A SIMULATION ENVIRONMENT FOR MULTIPLE PROJECT RESOURCE OPTIMIZATION

by
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Bachelor of Engineering, Stevens Institute of Technology, May 1978

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Submitted to the System Design and Management Program
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Abstract

This thesis develops a numerical simulation environment as a management support tool applicable to the selection and scheduling of multiple, concurrent research and development projects under conditions of constrained resources and uncertain program requirements. A prototype version of this software tool, called SEMPRO (Simulation Environment for Multiple Project Resource Optimization), is developed to capture an operational model of the NASA Dryden Flight Research Center flight and a representative research project portfolio. An attribute-driven Work Breakdown Schedule generates resource-loaded activity networks for each entry in the research project portfolio. The project selection and project coordination problems are formulated as Binary Integer Linear Programming problems, as extensions of the traditional Resource Constrained Project Scheduling Problem (RCPSP). To alleviate the computational obstacles associated with these NP Hard problems, a Lagrange Relaxation formulation is used to generate a near-optimal, time-phased sequence for execution of the selected project activity networks. Stochastic, non-linear, discrete-event simulation dynamics are then employed to validate these linear optimization solutions against a representative model of the organization's research and development project operational processes. The SEMPRO prototype is written in the Microsoft Excel Visual Basic Application language to facilitate project management visualization and knowledge transfer.

Author Biographical Information

Following undergraduate education at Stevens Institute of Technology, Mr. Sharkey began his professional career in 1978 as an RF design engineer at the Motorola Government Electronics Division in Scottsdale, Arizona. Upon completing graduate studies at the University of Arizona, Mr. Sharkey joined the NASA team at the Marshall Space Flight Center in Huntsville, Alabama in 1982. As a member, and later chief, of the Precision Pointing Controls System Branch, Mr. Sharkey developed expertise in the dynamics and control of flexible, multi-body spacecraft, and applied that knowledge in support of space telescope projects including the Hubble Space Telescope, the Spacelab Instrument Pointing System, and the Advanced X-Ray Astrophysical Facility. Mr. Sharkey transferred to the NASA Johnson Space Center in 1994 to manage development of the S1 and P1 Integrated Truss Segments for the International Space Station program. At the completion of truss development work in 1998, Mr. Sharkey transferred to the NASA Dryden Flight Research Center (DFRC) as a senior project manager, contributing to the F-18 Systems Research Aircraft (SRA) and the Environment Research Aircraft and Sensors Technology (ERAST) flight research projects. Mr. Sharkey is presently a member of the NASA DFRC planning office, responsible for the formulation of advance project concepts in the areas of unmanned aerial vehicles, intelligent flight systems, and advanced Earth Science atmospheric observation platforms.

Disclaimer

Information contained in this research thesis pertaining to the National Aeronautics and Space Administration (NASA) and the NASA Dryden Flight Research Center (DFRC) are provided for academic purposes only, and by no means are intended to convey official NASA positions, policy or plans. No guarantees are provided or implied regarding the accuracy of resource availability or project requirements information

Dedication

This thesis is dedicated to the memory of my father, John E. Sharkey, who challenged me to pursue a career with NASA as challenging and rewarding as his own; to my mother, Loretto Malony Sharkey, who instilled in me a lifelong love for learning and discovery; to my wife, Judy, who provided the unending support and encouragement needed to see this mid-career endeavor through to completion; and to my son, Mario, who in the final tally was able to finish his Master's thesis before I finished mine.

Acknowledgement

The author would like to thank Professor Thomas A. Roemer at the MIT Sloan School of Management for his enthusiastic and generous sharing of ideas, time and expertise while guiding the development of this thesis; and Dr. Charlie Boppe of the MIT Department of Aeronautics and Astronautics for providing the motivating insights on the subject of discrete event simulations. Special thanks to the faculty and staff in the Systems Design and Management (SDM) program office, especially Mr. Dennis Mahoney and Mr. Ted Hoppe, for providing superior, customer-oriented support throughout the entire SDM curriculum, at a level that is unmatched in graduate school cultures. The holistic philosophy underlying the SDM program has more than met the promise of a transformational experience. The foresight and commitment of Mr. Kevin L. Petersen, Director of the NASA Dryden Flight Research Center, and Mr. Daniel S. Goldin, former NASA Administrator, are gratefully acknowledged in sustaining the investment in the Systems Design and Management program for an entire cadre of NASA engineering managers.

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Glossary of Symbols and Acronyms

Acronyms:

AAW	Active Aero-elastic Wing project
AFRL	Air Force Research Laboratory
APSP	Aggregate Project Selection Problem
ARC	Ames Research Center
BILP	Binary Integer Linear Programming
DARPA	Defense Advanced Research Projects Agency
DFRC	Dryden Flight Research Center
DHS	Department of Homeland Security
DoD	Department of Defense
DOE	Department of Energy
FAA	Federal Aviation Administration
FTE	Full Time Equivalent
G&A	General and Administrative
GRC	Glenn Research Center
LaRC	Langley Research Center
LR	Lagrange Relaxation
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NOAA	National Oceanic and Atmospheric Administration
OGA	Other Government Agency
PCP	Project Coordination Problem (BILP formulation)
PCP_j	Project Coordination Problem (Lagrange Relaxation formulation)
PSP	Project Selection Problem
R&D	Research & Development
RCPSP	Resource Constrained Project Scheduling Problem
RTO	Responsible Test Organization
SDM	Systems Design and Management
SEMPRO	Simulation Environment for Multiple Project Resource Optimization
SPI	Schedule Performance Index
UCAV	Unmanned Combat Air Vehicle project
VBA	Visual Basic Application software programming language
WBS	Work Breakdown Schedule
WYE	Work Year Equivalent

Symbols:

C_m	capacity limits of department *m* M number of line departments
J_C	total cost function for PCP
J_{PSP}	optimization cost function for PSP
J_{PCP}	optimization cost function for PCP
J_{LR}	optimization cost function for the Lagrange Relaxation version of PCP
Nj	number of activities for project j
P	maximum number of projects

$S_j(i)$	set of successor activities following activity *i* on project *j*
T	time horizon of interest; maximum time increment for index *t*
W_j	penalty cost coefficient for late completion of project *j*
$X_{j,i,t}$	decision variable for PCP, PCPj and PSP: $X_{j,i,t} = 1$ if activity *i* of project *j* is active at or before time *t*
$X^f_{j,i,t}$	a feasible decision variable solution to the PCP
$X^*_{j,i,t}$	optimal decision variables to the PCP
Z_D	best lower bound for J_{PCP} during Lagrange Relaxation iteration loop
$a_{j,i}$	activity *i* of project *j*
b_m	m^{th} line department
$f_{j,i}$	completion time for activity *i* of project *j*
f_j	completion time of project *j* s_j completion time of project *j*
$\hat{f}_j$	target completion time of project *j*
$n_{j,i}$	heuristic weighting coefficient for activity *i* of project *j*
$r_{m_{j,i}}$	resource requirement for activity *i* of project *j*
$s_{j,i}$	start time for activity *i* of project *j*
s_j	start time of project *j*
$\hat{s}_j$	target start time of project *j*
α	acceleration parameter for Lagrange Relaxation iteration loop
β	derating factor for Lagrange Relaxation iteration loop
$\gamma^l_{m,t}$	Coefficient for the Lagrange Relaxation cost function at the l^{th} iteration
$\delta_{j,i}$	nominal duration of activity *i* of project *j*
$\lambda_{m,t}$	Lagrange multiplier for department *m* at time t
$\lambda^l_{m,t}$	Lagrange multiplier value for department *m* at time t at the l^{th} iteration
ϕ_m	cost incurred for use of department *m* resources per unit of time *t*.

