]:=Ar1[M,K+2];
              Ar1[M,K]:=Tmp1;
              Ar1[M,K+2]:=Tmp2;
              Tmp1:=Ar1[L,K];
              Tmp2:=Ar1[L,K+2]
            end;
        end;
      end;

{* compress Ar1 matrix into Ar2 matrix; eliminating duplicate times }

  Tmp1:=0;                              {* Time }
  Tmp2:=0;                              {* Resources }

  for K:= 1 to 2 do                     {* 2 passes through matrix }

  begin
    L:=1;                               {* initialize Ar1 index }
```

```
    N:=1;                              {* initialize Ar2 index }

    while (L<=2*NAct) do               {* Run until Sched / Act done }
      begin
        Tmp1:=Ar1[L,K];                {* Time = current value in Ar1 }
        Tmp2:=0;                       {* initialize resource cumulator }
        M:=L;                          {* initialize cumulator pointer }

        while (Tmp1=Ar1[M,K]) do       {* as long as current time=time ...}
          begin
            Tmp2:=Tmp2+Ar1[M,K+2];     {* add curr resources into cumulator }
            M:=M+1;                    {* increment cumulator pointer }
            L:=L+1;                    {* increment Ar1 pointer }
          end;                         {* loop until time <> time ...}

        Ar2[N,K]:=Tmp1;                {* put value of time into Ar2 }
        Ar2[N,K+2]:=Tmp2;              {* put value of cum res into Ar2 }
        N:=N+1;                        {* increment Ar2 pointer }

      end;                             {* loop through sched/act ...}

  end;                                 {* Both Sched and Act complete }


{* transfer Ar2 resource deltas into Ar1 resource levels }

  Tmp1:=0;                             {* scheduled level cumulator }
  Tmp2:=0;                             {* actual level cumulator }

  for K:=1 to 102 do
    for L:=1 to 4 do
      Ar1[K,L]:=0;

  for K:=1 to 102 do
    begin
      Ar1[K,1]:=Ar2[K,1];
      Ar1[K,2]:=Ar2[K,2];
      Tmp1:=Tmp1+Ar2[K,3];
      Tmp2:=Tmp2+Ar2[K,4];
      Ar1[K,3]:=Tmp1;
      Ar1[K,4]:=Tmp2;
     end;


{* cumulate area under the scheduled resource profile }

  Den:=0;                              {* scheduled resource profile area }

  for k:=1 to 102 do
    if Ar1[K+1,1]<>0 then
      Den:=Den+((Ar1[K+1,1]-Ar1[K,1])*(Ar1[K,2]));

{* cumulate areas between the actual/scheduled resource profiles }


  K:=1;                                {* Index for Schedule   }
  L:=1;                                {* Index for Actual     }
  Tmp1:=0;                             {* Current # resources Scheduled }
  Tmp2:=0;                             {* Current # resources Actual }
```

```
TLast:=0;                               {* Time of last event }
Num1:=0;                                {* cumulate S3I time Sched>Actual }
Num2:=0;                                {* cumulate S3O time Actual>Sched }
Dum:=0;                                 {* dummy to carry current area calc }
Done:=False;                            {* exit criteria for cumulating loop }


while (Done=False) do                   {* Run until both Sched and Act done }
  begin                                 {* Go until done loop }

    if Ar1[K,1] = Ar1[L,2] then         {* Sched Time = Actual Time }
      begin

        Dum:=(Ar1[K,1]-TLast)*(Tmp1-Tmp2);
        if Dum>0 then Num1:=Num1+Dum else Num2:=Num2+(-1*Dum);

        Tmp1:=Tmp1+Ar1[K,3];            {* Update resources in use Sched }
        Tmp2:=Tmp2+Ar1[L,4];            {* Update resources in use Actual }

        TLast:=Ar1[K,1];                {* Sched=Act Time was the last event }

        K:=K+1;                         {* increment both counters and }
        L:=L+1;                         {* start again }
      end

    else                                {* Sched Time <> Actual Time }
      begin                             {* Sched Time <> Actual Time loop }
        if Ar1[K,1] < Ar1[L,2] then     {* Sched Time < Actual Time }
          begin

            Dum:=(Ar1[K,1]-TLast)*(Tmp1-Tmp2);
            if Dum>0 then Num1:=Num1+Dum else Num2:=Num2+(-1*Dum);

            Tmp1:=Tmp1+Ar1[K,3];        {* Update resources in use Sched }

            TLast:=Ar1[K,1];            {* Sched Time was the last event }

            K:=K+1;
          end

        else                            {* Sched Time not <= Actual Time }
        if Ar1[K,1] > Ar1[L,2] then     {* Sched Time > Actual Time }
          begin

            Dum:=(Ar1[L,2]-TLast)*(Tmp1-Tmp2);
            if Dum>0 then Num1:=Num1+Dum else Num2:=Num2+(-1*Dum);

            Tmp2:=Tmp2+Ar1[L,4];        {* Update resources in use Actual }

            TLast:=Ar1[L,2];            {* Actual Time was the last event }

            L:=L+1;
          end

        else                            {* Sched Time not <=> Actual Time?! }
      end;                              {* Sched Time <> Actual Time Loop }


  if ((Ar1[K+1,3]=0) and (Ar1[K+2,3]=0)) then     {* Schedule has expired }
```

```
      begin
        Ar1[K+1,1]:=Ar1[L+1,2];          {* force another pass }
      end
    else

    if ((Ar1[L+1,4]=0) and (Ar1[L+2,4]=0)) then    {* Actuals have expired }
      begin
        Ar1[L+1,2]:=Ar1[K+1,1];          {* force another pass }
      end
    else;

    if ((Ar1[K,3]=0)and(Ar1[K+1,3]=0)and(Ar1[L,4]=0)and(Ar1[L+1,4]=0))
      then Done:=True else;

    if ((L>=2*NAct) or (K>=2*NAct)) then Done:=True else;

    end;                                 {* Go until done loop }
                                         {* Both Sched and Act have expired }


  S3I:=Num1/Den;

  S3O:=Num2/Den;

{********************************************************}
{ convert spd & dis to factor names                      }

  if spd = 0 then A1:='none'else
    A1:='some';

  if dis = 0 then A2:='none' else
    if dis = 1 then A2:='infq' else
      A2:='freq';

{********************************************************}
{* format all numerical values into strings for writing }

Str(ARU:  1:5, A3);
Str(MRU:  1:5, A4);
Str(AARU: 2:5, B1);
Str(RARU: 2:5, B2);
Str(AMRU: 2:5, B3);
Str(RMRU: 2:5, B4);
Str(PDur: 3:3, B5);
Str(ADur: 3:3, B6);
Str(RDur: 2:4, B7);
Str(SNPV: 8:2, B8);
Str(ANPV: 8:2, B9);
Str(RNPV: 2:4, B10);
Str(S1L:  4:4, C1);
Str(S1E:  4:4, C2);
Str(S1:   4:4, C3);
Str(S2I:  2:4, C4);
Str(S2O:  2:4, C5);
Str(S2:   2:4, C6);
Str(S3I:  4:4, C7);
Str(S3O:  4:4, C8);


{********************************************************}
```

```
{* Write converted data strings to File4                  }

Write(File4,Name,'  ',Sked,'  ',Exec,'  ',A1,'  ',A2,NAc,MDF,NDR,NCR,ARC,MRC);
Write(File4,'  ',A3,'  ',B1,'  ',B2,'  ',A4,'  ',B3,'  ',B4,'  ');
Write(File4,B5,'  ',B6,'  ',B7,'  ',B8,'  ',B9,'  ',B10,'  ');
WriteLn(File4,C1,' ',C2,' ',C3,'  ',C4,' ',C5,' ',C6,'  ',C7,' ',C8);