Indices

i	activity index:: $i = 1,2,\ldots Nj$
j	project index: $j = 1,2,\ldots P$
k	successor activity index:
l	iteration index for Lagrange Relaxation loop
l_{max}	maximum number of Lagrange Relaxation iterations
m	line department index: $m = 1,2,\ldots M$
q	index for perturbation heuristic loop
q_{max}	maximum number of heuristic perturbation decisions
r	Lagrange Relaxation convergence counter
r_{max}	maximum number of Lagrange Relaxation iterations without improvement in J_{LR}
t	time index:: $t = 1,2,\ldots T$

1 Introduction

The problem of selecting a viable set and sequence of concurrent projects in the presence of large uncertainty and resource constraints is widespread in today's research and development environment. Traditional methods to address this concern are often associated with qualitative weighting and scoring schemes that assess strategic fit and benefits against program risk, resource constraints and impacts to on-going activities[1]. The focus of this research thesis is the development of a dynamic computational planning tool capable of selecting, scheduling and validating a feasible set and execution sequence of R&D projects from a candidate portfolio of future projects. Since the fundamental problem is characteristically high-order, non-linear and stochastic, the proposed planning tool addresses the problem in a layered, hierarchical approach. Development of an operational prototype of the proposed planning tool, called SEMPRO© for Simulation Environment for Multiple Project Resource Optimization, is a key contribution of this thesis.

1.1 Background and Motivation

The underlying motivation for development of SEMPRO is twofold. First and foremost, SEMPRO addresses a clear and present need to incorporate state-of-the-art strategic planning tools at the NASA Dryden Flight Research Center (DFRC). Senior management at DFRC is presently transforming the Center research and development processes in the context of strategic management. Historically, the NASA/DFRC planning horizon has only extended one to two years into the future. However, the technical complexity, program uncertainty, and human resource strategies in the current government Research and Development (R&D) environment demands more capable long-term strategic planning processes and decision support tools. The second motivating factor is a desire to examine the potential use of numerical simulation models in the development and validation of project portfolio management policies, in a manner analogous to that used to develop aerospace vehicle flight simulations and control laws. NASA/DFRC has established world-class capabilities in the development and use of simulation models to guide development of flight research test plans

[1] See for example: Cook, Wade D. and Lawrence M. Seiford. "R&D Project Selection in a Multidimensional Environment: A Practical Approach." The Journal of the Operational Research Society Vol. 33, Issue 5 (May 1982): 397-405.

and procedures, and to develop and validate complex, high performance, non-linear flight vehicle control systems. Adapting the "modeling, simulation and control law" framework to the development of project and organizational control policies is a compelling extension of this traditional aerospace approach, and easily assimilated into the organizational culture. Although the SEMPRO software prototype model is tailored specifically towards the current DFRC operational model, the general approach and methodology is readily extendable to the more general case.

1.2 Thesis Problem Statement

The thesis problem statement can be stated as follows: Given a planning time horizon, a set of line departments (or "branches" in the NASA/DFRC vernacular) with known resource capacity limits, a set of candidate R&D projects with known estimates for project activity resource requirements and duration times, find and validate a feasible sub-set of projects and project activity start and completion times which maximizes the Net Earned Value of completed projects while satisfying the resource constraints. Several variations of this basic problem are also presented and discussed in the thesis.

1.3 Summary of Approach

1.3.1 Methods employed:

The SEMPRO prototype integrates several system engineering and project management methodologies that are central to the Systems Design and Management curriculum. Particular emphasis is placed on systems engineering, project management, systems optimization, and system dynamics elements. The over-arching principle of matching system architectures (in this case, flight research processes) to organizational structure and strategy is embedded throughout the thesis. The systems engineering practice of managing complexity and uncertainty by use of discrete event simulations is a foundational element of the thesis. The principle of functional decomposition and characterization via key attributes enables use of an automatic Work Breakdown Schedule (WBS)[2] generator as the primary input to the project selection, scheduling and simulation modules. Systems optimization theory allows use of

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[2] By abuse of terminology, this thesis defines "Work Breakdown Schedule" as a time-sequenced activity network associated with a project Work Breakdown Structure. Reference the NASA Work Breakdown Structure Reference Guide, Revision 3, May 1994 available at http:www.

standard linear programming techniques to allocate resources to competing projects in a constrained environment. Finally, elements from system dynamics, operations and project management dealing with the effects of hidden feedback processes, process bottlenecks and learning curves on workforce productivity and quality are essential in capturing the non-linear interactions between competing projects.

Development of a software program tool to simulate project portfolio management requires the integration of multiple engineering disciplines from a systems management perspective. The engineering content is evident in several areas. For example, aircraft systems engineering is employed to perform functional decomposition of a wide variety of future aerospace vehicles, ranging from hypersonic X-plane demonstrators to unmanned aerial vehicles and intelligent flight control sub-systems. Mathematical programming techniques are employed to formulate and solve the project selection and scheduling problem. Advanced software engineering methods are employed to design, code, test and utilize a moderately complex, object-oriented simulation code in the Excel Visual Basic Application (VBA) programming environment.

Management content of the thesis is also evident at multiple levels. Designing representative operational models for the implementation of individual projects and for the management of concurrent, competing projects requires significant insight into organizational processes and cultural tendencies. Recognizing the simulation features and output metrics that would be required by senior management to first validate simulation results, and then be useful in the strategic planning process, are also key elements in the thesis.

1.3.2 SEMPRO Overview Description

The SEMPRO prototype is a moderately complex software program (5700 lines of code comprising 72 different subroutines and functions) written in the Microsoft Excel© VBA language. The prototype version is tailored specifically to the NASA/DFRC operating model. Key operating features and functions include:

- A database-driven input/output structure for capturing project attribute descriptions for each entry in a project portfolio, and generating executable resource allocations and project implementation schedules.

- Automatic, attribute-driven WBS generation that is resource loaded to WBS Level 3 for each project entry in the candidate project portfolio;

- A project selection module that identifies a locally optimal sub-set of realizable R&D projects from the candidate project portfolio, based upon an objective function that rewards project completion based upon simplified WBS Level 1 project descriptions;

- A multiple-project implementation schedule module that properly sequences the WBS Level 2 activity networks for the sub-set of realizable projects;

- A WBS Level 3 simulation module that validates the multiple-project implementation schedule in a high-order, non-linear, stochastic, discrete event simulation environment.

1.4 Relationship to Previous Work and Publications

The two primary research topics in this thesis are: (i) development of project selection and coordination algorithms using linear programming techniques; and (ii) development of a stochastic, non-linear simulation environment that integrates project selection and coordination algorithms with discrete event and system dynamic representations of the NASA/DFRC operating model. The first topic has been widely studied over the past three decades, in terms of both the Resource Constrained Project Scheduling Problem (RCPSP) and the Project Selection Problem (PSP). The RCPSP strives to minimize the total work flow time for production of single items or small job shop batches[3], subject to constant resource constraints. Brucker[4] , Mingozzi[5] and Demeulemeester[6] provide excellent surveys of recent RCPSP solution methods and current research interests. Fundamentally, the RCPSP is a combinatorial problem that can be notoriously difficult to solve. RCPSP solution methods

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[3] Reference: Lloyd, Errol L.. "Concurrent Task Systems." Operations Research,Vol.29, No. 1 (Jan.-Feb. 1981): 189-201. See also Dobson, Gregory and Uday Karmarkar. "Simultaneous Resource Scheduling to Minimize Weighted Flow Times." Operations Research, Vol. 37, No. 4 (July-August, 1989): 592-600.

[4] Reference: Brucker, and Andreas Drexl, Rolf Mohring, Klaus Neumann Erwin Pesch. "Resource Constrained Project Scheduling: Notation, Classification, models and methods." European Journal of Operations Research Vol. 112 (1999): 3-41.

[5] Reference: Mingozzi, A. and V. Maniezzo, S. Ricciardelli, L. Bianco. "An Exact Algorithm for the Resource Constrained Project Scheduling Problem Based on a New Mathematical Formulation." Management Science, Vol. 44, Issue 5 (May, 1998): 714-729.

[6] Reference: Demeulemeester, Erik L. and Willy S. Herroelen. "New Benchmark Results for the Resource Constrained Project Scheduling Problem." Management Science, Vol. 43, No. 11 (Nov. 1997): 1485-1492.

have been extended to address the Project Selection Problem. Freeman[7] describes an early method to address R&D project portfolio selection with a probabilistic cost function, utilizing Linear Programming (LP) relaxation to make the problem tractable with computational methods available in the late 1970's. However, this method admits fractional projects as part of the LP solution. Evans[8] developed an integer programming approach for project selection that is tailored specifically for long-term strategic planning of NASA space exploration missions. The method selects an optimal set of projects as measured by mission benefit objective functions; but only accommodates overall project cost and mission duration (ie, the WBS Level 1 element) as constraint coefficients. Roemer[9] defines a Project Coordination Problem (PCP) to establish a near-optimal solution for directed activity networks for multiple concurrent projects, by minimizing a weighted cost for late project completions. Roemer transforms the Non Polynomial-difficult PCP into a standard network flow problem using Lagrangian relaxation methods. This thesis directly employs the Roemer PCP formulation, and extends that formulation to also solve the Project Selection Problem and other similar variations. Numerical solution of these algorithms within the SEMPRO prototype environment is accomplished with numerical kernels provided with the Microsoft Excel© Solver application program.

The second primary research topic is also a current area of interest in the management sciences. Ford and Sterman[10] developed a 5th order continuous time, system dynamics model to represent interactions between distinct design phases of a single product development cycle. Repenning[11] addressed multi-project resource dependency from a low-order, systems dynamics perspective consistent with periodic manufacturing cycles in the automotive industry. The system dynamics model emphasizes the propagation effect of design errors into downstream

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[7] Reference: Freeman, P. and A.E. Gear. "A Probabilistic Objective Function for R&D Portfolio Selection." Operational Research Quarterly (1970-1977), Vol. 22, Issue 3 (Sep. 1971): 253-265.

[8] Reference: Evans, Gerald W. and Robert Fairborn. "Selection and Scheduling of Advanced Missions for NASA Using 0-1 Integer Linear Programming." The Journal of Operational Research Society, Volume 40, Issue 11 (Nov., 1989): 971-981.

[9] Reference: Roemer, Thomas A. "Coordinating New Product Development Projects." Unpublished white paper, MIT Sloan School of Management, 2000.

[10] Reference: Ford, David N. and John D. Sterman. "Dynamic Modeling of Product Development Processes." Unpublished white paper, MIT Sloan School of Management, Jan. 1997. See also Sterman, John D. "System Dynamics Modeling for Project Management." Unpublished white paper, MIT Sloan School of Management, 1992 (from graduate course readings in MIT 15.983/Systems and Project Management).

[11] Reference: Repenning, Nelson. "Resource Dependence in Product Development Improvement Efforts." Unpublished white paper, MIT Sloan School of Management, Dec. 1999.

production processes, using a highly aggregate, 4^{th} order continuous time representation for each project development cycle. More recently, Subranabian[12] et al developed a simulation model, called SIM-OPT, that integrates RCPSP and discrete event simulation into a stochastic R&D project pipeline analysis tool. SIM-OPT employs a project task scheduling module to first initialize, and subsequently adjust, a project pipeline execution sequence in the presence of uncertain resource requirements, task durations and quality outputs. A separate SIM-OPT module performs discrete event simulations of a "here-and-now" project execution sequence, until inherent random processes or constraint violations render the desired project sequence invalid. Closing the loop between these two SIM-OPT modules allows Monte Carlo simulations to be performed against a prescribed portfolio of R&D projects. The SEMPRO prototype is similar in principle and motivation to SIM-OPT, but differs significantly in terms of implementation methodologies. Whereas SIM-OPT almost always starts with an infeasible project execution sequence due to over-subscribed resources, SEMPRO combines PSP and PCP solutions to initialize the simulation with a feasible set, sequence and phasing of concurrent projects. In addition, SEMPRO incorporates system dynamics models coupled with discrete event task input and output queues to capture internal feedback loops associated with project quality and rework, as well as project management and organizational control decisions. SEMPRO also employs an attribute-driven Work Breakdown Schedule as the basis for project definition, selection, coordination and simulation. Finally, SEMPRO provides the basic building blocks to create an operational model of an R&D organization in terms of dynamic resource allocation and project task execution.

1.5 Overview of Contents and Primary Results

This sub-section provides a brief overview of the remaining thesis contents. Section 2.0 provides background information on the NASA/DFRC organizational structure, resource availability, and customer base. A characterization of flight research projects is provided, leading to a description of the SEMPRO Work Breakdown Schedule generator. The section ends with an example of a potential future project portfolio.

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12 Reference: Subramanian, Dharmashankar and Joseph F. Pekny, Gintaras V. Reklaitis. "A Simulation-Optimization framework for addressing combinatorial and stochastic aspects of an R&D pipeline management problem." Computers and Chemical Engineering 24 (2000): 1005-1011.

Section 3.0 provides the primary theoretical contributions of the thesis. Formulation and solution methods are detailed for the fundamental mathematical programming problems of multiple-project selection and schedule coordination. Simplified illustrative examples are provided to clarify terminology, highlight the structure of the formulation, and describe the computational behavior of the solution algorithms.

Section 4.0 provides an overview of the SEMPRO software system architecture, and provides functional descriptions of the primary software modules. Key terms of reference are provided, along with examples of input and output data structures. Details are provided on the discrete event simulation algorithm, along with the integration the WBS generator, PCP, PSP and simulation modules. A simulated, real-time workforce allocation scheme is described, in which the assignment of individual employees to specific projects is based upon an operational model of the current DFRC project management system.

Section 5.0 discusses potential applications of the SEMPRO planning tool to current problems of interest to the NASA DFRC management team. Section 5.1 describes the use of the Project Selection Algorithm in determining throughput and capacity limits for flight research and development projects. Section 5.2 discusses the use of SEMPRO during the early formulation stage for complex, multi-project research and development programs. Section 5.3 discusses the use of SEMPRO as a training simulator for developing and evaluating project management planning and control strategies. Section 5.4 discusses the use of SEMPRO as a management decision support tool to help refine and validate operational processes, programmatic decisions, and project performance metrics. Section 5.5 summarizes results obtained with the SEMPRO prototype on an example DFRC project portfolio.

Section 6.0 summarizes the primary contributions from this research project, and highlights areas for improvement and follow-on development. The SEMPRO prototype is shown to work adequately for concept demonstration purposes, capable of selecting and sequencing a realizable subset of projects that achieve strategic R&D goals in the presence of resource constraints. However, additional software development work would be required to provide a robust, operational version of SEMPRO compatible with standard business practices and management information systems.

2 DFRC Research and Development Project Environment

This section provides an overview of the NASA Dryden Flight Research Center. This background information supports the subsequent development in Section 4.0 of an operational model of the R&D project management processes at DFRC.

2.1 Center Description

2.1.1 Center Historical Background

As one of ten NASA field centers, the Dryden Flight Research Center (DFRC) has a rich history in conducting breakthrough flight research programs. The Center origins trace back to the earliest days of high speed flight research and X-planes demonstrators under NASA's predecessor organization, the National Advisory Committee for Aeronautics (NACA). The rocket-powered Bell X-1 Mach 1 demonstrator (a joint U.S. Air Force and NACA project) and the DF-558 Skyrocket Mach 2 demonstrator are primary flight research examples from the 1940 era. These revolutionary accomplishments were followed by the X-15 hypersonic demonstrator in the 1950's and 1960's (also a joint NASA/Air Force program); the lunar lander flight trainer, and the M2-F1 and HL-10 lifting body demonstrators in the mid-to-late 1960's; the space shuttle orbiter prototype, Enterprise, in the 1970's; the X-29 forward-swept wing technology demonstrator in the mid 1980's; and the X-31 thrust-vectoring technology demonstrator in the early 1990's. In each of these examples, DFRC contributions were primarily aligned with the Responsible Test Organization (RTO) function, a supporting role within much larger program offices or sponsoring organizations.

Only four of the ten NASA field Centers (see Figure 2.1) have primary aerospace research and technology development responsibilities: the Langley Research Center in Hampton, Virginia; the Glenn Research Center in Cleveland, Ohio; the Ames Research Center in Sunnyvale, California; and DFRC at Edwards, California. The remaining six NASA Centers have primary responsibility in spaceflight development and operations. The Dryden Flight Research Center is currently the designated NASA Center of Excellence for atmospheric flight research. This entails a strong emphasis on flight vehicle systems integration and flight test operations, in a manner analogous to the payload integration and space vehicle launch operations at the Kennedy Space Center.