{*************************************************************************}

ReadLn(File2);                          {* next line of simulation data  }

end;                                    {* Next J- # reps/prob in File 2 }

ReadLn(File1);                          {* next line of schedule data    }

end;                                    {* Next I- # probs in Files 1 & 3}

{*************************************************************************}

Close(File1);
Close(File2);
Close(File3);
Close(File4);

end.
```

```
{*****************************************************************************}
{                                                                             }
{                                CONV1.PAS                                    }
{                                                                             }
{  File1:  Input file; problem characteristics from schedule data file       }
{  File3:  Input file; unconstrained CPM CPL from Patterson Set              }
{  File2:  Output file; the calculated results of this conversion program    }
{                                                                             }
{  ArIn1:  Array (60x11) problem information from File1 (single problem)     }
{  ArIn2:  Array (110x1) unconstrained, CPM CPL for Patterson set            }
{  ArOut:  Array (30x18) converted sim data (each factor set) to File3       }
{                                                                             }
{                                                                             }
{                                                                             }
{*****************************************************************************}
program Convert;

var
  File1, File2, File3: Text;

  ArIn1:  array[1..60, 1..11] of Real;
  ArIn2:  array[1..110, 1..1] of Integer;

  NAct, NRes, Dum2, CPL, UNC, I, J, K, NArc, PArc:  Integer;

  Res1, Res2, Res3, MDF, NDR, NCR, ARC, MRC, ARU, MRU:  Real;
  Lod1, Lod2, Lod3, Cap1, Cap2, Cap3:  Real;

  Nam1, Dum1, FileName:  String[12];
  B1, B2, B3, B4, B5, B6, B7, B8, B9:  String;
```

```
{****************************************************************************}

begin

  Write('Please enter problem data input filename:  ');
    ReadLn(FileName);
    Assign(File1, FileName);

  Write('Please enter unconstrained CPL data input file name:  ');
    ReadLn(FileName);
    Assign(File3, FileName);

  Write('Please enter conversion data output filename:  ');
    ReadLn(Filename);
    Assign(File2, FileName);

  Reset(File1);
  Reset(File3);
  ReWrite(File2);

{*****************************************************************}
{* initialize ArIn1 matrix containing Patterson problem data      }

for I:=1 to 18 do                        {* number of problems in File1 }
begin

  ReadLn(File1, NAct, NRes, Nam1);
  ReadLn(File1, Dum1, Res1, Res2, Res3, Dum2, CPL);
  ReadLn(File3, UNC);

  for J:=1 to NAct do
    begin
      for K:=1 to 11 do
        Read(File1, ArIn1[J, K]);
    end;

  ReadLn(File1);

{*****************************************************}
{* calculate Makespan Delay Factor MDF/B3             }

  MDF:=CPL/UNC;

{*****************************************************}
{* calculate Network Density Ratio NDR/B4             }

  NArc:=0;

  for J:=1 to NAct do
    begin
      for K:=4 to 8 do
        begin
          if ArIn1[J, K]<>0
            then  NArc:=NArc+1
            else
        end;
    end;

  NDR:=NArc/NAct;
```

```
{**********************************************************}
{* calculate Network Complexity Ration NCR/B5             }

  PArc:=0;

  for J:=1 to NAct-1 do
    PArc:=PArc+J;

  NCR:=NArc/PArc;

{**********************************************************}
{* calculate Average Resource Constrainedness ARC/B6      }

  Lod1:=0;
  Lod2:=0;
  Lod3:=0;

  Cap1:=UNC*Res1;
  Cap2:=UNC*Res2;
  Cap3:=UNC*Res3;

  for J:=1 to NAct do
  begin
    Lod1:=Lod1+ArIn1[J,9]*ArIn1[J,3];
    Lod2:=Lod2+ArIn1[J,10]*ArIn1[J,3];
    Lod3:=Lod3+ArIn1[J,11]*ArIn1[J,3];
  end;

  ARC:=(Lod1+Lod2+Lod3)/(Cap1+Cap2+Cap3);

{**********************************************************}
{* calculate Maximum Resource Constrainedness MRC/B7      }

  if (Lod1/Cap1) > (Lod2/Cap2)
    then MRC:=(Lod1/Cap1)
    else MRC:=(Lod2/Cap2);

  if (Lod3/Cap3) > MRC
    then MRC:=(Lod3/Cap3)
    else;

{**********************************************************}
{* calculate Average Resource Utilization ARU/B8          }

  Cap1:=CPL*Res1;
  Cap2:=CPL*Res2;
  Cap3:=CPL*Res3;

  ARU:=(Lod1+Lod2+Lod3)/(Cap1+Cap2+Cap3);

{**********************************************************}
{* calculate Maximum Resource Utilization MRU/B9          }

  if (Lod1/Cap1) > (Lod2/Cap2)
    then MRU:=(Lod1/Cap1)
    else MRU:=(Lod2/Cap2);

  if (Lod3/Cap3) > MRU
    then MRU:=(Lod3/Cap3)
```

```
    else;

{*****************************************************}
{* format all real values into strings for writing      }

Str(NAct: 2,   B1);
Str(CPL:  3,   B2);
Str(MDF:  2:5, B3);
Str(NDR:  2:5, B4);
Str(NCR:  2:5, B5);
Str(ARC:  2:5, B6);
Str(MRC:  2:5, B7);
Str(ARU:  2:5, B8);
Str(MRU:  2:5, B9);

{*****************************************************}
{* Write converted data strings to File2                }

  Write(File2,Nam1,'  ',B1,'  ',B2,'  ',B3,'  ',B4,'  ');
  WriteLn(File2,B5,'  ',B6,'  ',B7,'  ',B8,'  ',B9);

{****************************************************************}

ReadLn(File1);                          {* skip the blank line    }

end;                                    {* num of probs in File1  }

{****************************************************************}

Close(File1);
Close(File2);
Close(File3);

end.
```

```
{*************************************************************************}
{                                                                         }
{                              CONVERT.PAS                                }
{                                                                         }
{  File1:  Input file; problem schedule data                              }
{  File2:  Input file; simulation output data 30 reps x 6 factor combos   }
{  File3:  Input file; problem characteristics from Demographics file     }
{  File4:  Output file; the calculated results of this conversion program }
{                                                                         }
{  ArIn1:  Array (60x11) problem schedule characteristics from File1      }
{  ArIn2:  Array (60x10) simulation output data from File2 (reps x factors) }
{                                                                         }
{                                                                         }
{                                                                         }
{*************************************************************************}
program Convert;

const
  Cost1 = 25;
  Cost2 = 25;
  Cost3 = 25;
```

```
  R = -0.06;

var

  Done: Boolean;

  File1, File2, File3, File4: Text;

  NAct, NRes, Dis, Dum2, CPL, I, J, K, L, M, N:  Integer;

  ArIn1:  array[1..51, 1..11] of Real;
  ArIn2:  array[1..51, 1..10] of Real;
  Ar1, Ar2:  array[1..102, 1..4] of Real;

  Res1, Res2, Res3, DT1, DT2, DT3, Lod1, Lod2, Lod3, Cap1, Cap2, Cap3:  Real;
  ADur, RDur, Spd, AARU, AMRU, SNPV, ANPV, PMT, EPMT, APMT, Num1, Num2:  Real;
  Den, S1L, S1E, S1, S2I, S2O, S2, S3I, S3O, S3, ResLod, Tmp1, Tmp2: Real;
  Dum, TLast:  Real;

  Filename,A1,A2,B1,B2,B3,B4,B5,B6,C1,C2,C3,C4,C5,C6,C7,C8,C9:  String;
  Name:  String[12];
  NAc:  String[4];
  CP:  String[5];
  MDF, NDR, NCR, ARC, MRC, ARU, MRU: String[9];
  Nam1, Nam2, Dum1:  String[12];
  Sked, Exec:  String[3];

{*************************************************************************}

begin

  Write('Please enter schedule data input filename:  ');
    ReadLn(FileName);
    Assign(File1, FileName);

  Write('Please enter simulation data input filename:  ');
    ReadLn(FileName);
    Assign(File2, FileName);

  Write('Please enter problem demographic data input filename:  ');
    ReadLn(FileName);
    Assign(File3, FileName);