Flight research projects invariably involve either unique, one-of-a-kind, flight demonstration vehicles or advanced flight system technology demonstrators flown on highly instrumented testbed vehicles. Since the flight test phase of aerospace vehicle R&D programs typically occur late in the development cycle, the portfolio of future projects at DFRC has traditionally been over-subscribed within any two-year time horizon and virtually empty in time horizons beyond five years.

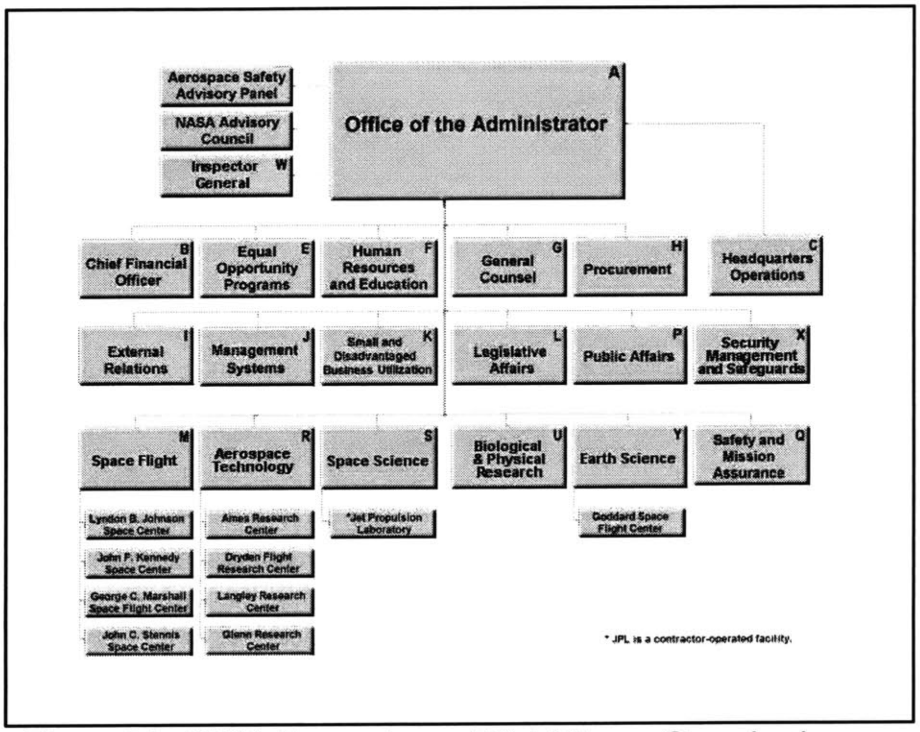

Figure 2-1 NASA Enterprise and Field Center Organization

The present DFRC operational model has evolved over the past several decades to facilitate RTO alignment with much larger program offices and organizations. In the past, this approach had focused DFRC efforts on a small number of concurrent programs at any given time. More recently the nature of flight research has evolved into increasingly complex and highly integrated airframe, propulsion, flight and ground systems. The program risk and development schedules have greatly increased accordingly. In addition, the DFRC customer base has also dramatically increased such that the portfolio of prospective projects at DFRC now far exceeds capacity limits under the current operational model. For example, the recent ramp-up and subsequent cancellation of the high priority X-33 and X-34 programs in 1999 and 2000 had substantial negative impacts on other concurrent flight programs such as the X-

37/X-40 project sponsored by the Marshall Space Flight Center and Boeing Aerospace Corporation; the X-38/CRV project sponsored by the Johnson Space Center; and the X-43A hypersonic project jointly sponsored by the Langley Research Center and DFRC. Moreover, the constraints imposed by this suite of externally sponsored programs has significantly curtailed the set of internal projects achievable within the DFRC Flight Research base research and technology program, resulting in an observed loss of workforce performance and morale. These factors highlight the need to utilize advanced strategic planning tools to support R&D project selection and scheduling.

2.1.2 Strategic Vision and Mission Statements

To address the long-term planning needs for the Center, DFRC senior management has recently developed the following Strategic Vision and Mission Statements.

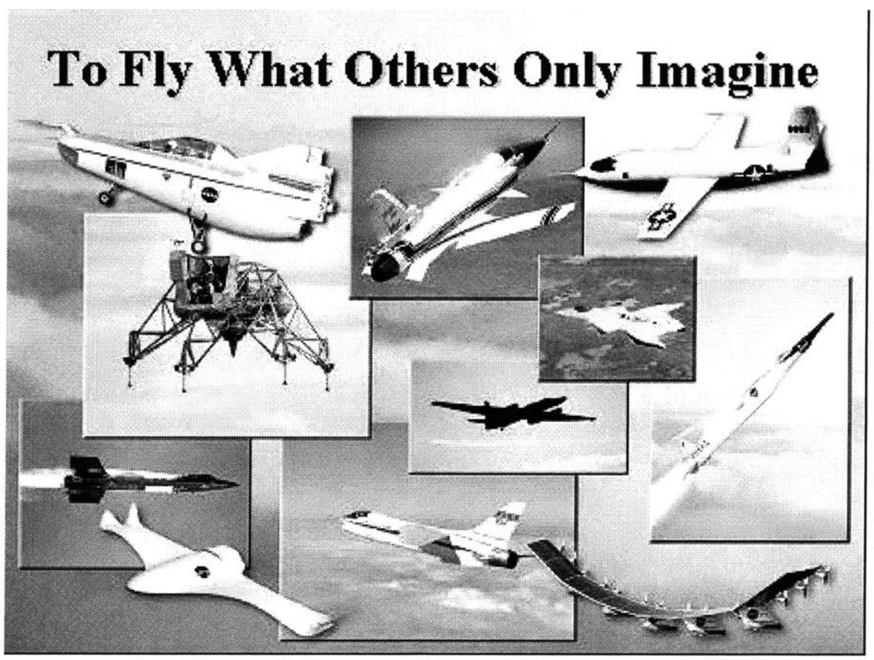

Figure 2-2 DFRC Vision Statement

DFRC Mission Statement

Dryden develops experiments and conducts flights to advance technology for future aerospace vehicles, to understand and protect our environment, and to inspire the next generation. DFRC will:

- **perform flight research and technology integration to revolutionize aviation, advance space transportation, and pioneer aerospace technology,**
- **conduct airborne remote sensing and *in situ* observations,**
- **support operations of the Space Shuttle and the International Space Station,**

..for NASA and the Nation.

2.1.3 Organizational structure

DFRC is managed as a matrix R&D organization. The office organizations grouped in the middle of Figure 2.3 comprise the basic General and Administrative (G&C) functions; the lower tier of "directorate" organizations, along with the Safety and Mission Assurance Office (Code S), perform the vast majority of scientific and engineering functions. The Aerospace Projects Directorate (Code P) and the Airborne Science Directorate (Code Y) comprise the primary business units for the Center, while the Research Engineering Directorate (Code R), the Research Systems Directorate (Code M) the Flight Operations Directorate (Code O), and the Office of Safety and Mission Assurance (Code S) provide the engineering, scientific and technician service pools. Each service pool directorate contains approximately 5-7 branches, with each branch containing 10 to 30 civil service personnel. The DFRC operational model considered for this research effort focuses entirely on the matrix relationship between the Aerospace Projects Directorate and the service pools.

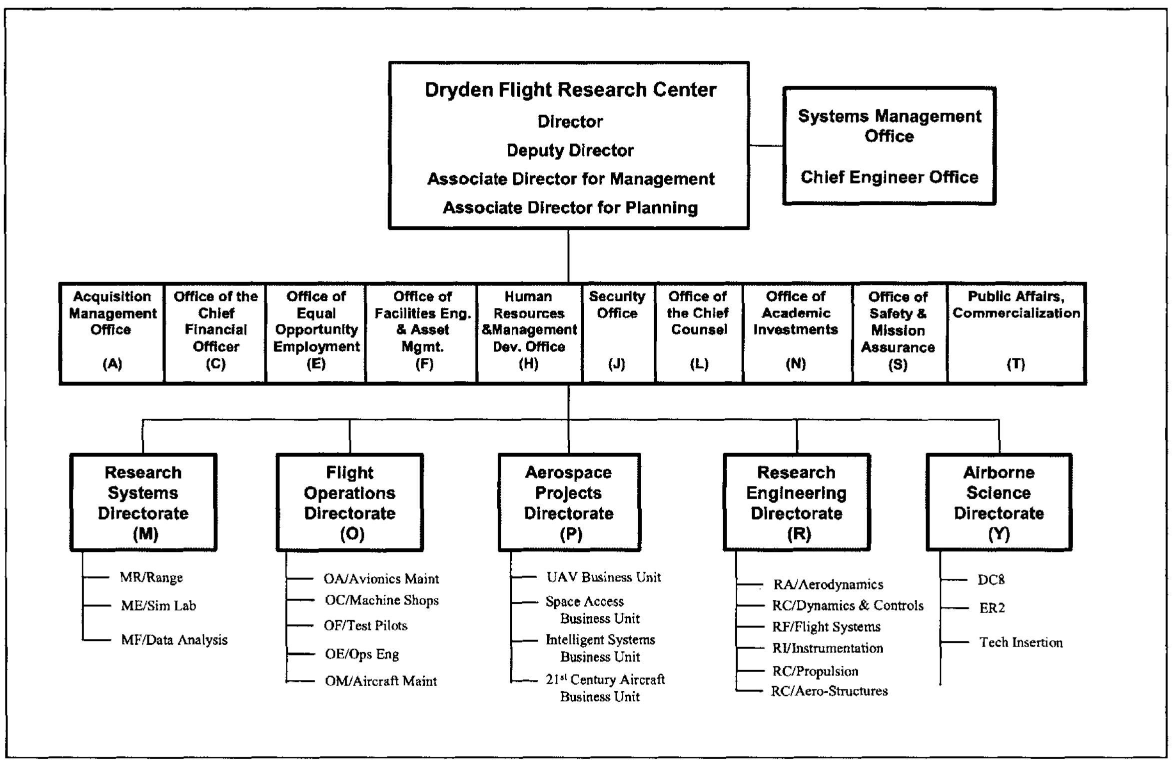

Figure 2-3 Current DFRC Organization Structure

2.1.4 Resource summary

Figures 2.4 and 2.5 provide insight into the Center resource availability and distribution to the primary service pools and project organizations; for convenience, all other Center organizations have been captured under the "G&A" heading. The total Center workforce consists of approximately 570 civil servant employees together with approximately 560 additional on-site support contractors. The current NASA budget system uses the terminology of Full-Time-Equivalents (FTE) and Work-Year-Equivalents (WYE) as the accounting unit of measure for civil servants and on-sight support contractors, respectively. Over the past few years, the DFRC annual operating budget has averaged $180M, with as much as +/- 10% in year-to-year variations. Approximately 16% of the total Center workforce, and 26% of the Center operating budget, are allocated to G&A functions; the remainder is focused on the execution of either aerospace projects or airborne science campaigns. The current DFRC project portfolio is fairly well balanced, as shown in Figure 2.5.

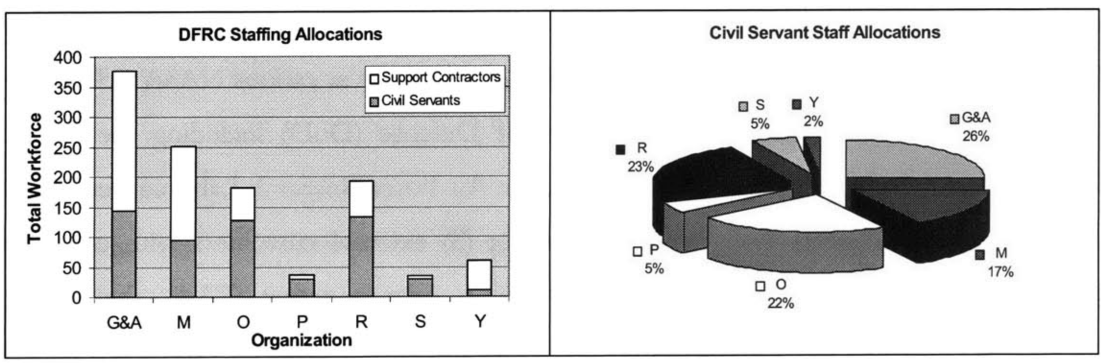

Figure 2-4 DFRC FY04 Staffing Allocations

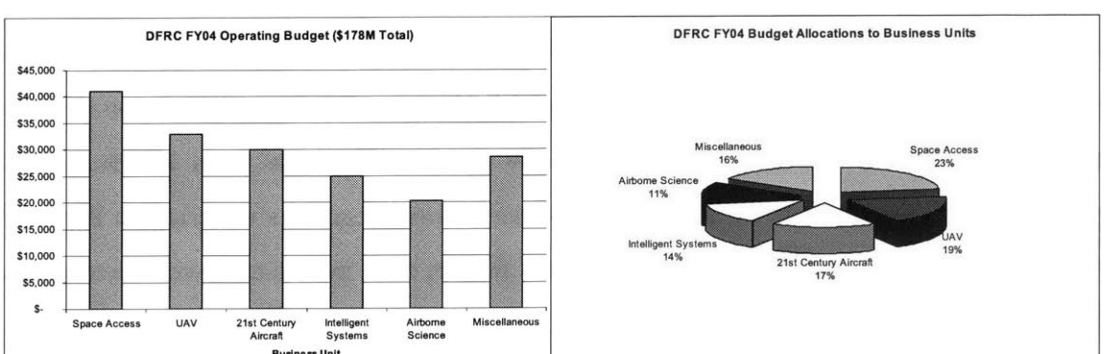

Figure 2-5 DFRC FY04 Budget Allocations

2.2 Customers and Market Segments

2.2.1 Strategic Intent: Expanded Flight Research Market

The emerging DFRC strategic growth plan includes the following statement of intent with respect to the Center's primary business units:

We will be recognized as the premier flight research and test organization for the validation of high-risk, emerging aerospace technology concepts and worldwide airborne science operations.

- We will be leaders in the application of intelligent systems to aerospace vehicles
- We will aggressively seek a responsible role for the nation's hypersonic research and Space Access programs
- We will be recognized as the premier center for UAV technology and operations
- We will employ leading edge science platforms that will enable new earth science missions to be performed

The corresponding customer base targeted by these strategic intents can be segmented into four primary market segments: (1) internal NASA customers including Enterprise level programs at NASA Headquarters (HQ) and lower level projects at various NASA field centers; (2) external customers within the Department of Defense (DoD) including the Defense Advanced Research Projects Agency (DARPA), the Air Force Research Laboratories (AFRL) and the Navy Air Systems Command (NAVAIR); (3) external customers with other civil government agencies including the Federal Aviation Administration (FAA), the National Oceanic and Atmospheric Administration (NOAA), the Department of Homeland Security (DHS), and the Department of Energy (DOE); and (4) external customers within the U.S. aerospace industry including airframe companies such as Boeing, Northrop Grumman, Lockheed Martin , Gulfstream, and General Atomics, along with aerospace subsystem providers such as Pratt & Whitney, Honeywell, and BAE Systems. At any given point of time, the portfolio of R&D projects at DFRC usually contains elements from all four market segments. However the balance of business between these segments experiences large, and sometimes rapid, swings as dictated by exogenous factors such as federal government politics and the strength of the aerospace market sector.

Figure 2.6 provides a rough summary of major flight research projects at DFRC over the period of FY98 – FY03. Of the twenty-five projects shown, eleven were cancelled well into the project development cycle. In 8 of the 11 cases, the project cancellation was due to external program decisions beyond the control of DFRC management. The remaining 3 were internal project cancellations made by DFRC senior management to accommodate external projects with higher priorities within the Agency. In addition, four projects experienced significant schedule over-runs, but were allowed to continue towards completion. This recent performance indicates a period of highly unstable and uncertain project resource requirements, leading to low workforce morale and high turnover rates. Capturing these qualitative characteristics is a primary objective in developing the SEMPRO system architecture.