  Write('Please enter conversion data output filename:  ');
    ReadLn(Filename);
    Assign(File4, FileName);

  Write('Please enter scheduling method used (3 char):  ');
    ReadLn(Sked);

  Write('Please enter execution method used (3 char):  ');
    ReadLn(Exec);

  Reset(File1);
  Reset(File2);
  Reset(File3);
  ReWrite(File4);

{*****************************************************************}
{* initialize ArIn1 & ArIn2 matrices containing problem data      }
```

```
for I:=1 to 18 do                          {* number of problems      }

begin

  ReadLn(File1, NAct, NRes, Nam1);
  ReadLn(File1, Dum1, Res1, Res2, Res3, Dum2, CPL);

  for K:=1 to NAct do
    begin
      for L:=1 to 11 do
        Read(File1, ArIn1[K, L]);
    end;

  ReadLn(File1);                           {* skip the blank line     }


  ReadLn(File3, Name, NAc, CP, MDF, NDR, NCR, ARC, MRC, ARU, MRU);


{*************************************************************}
{* initialize ArIn2 matrix containing 30 reps x 6 factors sim data}

for J:=1 to 360 do                         {* number of reps in File2}
                                           {  for each problem       }
begin

  ReadLn(File2, Nam2, Spd, Dis, DT1, DT2, DT3);

  for K:=1 to NAct do
    begin
      for L:=1 to 10 do
        Read(File2, ArIn2[K, L]);
    end;

    ReadLn(File2);                         {* skip the blank line     }


{*******************************************************}
{*  assign actual project duration ADur                }

  ADur:=ArIn2[NAct, 5];

{*******************************************************}
{* calculate percent project duration over sched PDur   }

  RDur:=ADur/CPL;

{*******************************************************}
{* calculate Actual Average Resource Utilization AARU   }

  Lod1:=0;
  Lod2:=0;
  Lod3:=0;

  Cap1:=ADur*Res1;
  Cap2:=ADur*Res2;
  Cap3:=ADur*Res3;

  for K:=1 to NAct do
```

```
  begin
    Lod1:=Lod1+ArIn2[K,8]*ArIn2[K,7];
    Lod2:=Lod2+ArIn2[K,9]*ArIn2[K,7];
    Lod3:=Lod3+ArIn2[K,10]*ArIn2[K,7];
  end;

  AARU:=(Lod1+Lod2+Lod3)/(Cap1+Cap2+Cap3);

{*******************************************************}
{* calculate Actual Maximum Resource Utilization AMRU   }

  if (Lod1/Cap1) > (Lod2/Cap2)
    then AMRU:=(Lod1/Cap1)
    else AMRU:=(Lod2/Cap2);

  if (Lod3/Cap3) > AMRU
    then AMRU:=(Lod3/Cap3)
    else;

{*******************************************************}
{* calculate project Net Present Values A/S/RNPV        }

  SNPV:=0;
  ANPV:=0;
  PMT:=0;

  for K:=1 to NAct do
  begin
    SNPV:=SNPV+((Cost1*ArIn2[K,8]*ArIn2[K,6])*(exp(R*ArIn2[K,4])));
    SNPV:=SNPV+((Cost2*ArIn2[K,9]*ArIn2[K,6])*(exp(R*ArIn2[K,4])));
    SNPV:=SNPV+((Cost3*ArIn2[K,10]*ArIn2[K,6])*(exp(R*ArIn2[K,4])));
    ANPV:=ANPV+((Cost1*ArIn2[K,8]*ArIn2[K,7])*(exp(R*ArIn2[K,5])));
    ANPV:=ANPV+((Cost2*ArIn2[K,9]*ArIn2[K,7])*(exp(R*ArIn2[K,5])));
    ANPV:=ANPV+((Cost3*ArIn2[K,10]*ArIn2[K,7])*(exp(R*ArIn2[K,5])));
  end;

  PMT:=1.5*(SNPV/(exp(R*ArIn2[NAct,4]))); {* what the firm will charge}

  EPMT:=PMT*(exp(R*ArIn2[NAct,4]));       {* Expected NPV the payment}
  APMT:=PMT*(exp(R*ArIn2[NAct,5]));       {* Actual NPV of the payment}

  SNPV:=EPMT-SNPV;                        {* Firm's expected total NPV}
  ANPV:=APMT-ANPV;                        {* Firm's actual total NPV}


{*******************************************************}
{* calculate project Stability S1/L/E (act deviation)   }

  Num1:=0;
  Num2:=0;
  Den:=0;

  for K:=1 to NAct do
  begin
    if ArIn2[K,3] > ArIn2[K,2]
      then Num1:=Num1+ArIn2[K,3]-ArIn2[K,2]
      else;
    if ArIn2[K,3] < ArIn2[K,2]
      then Num2:=Num2+ArIn2[K,2]-ArIn2[K,3]
      else;
```

```
    Den:=Den+ArIn2[K,7];
  end;

  Den:=NAct*ArIn2[Nact,5]-Den;

  S1L:=1-(Num1/Den);
  S1E:=1-(Num2/Den);
  S1:=(Num1+Num2)/NAct;

{********************************************************}
{* calculate project Stability S2/I/O (res-weighted dis)}

  Num1:=0;
  Num2:=0;

  Den:=ArIn2[NAct,5]*Res1-DT1;
  Den:=Den+ArIn2[NAct,5]*Res2-DT2;
  Den:=Den+ArIn2[NAct,5]*Res3-DT3;


  for K:=1 to NAct do
  begin
    if ArIn2[K,3]-ArIn2[K,2]>0              {* AST>SST (idle)  }
      then Num1:=Num1+ArIn2[K,3]-ArIn2[K,2] {* add to Num1     }
      else;
    if ArIn2[K,4]-ArIn2[K,5]>0              {* SFT>AFT (idle)  }
      then Num1:=Num1+ArIn2[K,4]-ArIn2[K,5] {* add to Num1     }
      else;
    if ArIn2[K,2]-ArIn2[K,3]>0              {* SST>AST (over)  }
      then Num2:=Num2+ArIn2[K,2]-ArIn2[K,3] {* add to Num2     }
      else;
    if ArIn2[K,5]-ArIn2[K,4]>0              {* AFT>SFT (over)  }
      then Num2:=Num2+ArIn2[K,5]-ArIn2[K,4] {* add to Num2     }
      else;
  end;

  S2I:=1-(Num1/Den);
  S2O:=1-(Num2/Den);
  S2:=S2I+S2O-1;

{********************************************************}
{* calculate Stability S3/I/O  (res profile mismatch)   }

{* initialize matrices Ar1 & Ar2 }

  for K:=1 to 102 do
    for L:=1 to 4 do
      begin
        Ar1[K,L]:=0;
        Ar2[K,L]:=0;
      end;

  for K:=1 to NAct do
    for L:=1 to 2 do
      begin
        Ar1[K,L]:=ArIn2[K,L+1];
        Ar1[K,L+2]:=ArIn2[K,8]+ArIn2[K,9]+ArIn2[K,10];
        Ar1[K+NAct,L]:=ArIn2[K,L+3];
        Ar1[K+NAct,L+2]:=-1*(ArIn2[K,8]+ArIn2[K,9]+ArIn2[K,10]);
      end;
```

```
{* chronologic sort matrix Ar1 scheduled (1,3) and actual (2,4) columns }

  for K:=1 to 2 do
    for L:=1 to 2*NAct do

      begin
        Tmp1:=Ar1[L,K];
        Tmp2:=Ar1[L,K+2];

        for M:=L+1 to 2*NAct do
        begin
          if Tmp1>Ar1[M,K] then
            begin
              Ar1[L,K]:=Ar1[M,K];
              Ar1[L,K+2]:=Ar1[M,K+2];
              Ar1[M,K]:=Tmp1;
              Ar1[M,K+2]:=Tmp2;
              Tmp1:=Ar1[L,K];
              Tmp2:=Ar1[L,K+2]
            end;
        end;
      end;

{* compress Ar1 matrix into Ar2 matrix; eliminating duplicate times }

  Tmp1:=0;                              {* Time }
  Tmp2:=0;                              {* Resources }

  for K:= 1 to 2 do                     {* 2 passes through matrix }

  begin
    L:=1;                               {* initialize Ar1 index }
    N:=1;                               {* initialize Ar2 index }

    while (L<=2*NAct) do                {* Run until Sched / Act done }
      begin
        Tmp1:=Ar1[L,K];                 {* Time = current value in Ar1 }
        Tmp2:=0;                        {* initialize resource cumulator }
        M:=L;                           {* initialize cumulator pointer }

        while (Tmp1=Ar1[M,K]) do        {* as long as current time=time ...}
          begin
            Tmp2:=Tmp2+Ar1[M,K+2];      {* add curr resources into cumulator }
            M:=M+1;                     {* increment cumulator pointer }
            L:=L+1;                     {* increment Ar1 pointer }
          end;                          {* loop until time <> time ...}

        Ar2[N,K]:=Tmp1;                 {* put value of time into Ar2 }
        Ar2[N,K+2]:=Tmp2;               {* put value of cum res into Ar2 }
        N:=N+1;                         {* increment Ar2 pointer }

      end;                              {* loop through sched/act ...}

  end;                                  {* Both Sched and Act complete }


{* cumulate areas under the resource profiles }
```

```
K:=1;                                  {* Index for Schedule   }
L:=1;                                  {* Index for Actual     }
Tmp1:=0;                               {* Current # resources Scheduled }
Tmp2:=0;                               {* Current # resources Actual }
TLast:=0;                              {* Time of last event }
Num1:=0;                               {* cumulate S3I time Sched>Actual }
Num2:=0;                               {* cumulate S3O time Actual>Sched }
Dum:=0;                                {* dummy to carry current area calc }
Den:=0;                                {* total resource profile area }
Done:=False;                           {* exit criteria for cumulating loop }


while (Done=False) do                  {* Run until both Sched and Act done }
  begin                                {* Go until done loop }

    if Ar2[K,1] = Ar2[L,2] then        {* Sched Time = Actual Time }
      begin

        Dum:=(Ar2[K,1]-TLast)*(Tmp1-Tmp2);
        if Dum>0 then Num1:=Num1+Dum else Num2:=Num2+(-1*Dum);

        Den:=Den+(Ar2[K,1]-TLast)*(Tmp1+Tmp2);  {* Sched + Actual area }

        Tmp1:=Tmp1+Ar2[K,3];           {* Update resources in use Sched }
        Tmp2:=Tmp2+Ar2[L,4];           {* Update resources in use Actual }

        TLast:=Ar2[K,1];               {* Sched=Act Time was the last event }

        K:=K+1;                        {* increment both counters and }
        L:=L+1;                        {* start again }
      end

    else                               {* Sched Time <> Actual Time }
      begin                            {* Sched Time <> Actual Time loop }
        if Ar2[K,1] < Ar2[L,2] then    {* Sched Time < Actual Time }
          begin

            Dum:=(Ar2[K,1]-TLast)*(Tmp1-Tmp2);
            if Dum>0 then Num1:=Num1+Dum else Num2:=Num2+(-1*Dum);

            Den:=Den+(Ar2[K,1]-TLast)*(Tmp1+Tmp2);  {* Sched + Actual area }

            Tmp1:=Tmp1+Ar2[K,3];       {* Update resources in use Sched }

            TLast:=Ar2[K,1];           {* Sched Time was the last event }

            K:=K+1;
          end

        else                           {* Sched Time not <= Actual Time }
        if Ar2[K,1] > Ar2[L,2] then    {* Sched Time > Actual Time }
          begin

            Dum:=(Ar2[L,2]-TLast)*(Tmp1-Tmp2);
            if Dum>0 then Num1:=Num1+Dum else Num2:=Num2+(-1*Dum);

            Den:=Den+(Ar2[L,2]-TLast)*(Tmp1+Tmp2); {* Sched + Actual area }

            Tmp2:=Tmp2+Ar2[L,4];       {* Update resources in use Actual }
```

```
            TLast:=Ar2[L,2];           {* Actual Time was the last event }

            L:=L+1;
          end

        else                           {* Sched Time not <=> Actual Time?! }
      end;                             {* Sched Time <> Actual Time Loop }



  if ((Ar2[K+1,3]=0) and (Ar2[K+2,3]=0)) then    {* Schedule has expired }
    begin
      Ar2[K+1,1]:=Ar2[L+1,2];          {* force another pass }
    end
  else

  if ((Ar2[L+1,4]=0) and (Ar2[L+2,4]=0)) then    {* Actuals have expired }
    begin
      Ar2[L+1,2]:=Ar2[K+1,1];          {* force another pass }
    end
  else;

  if ((Ar2[K,3]=0)and(Ar2[K+1,3]=0)and(Ar2[L,4]=0)and(Ar2[L+1,4]=0))
    then Done:=True else;

  if ((L>=2*NAct) or (K>=2*NAct)) then Done:=True else;

  end;                                 {* Go until done loop }
                                       {* Both Sched and Act have expired }
 S3I:=1-Num1/Den;

 S3O:=1-Num2/Den;

 S3:=S3I+S3O-1;

{********************************************************}
{* format all numerical values into strings for writing }

Str(Spd:  1:1, A1);
Str(Dis:  2,   A2);
Str(AARU: 2:5, B1);
Str(AMRU: 2:5, B2);
Str(ADur: 3:3, B3);
Str(RDur: 2:4, B4);
Str(SNPV: 6:2, B5);
Str(ANPV: 6:2, B6);
Str(S1L:  2:4, C1);
Str(S1E:  2:4, C2);
Str(S1:   4:4, C3);
Str(S2I:  2:4, C4);
Str(S2O:  2:4, C5);
Str(S2:   2:4, C6);
Str(S3I:  2:4, C7);
Str(S3O:  2:4, C8);
Str(S3:   2:4, C9);

{********************************************************}
{* Write converted data strings to File4                }
```

```
Write(File4,Name,'  ',Sked,'  ',Exec,'  ',A1,'  ',A2,NAc,MDF,NDR,NCR,ARC,MRC);
Write(File4,ARU,'  ',B1,MRU,'  ',B2,CP,'  ',B3,'  ',B4,'  ',B5,'  ',B6,'  ');
WriteLn(File4,C1,' ',C2,' ',C3,'  ',C4,' ',C5,' ',C6,'  ',C7,' ',C8,' ',C9);

{************************************************************************}

ReadLn(File2);                          {* next line of simulation data  }

end;                                    {* Next J- # reps/prob in File 2 }

ReadLn(File1);                          {* next line of schedule data    }

end;                                    {* Next I- # probs in Files 1 & 3}

{************************************************************************}

Close(File1);
Close(File2);
Close(File3);
Close(File4);