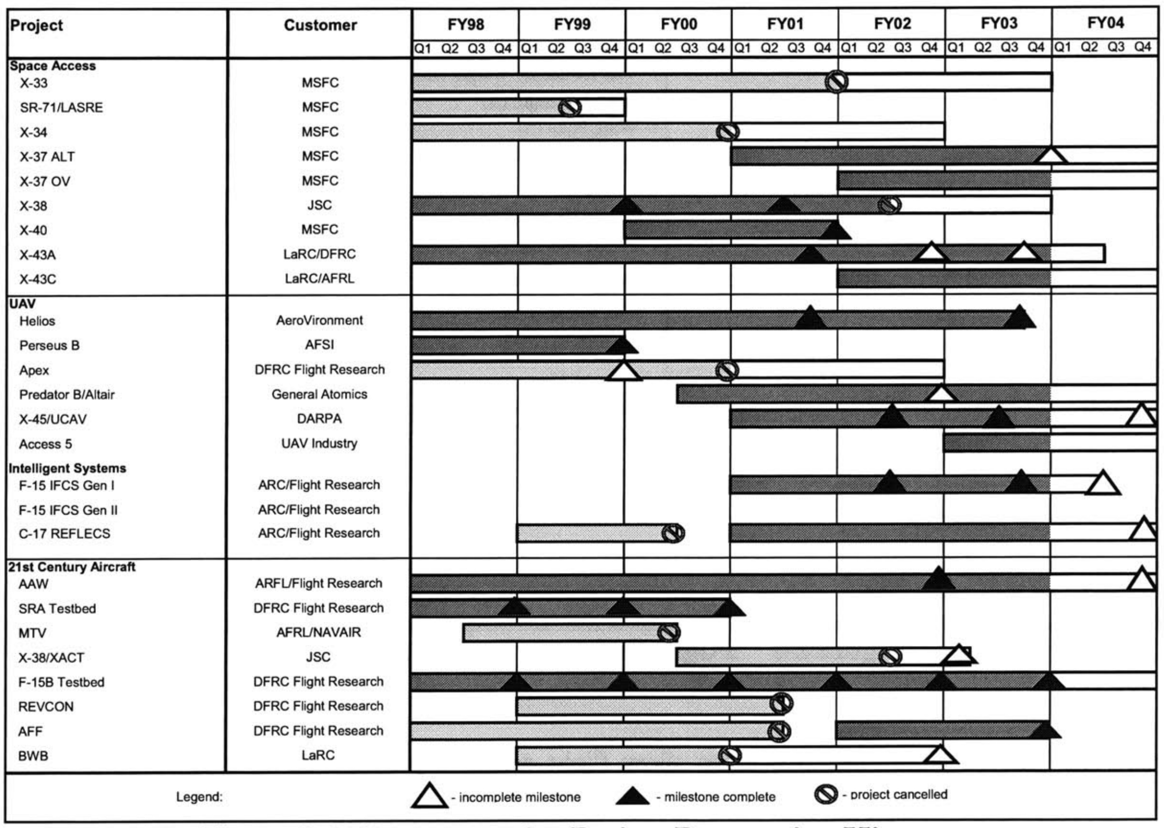

Figure 2-6 Representative Project Progression History

2.3 Nature of flight research projects

This section provides a top-level description of the major characteristics of flight research projects from a resource requirements perspective. This class of R&D project can be described in terms of dominant research characteristics and project activity flow networks, as governed by the programmatic, vehicle and technology attributes shown in Figure 2.7. These representative attributes were selected for illustrative purposes in this research thesis, and by no means constitute a complete set. The selected attributes provide the basis for the SEMPRO input data structure. This input data file is used to generate project WBS activity networks for each candidate project, and to determine the coefficients of the project selection and project coordination optimization cost functions.

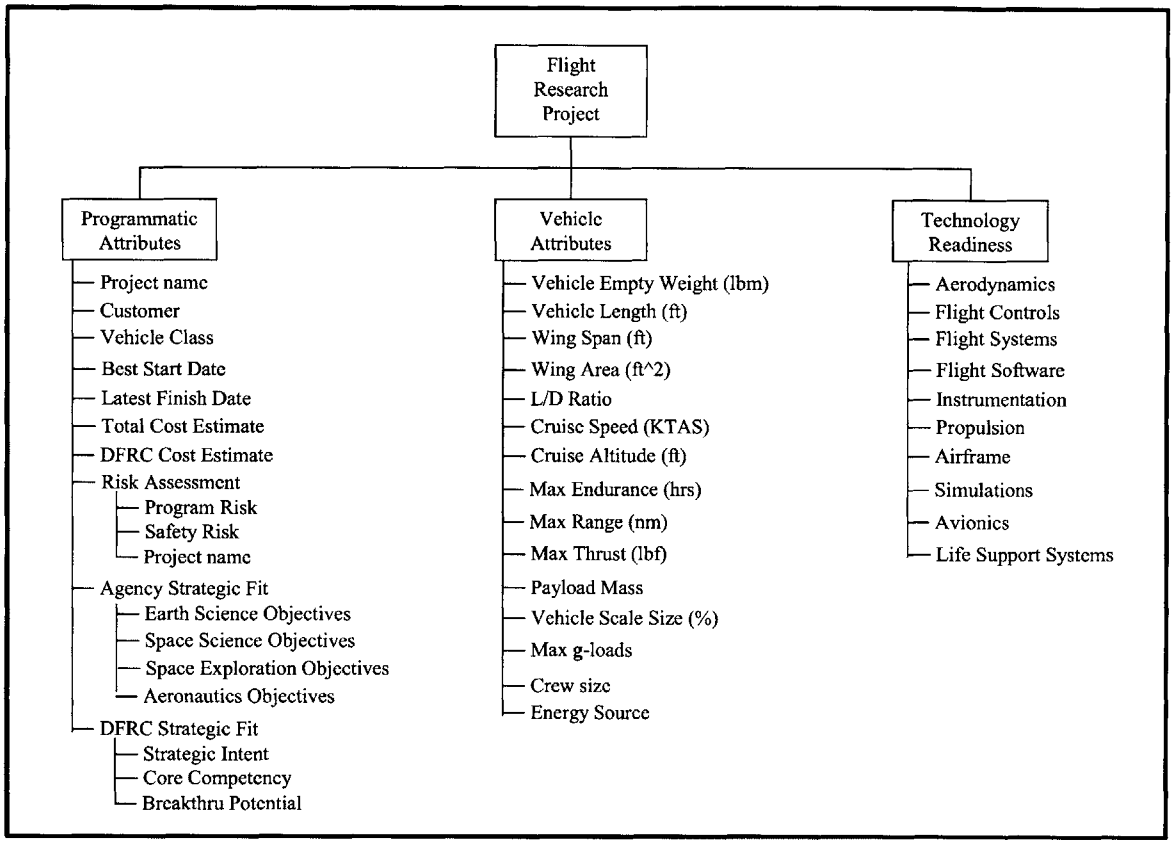

Figure 2-7 Flight Research Project Attributes

Current DFRC operational processes allow flight research projects to be classified into four SEMPRO reference categories:

(I) Internal X-plane projects;

(II) Testbed projects;

(III) External partnership projects;

(IV) Host mode projects.

The project durations and the extent of DFRC resource requirements vary significantly in each category. The Internal X-plane category represents major, revolutionary flight research projects with the largest resource requirements at DFRC and other NASA Centers, and with significant prime contractor participation. Category I examples include the X-3, X-15, X-29, X-31 and X-43A projects. The Testbed category captures advanced sub-system or component tests on one of several testbed aircraft, such as the F-15B, F-18A/B, C-17, and DC-8 vehicles. Flight test articles are provided by a variety of sources including the internal DFRC Flight Research project, other NASA Centers and program offices, other government agencies, universities and industry. The External Partnership category is the compliment to Category I, wherein an external aerospace industry partner leads the vehicle design and development phase, with NASA participation focused on the flight test phase. The Host Mode category captures flight test projects in which external customers utilize DFRC flight test infrastructure (aircraft hangers, machine shops, flight test range, etc) on a cost reimbursement basis, requiring the least amount of DFRC staffing support. Figure 8-1 though Figure 8-4 in Appendix 8.1 provide characteristic development schedules for each of the four project categories.