end.
```

APPENDIX L

NPV VS. RT

Figure L-1:
NPV vs. rt: OPT

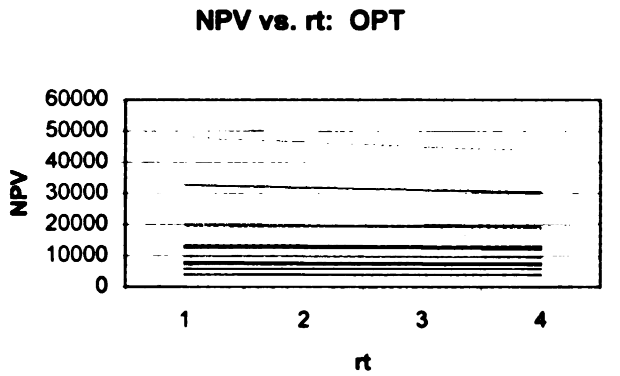


Table L-1:
NPV vs. rt: OPT

	rt Factor 1	2	3	4	Slope	%slope
HEUR013A	5910	5882	5854	5827	-28	-0.47
HEUR013C	13285	13147	13011	12877	-136	-1.04
HEUR048A	6664	6628	6592	6557	-36	-0.54
HEUR048C	16624	16426	16232	16040	-195	-1.19
HEUR056A	6660	6620	6580	6541	-40	-0.60
HEUR056C	19677	19445	19217	18992	-228	-1.18
HEUR014A	3910	3870	3831	3793	-39	-1.02
HEUR014B	7746	7619	7496	7374	-124	-1.64
HEUR014C	9978	9786	9599	9417	-187	-1.93
HEUR015A	6450	6387	6326	6265	-61	-0.97
HEUR015B	12721	12521	12325	12133	-196	-1.58
HEUR015C	16499	16170	15848	15535	-321	-2.01
HEUR105A	19591	19288	18991	18699	-297	-1.55
HEUR105C	48027	46473	44985	43561	-1489	-3.25
HEUR107A	20190	19862	19540	19226	-321	-1.63
HEUR107C	51635	49719	47899	46168	-1822	-3.73
HEUR110A	12646	12518	12393	12268	-126	-1.01
HEUR110C	32619	31862	31129	30419	-733	-2.33

Figure L-2:
NPV vs. rt: SLK

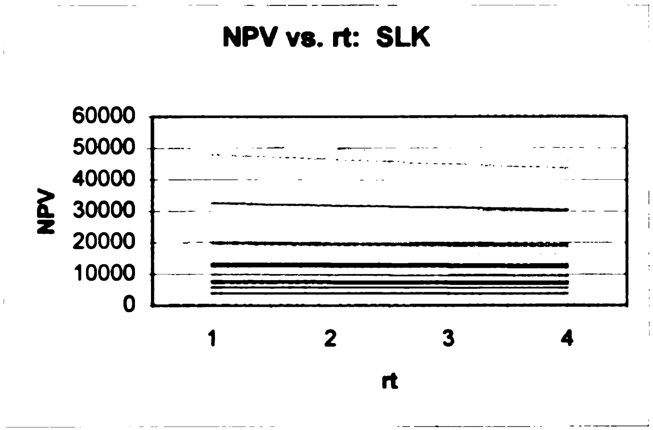


Table L-2:
NPV vs. rt: SLK

	rt Factor 1	2	3	4	Slope	%slope
HEUR013A	5909	5880	5852	5824	-28	-0.48
HEUR013C	13279	13134	12992	12851	-142	-1.09
HEUR048A	6661	6622	6583	6545	-39	-0.59
HEUR048C	16623	16424	16228	16035	-196	-1.20
HEUR056A	6660	6620	6580	6541	-40	-0.60
HEUR056C	19675	19441	19210	18983	-230	-1.19
HEUR014A	3910	3870	3831	3793	-39	-1.02
HEUR014B	7738	7605	7474	7346	-131	-1.74
HEUR014C	9952	9736	9525	9321	-211	-2.18
HEUR015A	6450	6388	6327	6266	-61	-0.96
HEUR015B	12697	12474	12257	12044	-218	-1.76
HEUR015C	16493	16158	15832	15514	-327	-2.04
HEUR105A	19583	19273	18970	18672	-304	-1.59
HEUR105C	48027	46474	44986	43562	-1488	-3.25
HEUR107A	20190	19862	19542	19227	-321	-1.63
HEUR107C	51614	49679	47840	46093	-1840	-3.77
HEUR110A	12642	12510	12381	12253	-130	-1.04
HEUR110C	32625	31874	31146	30441	-728	-2.31

Figure L-3:
NPV vs. rt: LFT

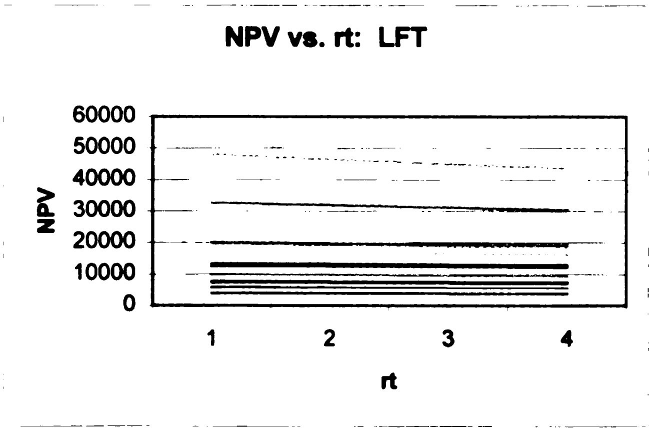


Table L-3:
NPV vs. rt: LFT

	rt Factor 1	2	3	4	Slope	%slope
HEUR013A	5909	5880	5851	5823	-29	-0.49
HEUR013C	13280	13138	12997	12858	-141	-1.08
HEUR048A	6661	6623	6585	6547	-38	-0.58
HEUR048C	16624	16427	16232	16041	-195	-1.19
HEUR056A	6660	6620	6580	6541	-40	-0.60
HEUR056C	19677	19444	19216	18990	-229	-1.18
HEUR014A	3910	3870	3831	3793	-39	-1.02
HEUR014B	7732	7592	7455	7321	-137	-1.82
HEUR014C	9963	9757	9557	9361	-201	-2.08
HEUR015A	6450	6388	6327	6266	-61	-0.96
HEUR015B	12715	12510	12309	12112	-201	-1.62
HEUR015C	16498	16167	15845	15531	-322	-2.01
HEUR105A	19584	19275	18973	18676	-303	-1.58
HEUR105C	48028	46476	44989	43566	-1487	-3.25
HEUR107A	20184	19851	19525	19206	-326	-1.66
HEUR107C	51619	49689	47855	46112	-1836	-3.76
HEUR110A	12642	12511	12382	12255	-129	-1.04
HEUR110C	32626	31875	31148	30443	-727	-2.31

Figure L-4:
NPV vs. rt: RSO

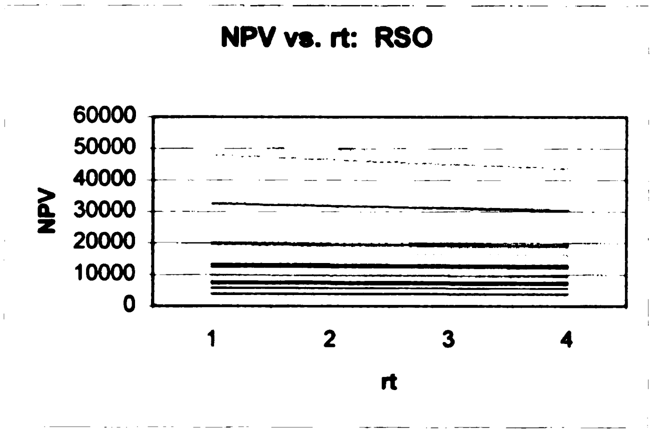


Table L-4:
NPV vs. rt: RSO

	rt Factor 1	2	3	4	Slope	%slope
HEUR013A	5910	5882	5854	5827	-28	-0.47
HEUR013C	13285	13147	13011	12877	-136	-1.04
HEUR048A	6663	6627	6591	6555	-36	-0.55
HEUR048C	16624	16426	16232	16040	-195	-1.19
HEUR056A	6657	6614	6572	6530	-42	-0.64
HEUR056C	19677	19445	19217	18992	-228	-1.18
HEUR014A	3907	3864	3822	3780	-42	-1.10
HEUR014B	7745	7618	7493	7371	-125	-1.65
HEUR014C	9978	9786	9598	9416	-187	-1.93
HEUR015A	6446	6380	6315	6251	-65	-1.03
HEUR015B	12720	12518	12321	12128	-197	-1.59
HEUR015C	16498	16168	15846	15533	-322	-2.01
HEUR105A	19585	19277	18975	18679	-302	-1.58
HEUR105C	48027	46473	44985	43561	-1489	-3.25
HEUR107A	20181	19845	19516	19195	-329	-1.67
HEUR107C	51635	49719	47899	46168	-1822	-3.73
HEUR110A	12645	12516	12390	12265	-127	-1.02
HEUR110C	32619	31862	31129	30419	-733	-2.33

Figure L-5:
NPV vs. rt: LSC

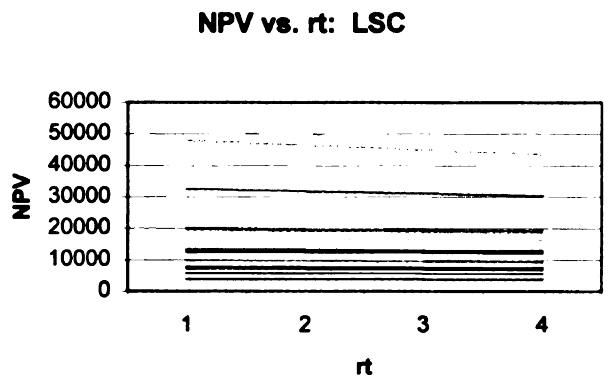


Table L-5:
NPV vs. rt: LSC

	rt Factor 1	2	3	4	Slope	%slope
HEUR013A	5908	5879	5849	5820	-29	-0.50
HEUR013C	13279	13134	12992	12851	-142	-1.09
HEUR048A	6661	6623	6584	6547	-38	-0.58
HEUR048C	16623	16424	16228	16035	-196	-1.20
HEUR056A	6657	6614	6571	6529	-43	-0.65
HEUR056C	19675	19441	19210	18983	-230	-1.19
HEUR014A	3908	3866	3825	3784	-41	-1.07
HEUR014B	7736	7600	7466	7336	-133	-1.77
HEUR014C	9953	9738	9528	9324	-210	-2.18
HEUR015A	6445	6378	6312	6246	-66	-1.04
HEUR015B	12695	12471	12252	12037	-219	-1.77
HEUR015C	16492	16156	15829	15509	-328	-2.05
HEUR105A	19580	19267	18960	18659	-307	-1.61
HEUR105C	48027	46474	44986	43562	-1488	-3.25
HEUR107A	20181	19845	19516	19195	-329	-1.67
HEUR107C	51614	49679	47840	46093	-1840	-3.77
HEUR110A	12642	12511	12382	12255	-129	-1.04
HEUR110C	32625	31874	31146	30441	-728	-2.31

Figure L-6:
NPV vs. rt: DCF

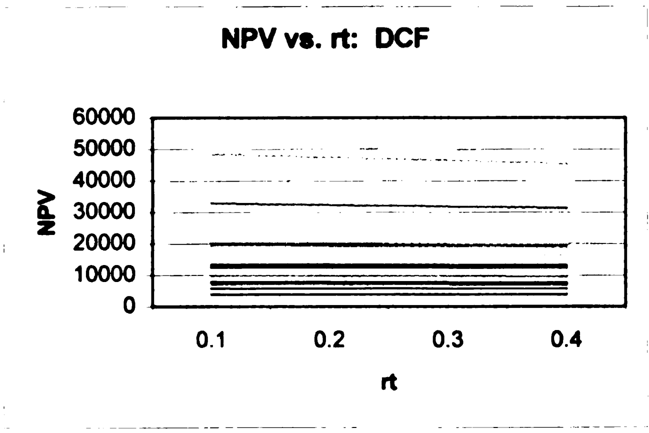


Table L-6:
NPV vs. rt: DCF

	rt Factor 1	2	3	4	Slope	%slope
HEUR013A	5916	5895	5874	5853	-21	-0.36
HEUR013C	13328	13232	13137	13043	-95	-0.72
HEUR048A	6671	6643	6615	6587	-28	-0.43
HEUR048C	16688	16553	16419	16286	-134	-0.81
HEUR056A	6673	6645	6618	6591	-27	-0.41
HEUR056C	19755	19600	19446	19293	-154	-0.79
HEUR014A	3921	3893	3865	3837	-28	-0.73
HEUR014B	7771	7670	7570	7471	-100	-1.31
HEUR014C	10016	9861	9709	9559	-152	-1.56
HEUR015A	6467	6423	6378	6334	-44	-0.69
HEUR015B	12765	12607	12452	12299	-155	-1.24
HEUR015C	16594	16355	16120	15890	-235	-1.44
HEUR105A	19665	19433	19205	18980	-228	-1.18
HEUR105C	48560	47502	46474	45475	-1028	-2.19
HEUR107A	20282	20042	19806	19574	-236	-1.18
HEUR107C	52291	50978	49709	48482	-1270	-2.52
HEUR110A	12679	12584	12490	12397	-94	-0.75
HEUR110C	32874	32360	31856	31363	-504	-1.57

Figure L-7:
NPV vs. rt: BCP

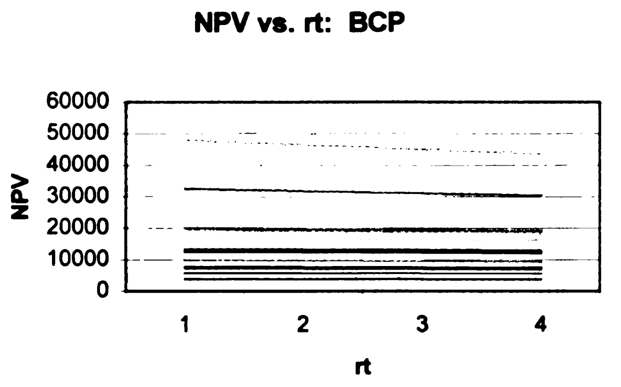


Table L-7:
NPV vs. rt: BCP

	rt Factor 1	2	3	4	Slope	%slope
HEUR013A	5908	5878	5849	5820	-29	-0.50
HEUR013C	13288	13152	13019	12887	-134	-1.02
HEUR048A	6659	6619	6579	6539	-40	-0.61
HEUR048C	16624	16427	16232	16040	-195	-1.19
HEUR056A	6660	6620	6580	6541	-40	-0.60
HEUR056C	19676	19444	19215	18989	-229	-1.18
HEUR014A	3910	3870	3830	3792	-39	-1.02
HEUR014B	7741	7610	7482	7357	-128	-1.70
HEUR014C	9960	9751	9548	9350	-203	-2.11
HEUR015A	6450	6388	6327	6266	-61	-0.96
HEUR015B	12705	12489	12279	12073	-211	-1.70
HEUR015C	16474	16121	15777	15443	-344	-2.15
HEUR105A	19556	19221	18892	18571	-328	-1.72
HEUR105C	48027	46474	44987	43562	-1488	-3.25
HEUR107A	20190	19862	19542	19227	-321	-1.63
HEUR107C	51609	49670	47827	46075	-1845	-3.78
HEUR110A	12636	12499	12364	12231	-135	-1.09
HEUR110C	32617	31859	31124	30413	-735	-2.33

APPENDIX M

DEGRADATION (PERCENT CHANGE)

Table M-1: Percent Change (variability none-some)

		ADUR	avg	WADC	avg	POOR	avg
OPT	FRN	-1.9	-2.2	-29.8	-28.3	-5.3	-4.9
	FRW	-2.9		-31.2		-5.5	
	NRN	-1.3		-23.5		-3.8	
	NRW	-2.7		-28.5		-4.9	
SLK	FRN	-1.6	-1.9	-29.8	-22.9	-5.3	-5.1
	FRW	-2.7		-31.7		-5.6	
	NRN	-1.1		-27.5		-4.6	
	NRW	-2.2		-27.6		-5.0	
LFT	FRN	-1.5	-3.8	-28.2	-27.8	-5.1	-4.9
	FRW	-2.6		-30.6		-5.4	
	NRN	-9.0		-24.9		-4.2	
	NRW	-2.2		-27.3		-4.9	
RSO	FRN	-2.1	-3.8	-26.1	-25.8	-2.9	-3.4
	FRW	-3.2		-31.4		-5.1	
	NRN	-1.3		-17.2		-1.3	
	NRW	-2.9		-28.4		-4.4	
LSC	FRN	-1.6	-2.1	-24.0	-25.9	-2.5	-3.4
	FRW	-2.8		-30.0		-5.0	
	NRN	-1.5		-23.8		-1.9	
	NRW	-2.6		-25.6		-4.3	
DCF	FRN	-1.1	-3.0	-28.0	-25.4	-5.9	-5.3
	FRW	-2.2		-28.5		-5.9	
	NRN	-7.2		-20.8		-4.4	
	NRW	-1.5		-24.4		-5.0	
BCP	FRN	-1.5	-2.9	-31.9	-30.2	-5.6	-5.3
	FRW	-2.6		-32.8		-5.8	
	NRN	-5.2		-28.0		-4.6	
	NRW	-2.1		-28.4		-5.1	

Table M-2: Percent Change (disruption none-frequent/short)

		ADUR	Avg	WADC	avg	POOR	avg
OPT	FRN	-2.0	-2.1	-22.7	-33.9	-3.2	-3.9
	FRW	-1.8		-25.7		-3.6	
	NRN	-2.7		-53.4		-4.5	
	NRW	-2.5		-33.8		-4.1	
SLK	FRN	-1.9	-2.1	-23.6	-34.9	-3.3	-3.9
	FRW	-1.7		-26.6		-3.6	
	NRN	-2.5		-56.0		-4.6	
	NRW	-2.2		-33.5		-4.1	
LFT	FRN	-1.8	-2.1	-22.9	-36.1	-3.2	-3.9
	FRW	-1.7		-26.1		-3.6	
	NRN	-2.6		-61.8		-4.9	
	NRW	-2.3		-33.4		-3.9	
RSO	FRN	-1.9	-2.0	-21.1	-32.0	-2.7	-3.4
	FRW	-1.8		-25.0		-3.4	
	NRN	-2.4		-49.1		-3.5	
	NRW	-2.5		-32.9		-3.9	
LSC	FRN	-2.0	-2.1	-21.1	-32.7	-2.5	-3.4
	FRW	-1.8		-26.1		-3.5	
	NRN	-2.2		-51.3		-3.4	
	NRW	-2.4		-32.6		-4.0	
DCF	FRN	-1.6	-1.7	-20.6	-32.5	-3.2	-3.8
	FRW	-1.4		-24.2		-3.8	
	NRN	-1.8		-50.7		-4.0	
	NRW	-1.9		-34.5		-4.3	
BCP	FRN	-1.6	-1.7	-20.4	-34.8	-2.9	-3.7
	FRW	-1.5		-24.5		-3.5	
	NRN	-1.5		-61.5		-4.5	
	NRW	-2.2		-32.9		-4.0	

Table M-3: Percent Change (disruption none-infrequent/long)

		ADUR	avg	WADC	avg	POOR	avg
OPT	FRN	-6.2	-5.4	-85.6	-80.0	-8.2	-7.6
	FRW	-5.4		-81.0		-8.0	
	NRN	-4.9		-76.1		-6.4	
	NRW	-5.8		-77.2		-7.8	
SLK	FRN	-6.2	-5.3	-87.6	-80.4	-8.4	-7.6
	FRW	-5.3		-82.8		-8.1	
	NRN	-4.4		-74.6		-6.4	
	NRW	-5.2		-76.5		-7.6	
LFT	FRN	-5.9	-5.0	-85.3	-78.9	-8.3	-7.5
	FRW	-5.2		-83.6		-8.1	
	NRN	-4.1		-73.5		-6.3	
	NRW	-4.9		-73.3		-7.4	
RSO	FRN	-6.1	-5.5	-82.1	-76.9	-7.1	-6.8
	FRW	-5.5		-79.9		-7.8	
	NRN	-4.5		-71.2		-4.9	
	NRW	-5.7		-74.5		-7.4	
LSC	FRN	-6.3	-5.5	-82.4	-77.4	-7.0	-7.0
	FRW	-5.6		-82.7		-8.1	
	NRN	-4.1		-67.5		-5.0	
	NRW	-5.8		-77.0		-7.7	
DCF	FRN	-5.6	-4.9	-83.3	-82.6	-8.7	-8.2
	FRW	-4.8		-80.9		-8.8	
	NRN	-4.4		-83.4		-6.8	
	NRW	-4.7		-82.8		-8.4	
BCP	FRN	-5.4	-4.7	-81.1	-78.6	-7.6	-7.3
	FRW	-4.8		-78.0		-7.6	
	NRN	-3.5		-80.4		-6.4	
	NRW	-4.9		-74.8		-7.4	

Table M-4: Percent Change (disruption frequent/short-infrequent/long)

		ADUR	avg	WADC	avg	POOR	avg
OPT	FRN	-4.1	-3.3	-62.9	-46.1	-5.0	-3.8
	FRW	-3.6		-55.2		-4.4	
	NRN	-2.2		-22.7		-1.9	
	NRW	-3.3		-43.4		-3.7	
SLK	FRN	-4.2	-3.2	-64.1	-45.5	-5.1	-3.7
	FRW	-3.5		-56.2		-4.5	
	NRN	-2.0		-18.6		-1.8	
	NRW	-2.9		-43.0		-3.5	
LFT	FRN	-4.0	-3.0	-62.4	-42.9	-5.1	-3.6
	FRW	-3.5		-57.4		-4.5	
	NRN	-1.7		-11.7		-1.4	