The development cycle for each category can be decomposed into six distinct project phases, with widely different DFRC resource requirements in each category. The project phases for a typical X-plane development cycle, such as the X-43A project, are illustrated in Figure 2-8. For the sake of simplicity, the six project phases are shown as a sequence of non-overlapping blocks of activities; in practice, this idealization is seldom realized. Nonetheless, each phase of a project contains clearly defined start and finish activities. Start-up activities for a project

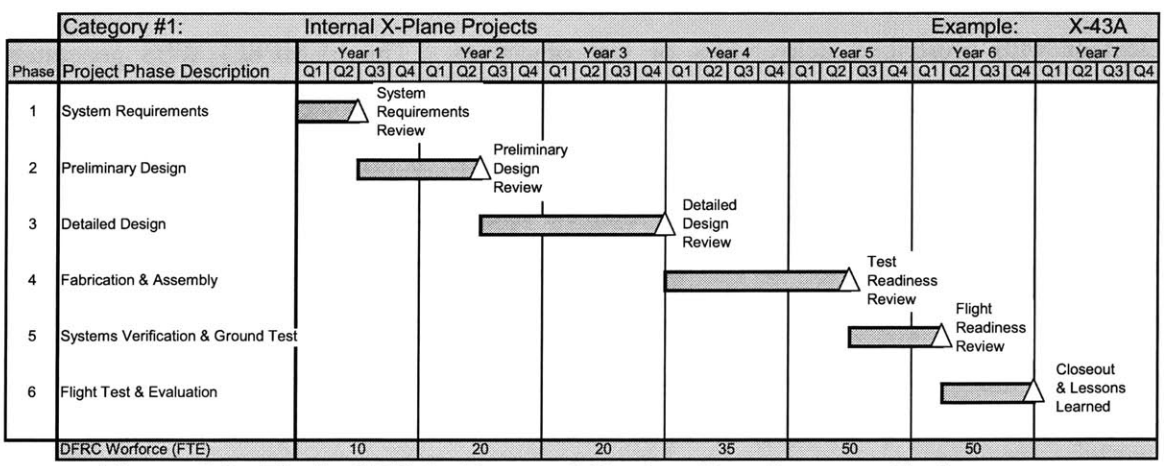

Figure 2-8 Typical Flight Research Project Development Cycle

phase typically involve an expansion or contraction of project team membership, combined with detailed task planning for the ensuing project phase. Each phase normally finishes with a thorough readiness review to assess preparation and risk for subsequent project phases. These readiness reviews serve as project "go/no-go" control gates. The management decision to proceed to the next project phase is determined largely by the cost, schedule, technical performance at the time of the review, coupled with an assessment of program risk (or probability of success) in comparison with other Center and Agency priorities. Once a project phase has started, it is typically allowed to work towards one of three different completion states: (1) successful completion; (2) cancellation; or (3) failure. Successful completion is established by successful completion of all WBS Level 3 tasks within a given phase, terminating with a successful readiness review for the next phase. Project cancellation is a senior management decision that almost always allows for orderly completion of a current project phase to enable potential re-start efforts. Project failure is determined by repeated failures to satisfy requirements for any WBS Level 3 project element within a given project phase. The allowable number of repeated task failures is a project management decision criteria. A project that reaches the failure state is typically allowed to partially complete Work-In-Process in an orderly manner, but without necessarily completing the project phase during which the series of failures occurred.

Reference activity networks for each of the six project phases are provided in Figure 8-7Figure 8-12 in Appendix 8.2. Each activity block within a project phase represents a WBS Level 2 element with prescribed deliverables or test objectives. The SEMPRO WBS generator provides a functional mapping from project attributes to the project WBS Level 2 activity networks. For the sake of simplicity in this thesis, the SEMPRO prototype assumes the activity networks for a given phase have identical structure and precedence relationships for every project in the portfolio. In this simplified case, the WBS generator need only adjust the activity resource requirements and task durations, based in part on the project category, risk and technology readiness attributes. In practice, DFRC projects operate as matrixed product development teams, completing multiple, concurrent tasks in a close-coupled, integrated manner. A project core management team typically comprises a dedicated project manager, chief engineer and flight operations engineer. The remaining project team members are typically assigned to one or two other concurrent projects.

2.4 Example Future Project Portfolio

Tables 2.1- 2.3 provide the key attributes for 18 different entries in an example flight research project portfolio. The portfolio contains a mixture of projects from the four main categories, with projects also in various stages of development. Table 2.1 lists the programmatic attributes; Table 2.2 lists test vehicle physical attributes, and Table 2.3 identifies the associated technology readiness levels (Figure 8-13 in Appendix 8.3 provides definitions of technology readiness levels). An example work breakdown schedule generated by SEMPRO for a Category I/Internal X-plane project is provided in Figure 8-5 and Figure 8-6 in Appendix 8.1.

Project					Schedule			Cost		Risk			Consequence			Agency Fit					Center Fit		
Project ID	Name	Customer	Project Category	Vehicle Class	Best Start	Latest Finish	Current Project Phase	Total Cost ($M)	DFRC Cost ($M)	Technical Risk	Program Risk	Safety Risk	Technical Risk	Program Risk	Safety Risk	Priority	Goal 1: Earth Science	Goal 2: Space Science	Goal 3: Space Exploration	Goal 4: Enabling	Strategic Fit	Core Competency	Breakthru Potential
1	X-43A	LaRC	B-52B	Space	1	21	T&V	$150	$75	5	3	1	5	3	1	H	0	0	6	9	Space	8	7
2	AAW	AFRL	F-18	DOD	1	18	FLT	$50	$30	3	6	7	3	6	7	L	0	0	0	6	Aero	7	5
3	Helios	ARC	UAV	ESE	1	18	Adv	$100	$30	4	5	1	4	5	1	M	3	3	0	6	UAV	3	7
4	X-37	MSFC	B-52H*	Space	1	25	CDR	$75	$35	5	5	5	5	5	5	H	0	0	9	0	Space	5	5
5	X-45	DARPA	UAV	DOD	1	25	FLT	$130	$25	5	2	5	5	2	5	L	0	0	0	6	UAV	4	6
6	PDE	GRC	F-15B	Aero	1	17	Adv	$50	$15	6	8	5	6	8	5	L	0	0	0	6	Aero	4	5
7	SSBJ	LaRC	X-plane	DEMO	9	28	Adv	#####	$95	M	M	H	3	6	7	L				M	Aero	M	H
8	BWB	LaRC	X-plane	DEMO	9	36	Adv	$250	$75	M	M	L	4	5	1	L				M	Aero	M	M
9	RBCC	MSFC	Testbed	F-15B	5	16	Adv	$100	$25	M	M	M	5	5	5	M			H		Space	M	H
10	Global Observer	ESE	Partner	UAV	4	40	Adv	#####	$120	H	H	M	3	6	7	M			H		Earth	M	H
11	IFCS I	ARC	Testbed	F-15	1	12	DD	$20	$12	M	M	M	4	5	1	L			L	L	IFS	H	M
12	IFCS II	ARC	Testbed	C-17	1	16	DD	$50	$50	M	M	M	5	5	5	L			L	L	IFS	H	M
13	Access 5	Industry	Partner	UAV	3	32	SR	$400	$48	L	M	H	3	6	7	M	L			L	UAV	M	M
14	UEET	GRC	Testbed	C-20	9	28	Adv	$400	$60	M	M	M	4	5	1	L	M			L	Aero	M	M
15	OSP	JSC	X-plane	B-52H	5	32	SR	#####	$95	M	L	H	5	5	5	H			H		Space	M	M
16	SLEP	JSC	Testbed	G 3	6	32	SR	$500	$45	L	M	M	3	6	7	H			H		Space	M	M
17	Mars A/C	SSE	X-plane	B-52H*	5	18	Adv	$125	$50	M	M	L	4	5	1	M		M		M	UAV	H	H
18	AAR	DARPA	Testbed	F-18	5	20	Adv	$100	$35	M	M	M	5	5	5	L				L	UAV	H	M