	NRW	-2.6		-39.9		-3.4	
RSO	FRN	-4.1	-3.3	-61.0	-44.9	-4.4	-3.4
	FRW	-3.7		-55.0		-4.4	
	NRN	-2.1		-22.1		-1.5	
	NRW	-3.2		-41.6		-3.4	
LSC	FRN	-4.2	-3.3	-61.3	-44.7	-4.6	-3.6
	FRW	-3.7		-56.6		-4.7	
	NRN	-2.0		-16.3		-1.5	
	NRW	-3.3		-44.4		-3.7	
DCF	FRN	-3.9	-3.2	-62.7	-50.0	-5.5	-4.4
	FRW	-3.4		-56.6		-5.0	
	NRN	-2.7		-32.7		-2.9	
	NRW	-2.7		-48.2		-4.0	
BCP	FRN	-3.8	-2.9	-60.6	-43.7	-4.7	-3.6
	FRW	-3.2		-53.4		-4.1	
	NRN	-2.0		-18.9		-1.9	
	NRW	-2.7		-41.9		-3.5	

BIBLIOGRAPHY

Boctor, F. "Some Efficient Multi-Heuristic Procedures for Resource-Constrained Project Scheduling." European Journal of Operational Research. v. 49 i. 1 (Nov 1990): 3-13.

Bowers, J. "Criticality in Resource Constrained Networks." Journal of the Operational Research Society. v. 46 (1995): 80-91.

Burt, J. "Planning and Dynamic Control of Projects Under Uncertainty." Management Science. v. 24, n. 3 (Nov 1977): 249-258.

Christofides, N., R. Alvarez-Valdes, and J. Tamarit. "Project Scheduling with Resource Constraints: A Branch and Bound Approach." European Journal of Operational Research. v. 29 i 3 (Jun 1987): 262-273.

Cohen, J. and P. Cohen. Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences. 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates, 1983.

Conover, W. J. Practical Nonparametric Statistics. 2nd ed. New York: John Wiley and Sons, 1980.

Davis, Edward. "Resource Allocation in Project Network Models- A Survey." The Journal of Industrial Engineering. v. 17, n. 4 (April 1966): 177-188.

—, and G. Heidorn. "An Algorithm for Optimal Project Scheduling under Multiple Resource Constraints." Management Science. v. 17, n. 12 (1971): B803-B816.

—. "Project Scheduling under Resource Constraints- Historical Review and Categorization." AIIE Transactions. v. 5, n. 4 (December 1973): 297-313.

—, and J. Patterson. "A Comparison of Heuristic and Optimal Solutions in Resource-Constrained Project Scheduling." Management Science. v. 21 n. 8 (April 1975): 944-955.

Demeulemeester, E., and W. Herroelen. "A Branch-And-Bound Procedure For The Multiple Resource-Constrained Project Scheduling Problem." Management Science. v. 38 i. 12 (Dec 1992): 1803-1818.

Elmaghraby, S., and W. Herroelen. "The Scheduling of Activities to Maximize the Net Present Value of Projects." European Journal of Operational Research. v. 49 i. 1 (Nov 1990): 35-49.

Ferderegruen, A., and M. Tzur. "Minimal Forecast Horizons and a New Planning Procedure for the General Dynamic Lot Sizing Model: Nervousness Revisited." Operations Research. v. 42, n. 3 (May 1994): 456-468.

Ho, C. "An Examination of a Distribution Resource Planning Problem: DRP System Nervousness." Journal of Business Logistics. v. 13, n. 2 (1992): 125-149.

Just, Michael R., and James P. Murphy. "The Effect Of Resource Constraints On Project Schedules." AACE Transactions. Iss: 1994 Transactions (1994): DCL21-DCL26.

Karp, R. "Reducibility Among Combinatorial Problems." From Complexity of Computer Applications, eds. Miller, R.; Thatcher, J. Plenum Press: New York (1972): 85-104.

Kelly, J. E. Jr., and M. Walker. "Critical Path Programming and Scheduling." Proc. East. Joint Comp. Conf. (1959): 160-173.

Kolisch, R., A. Sprecher, and A. Drexl. "Characterization and Generation of a General Class of Resource-Constrained Project Scheduling Problems." Management Science. v. 41, n. 10 (Oct 1995): 1693-1703.

Kropp, D., R. Carlson, and J. Jucker. "Use of Dynamic Lot Sizing to Avoid Nervousness in Material Requirements Planning Systems." Production and Inventory Management. Quarter 3 (1979): 49-57.

Laderman, J. M. "The Best Mutual Funds." Business Week. February 5, 1996: 100-103.

Lee, Yong-Il, and Thomas M. Gatton. "Construction Scheduling Based On Resource Constraints." AACE Transactions. Iss: 1994 Transactions (1994): CSC31-CSC36.

Mather, H. "Reschedule the Reschedules You Just Rescheduled- Way of Life for MRP?" Production and Inventory Management. Quarter 1 (1977): 60-79.

Metters, R. "A Method for Achieving Better Customer Service, Lower Costs, and Less Instability in Master Production Schedules." Production and Inventory Management Journal. Quarter 4 (1993): 61-65.

Neter, J., Kutner, M.H., Nachtsheim, C. J., and Wasserman, W. Applied Linear Statistical Models. 4th ed. Chicago: Richard D. Irwin, Inc., 1989.

Oguz, O., and H. Bala. "A Comparative Study Of Computational Procedures For The Resource Constrained Project Scheduling Problem." European Journal of Operational Research. v. 72 i. 2 (Jan 1994): 406-416.

Ozdamar, L., and G. Ulusoy. "A Local Constraint Based Analysis Approach To Project Scheduling Under General Resource Constraints." European Journal of Operational Research. v. 79 i. 2 (Dec 1994): 287-298.

—, and —. "A Survey On The Resource-Constrained Project Scheduling Problem." IIE Transactions. Vol: 27 Iss: 5 (Oct 1995): 574-586.

Padman, R., and D. Smith-Daniels. "Early-Tardy Cost Trade-Offs In Resource Constrained Projects With Cash Flows: An Optimization-Guided Heuristic Approach." European Journal of Operational Research. v. 64 i. 2 (Jan 1993): 295-311.

Pagell, M. "A Measure of Stability for Project Scheduling." Proceedings of the 1995 Annual Meeting of the Decision Sciences Institute. Boston: November 1995.

Partovi, F., and J. Burton. "Timing of Monitoring and Control of CPM Projects." IEEE Transactions on Engineering Management. v. 40, n. 1 (Feb 1993): 68-75.

Patterson, J. "The Effects of Problem Structure on Heuristic Performance." Naval Logistics Research Quarterly. v. 23, n. 1 (1976): 95-123.

—. "A Comparison Of Exact Approaches For Solving The Multiple Constrained Resource, Project Scheduling Problem." Management Science. v 30, i 7 (Jul 1984): 854-867.

—, F. Talbot, R. Slowinski, and J. Weglarz. "Computational Experience with a Backtracking Algorithm for Solving a General Class of Precedence and Resource-Constrained Scheduling Problems." European Journal of Operational Research. v. 49 i. 1 (Nov 1990): 68-79.

Pinder, Jonathan A., and Ann S. Maruchek. "A Comparison of Scheduling Heuristics for Maximizing Net Present Value." Proceedings of the Annual Meeting of the Decision Sciences Institute. New Orleans: November 1989.

—, and — "Using Discounted Cash Flow Heuristics to Improve Project Net Present Value." Journal of Operations Management. v. 14 (1996): 229-240.

Russell, A. H. "Cash Flows in Networks." Management Science. v. 16, n. 5 (Jan 1970): 357-373.

Russell, Robert A. "A Comparison of Heuristics for Scheduling Projects with Cash Flows and Resource Restrictions." Management Science. v. 32, n. 10 (Oct 1986): 1291-1300.

SAS Institute, Inc. SAS User's Guide: Basics, Version 5 Edition. Cary, NC: SAS Institute, Inc., 1985.

Simpson, W. "A Parallel Exact Solution Procedure for the Resource-Constrained Project Scheduling Problem." unpublished Ph.D. Dissertation, Indiana University, 1991.

—, and J. Patterson. "A Multiple-Tree Search Procedure For The Resource-Constrained Project Scheduling Problem." European Journal of Operational Research. v. 89, i. 3 (Mar 1996): 525-542.

Slowinski, R. "Multiobjective Network Scheduling with Efficient Use of Renewable and Non-renewable Resources." European Journal of Operational Research. v. 7 n. 3 (1981): 265-273.

Smith-Daniels, D., and V. Smith-Daniels. "Maximizing the Net Present Value of a Project Subject to Materials and Capital Constraints." Journal of Operations Management. v. 7, i. 1. (Oct 1987): 33-45.

—, and N. Aquilano. "Using a Late-Start Resource-Constrained Project Schedule to Improve Project Net Present Value." Decision Sciences. v. 18, i. 4 (Fall 1987): 617-630.

Sridharan, S., W. Berry, and V. Udayabhanu. "Measuring Master Production Schedule Stability under Rolling Planning Horizons." Decision Sciences. v. 19, n. 1 (1988): 147-166.

Steele, D. "The Nervous MRP System: How to Do Battle." Production and Inventory Management. Quarter 4 (1975): 83-89.

Talbot, Brian. "An Integer Programming Algorithm for the Resource-Constrained Project Scheduling Problem." unpublished Ph.D. Dissertation, Pennsylvania State University, 1976.

—. "Resource-Constrained Project Scheduling with Time-Resource Tradeoffs: The Nonpreemptive Case." Management Science. v. 28, i. 10 (Oct 1982): 1197-1210.

Ulusoy, G., and L. Ozdamar. "Heuristic Performance and Network/Resource Characteristics in Resource-Constrained Project Scheduling." Journal of the Operational Research Society. v. 40, i. 12 (Dec 1989): 1145-1152.

United States. Department of the Navy, Bureau of Ordnance, Special Projects Office. PERT Phase I Summary Report. Washington: July 1958.

Weist, J. "Some Properties of Schedules for Large Projects with Limited Resources." Operations Research. v. 12 (1964): 395-418.

Willis, R. "Critical Path Analysis and Resource Constrained Project Scheduling- Theory and Practice." European Journal of Operational Research. v. 21 (1985): 149-155.

Wysocki, Robert K., Robert Beck, Jr., and David B. Crane. Effective Project Management. New York, NY: John Wiley & Sons, Inc., 1995.

Yang, Kum Khiong, Lee Choo Tay, and Chee Chuong Sum. "A Comparison of Scheduling Rules for Maximizing Project Net Present Value." European Journal of Operational Research. v. 85 (1995): 327-339.

—. "Effects of Erroneous Estimation of Activity Durations on Scheduling and Dispatching a Single Project." Decision Sciences. v. 27, n. 2 (Spring 1996): 255-290.