Reference	Phase	Description
Adv	0	Advocacy
SR	1	System Requirements
PD	2	Preliminary Design
DD	3	Detailed Design
F&A	4	Fabricate & Assemble
Gnd	5	System V&V and Gnd Test
Flt	6	Flight Test and Evaluation

Table 2-1 Programmatic Attributes for a Candidate Project Portfolio

Project		Vehicle Attributes													
Index	Name	Aircraft GVTOW (lbm)	Length (ft)	Span (ft)	Wing area (ft^2)	L/D	Cruise (KIAS)	Cruise Altitude (ft)	Mission Duration (hr)	Max Thrust (lbf)	Payload Mass (lbm)	Scale	g-load	Crew	Energy Source
1	X-43A	12,000	12	3	36	2	5439	75000	0.05	1000	0	50%	3	0	LH2
2	AAW	30000	50	25	2500	7	971	50000	1	40000	10000	100%	9	1	JP4
3	Cyclogenesis	2000	35	45	787.5	30	220	60000	336	2000	400	100%	2	0	JP4
4	X-37 ALT	30000	45	15	500	3	699	50000	0.25	250	0	100%	3	0	N2H4
5	X-45A/UCAV	20000	25	30	1200	7	622	50000	1	15000	2000	100%	12	0	JP4
6	PDE	47000	64	43	1000	7	1554	60000	2	58000	10000	30%	9	1	JP4
7	SSBJ	125000	100	50	2000	10	1399	75000	3	54000	0	80%	3	1	JP4
8	BWB	50000	60	80	3500	20	684	45000	1	20000	0	50%	3	1	JP4
9	RBCC	47000	64	43	1000	7	1554	60000	2	58000	10000	25%	9	1	JP4
10	Global Observer	20000	50	25	1500	4	2331	75000	2400	25000	200	50%	2	0	LH2
11	IFCS I	47000	64	43	1000	7	1554	60000	2	58000	10000	100%	9	2	JP4
12	IFCS II	250000	90	76	3000	18	622	40000	2	80000	50000	100%	3	2	JP4
13	Access 5	10000	27	81	1000	37	220	50000	32	750	750	100%	2	0	JP4
14	UEET	250000	90	76	3000	18	622	40000	2	80000	50000	100%	3	2	JP4
15	OSP	35000	45	15	500	3	699	50000	0.25	250	1500	100%	3	0	N2H4
16	SLEP	30000	50	60	2500	18	684	52000	6	6000	2000	100%	3	2	JP4
17	Mars A/C	500	10	20	60	30	769	100000	1	0	50	100%	2	0	Battery
18	AAR	35000	50	25	2500	7	971	50000	1	40000	10000	100%	9	1	JP4

Table 2-2 Flight Vehicle Attributes for a Candidate Project Portfolio

						Technology Readiness Level																
Project		Key Technologies				RA		RC		RF		RI	RP		RS		FE	FR	OA	OF	OM	
Index	Name	Tech_1	Tech_2	Tech_3	CE or PI	Aerodynamics	Airframe	Flight Controls	Flight Test	Flight Systems	S/W	Instrumentation	Propulsion	Performance	Structures	Materials	Simulation	Range	Avionics	Pilot & Crew	Maintenance	
1	X-43A	scramjet			RP	5	4	5	7	6	6	8	3	3	9	9	9	8	9	8	8	
2	AAW	aeroelestic wing			RS	7	7	7	8	7	7	8	9	7	9	9	8	9	9	8	9	
3	Cyclogenesis	airframe	endurance	LH2 tanks	RA	6	6	6	7	7	6	9	9	6	3	9	7	6	9	7	8	
4	X-37 ALT	smart re-entry			RF	6	7	6	5	5	4	7	9	4	8	9	6	5	9	5	7	
5	X-45A/UCAV	autonomous s/w			RC	7	7	6	6	5	5	6	6	6	8	9	6	7	9	6	6	
6	PDE	pulse detonation	aero-acoustics		RP	9	9	9	6	9	9	8	3	5	7	9	8	9	9	9	8	
7	SSBJ	sonic boom shape	super-cruise		RA	3	5	6	7	9	9	5	7	3	6	6	5	5	9	9	8	
8	BWB	airframe	materials		RA	4	3	5	6	7	7	5	5	4	6	6	5	9	9	7	6	
9	RBCC	jet + rocket			RP	6	9	9	8	9	9	8	3	5	9	9	9	9	9	9	9	
10	Global Observer	flight controls	superconductors	PEM RFC	RC	5	5	6	7	5	7	7	5	5	6	6	5	8	5	6	6	
11	IFCS I	neural nets			RC	9	9	6	9	8	5	9	9	7	9	9	6	9	9	8	9	
12	IFCS II	neural nets			RC	9	9	6	9	8	5	9	9	7	9	9	6	9	9	8	9	
13	Access 5	DSA sensors	OTH comm	ATC procedures	OE	7	8	5	6	5	6	7	9	7	7	7	6	3	6	4	7	
14	UEET	superconductors	LH2 FC		RP	9	9	7	6	6	8	6	5	5	9	9	7	9	9	8	6	
15	OSP	re-entry			RF	8	7	7	7	8	6	7	9	5	8	9	8	5	9	6	7	
16	SLEP	MEMS	IVHM		RF	9	9	7	7	5	5	7	9	7	9	9	6	8	5	7	7	
17	Mars A/C	inflatable airframe	intelligenent control		RA	5	4	7	6	5	6	8	7	3	6	6	6	7	7	7	7	
18	AAR	precision formation	smart boom		RC	5	9	3	6	5	4	7	9	6	9	9	8	9	9	9	9	

Table 2-3 Technology Readiness Levels for a Candidate Project Portfolio

3 Project Selection and Scheduling Algorithm

The PCP and PSP linear programming algorithms transform the individual WBS models in the project portfolio into an integrated set of time-phased, directed activity networks[13] suitable for simulation and subsequent implementation. Section 3.1 provides a detailed development of the Project Coordination Problem (PCP) formulation and solution method outlined by Roemer[14]. Section 3.2 highlights a simplified numeric example of the PCP solution method, and compares computation times for the optimal BILP solution versus PCP solutions for a set of ten example problems. Extensions to other closely related problems are provided in Section 3.3. The level of detail is intended to facilitate follow-on research objectives, and to support the SEMPRO software coding and debugging process.

3.1 Project Coordination Problem

Research and development organizations typically engage in multiple concurrent projects in any given period of time. Most often, and especially in matrix organizations, these R&D projects must compete for staffing and other constrained resources from multiple line organizations. Since project staffing requirements tend to follow a bell-shaped distribution over the project development cycle, it is essential to properly time-phase the execution of all concurrent projects in a manner that limits peak workforce requirement while striving to utilize available staff to the most practical extent possible. This is especially critical in high technology organizations where the lag time to hire and train qualified staff can represent a significant percentage of the project development cycle. The Project Coordination Problem strives to minimize the weighted sum of project completion times for a given set of projects, subject to known resource limitations within line organizations. It is assumed that each project has an established Work Breakdown Schedule that defines a resource-loaded, directed activity network with known precedence relationships, activity durations and target project completion dates.

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[13] For example, a Program Evaluation Review Technique (PERT) network; see Moore, Jeffrey H. and Larry R. Weatherford. "Appendix 14: Project Management: PERT and CPM." Decision Modeling with Microsoft Excel. 6th Edition. Upper Saddle River, New Jersey: Prentice-Hall, 2001.

[14] Roemer, Thomas A. "Coordinating New Product Development Projects." Unpublished white paper, MIT Sloan School of Management, 2000.

3.1.1 Formulation

The PCP can be formulated using the following definitions: Let

- $t = 1,2,\ldots T$ represent a planning time horizon with uniform time increments;
- b_m , $m = 1,2,\ldots M$ represent the line departments (or "branches" in the NASA/DFRC vernacular) with known resource capacity limits;
- C_m , $m = 1,2\ldots M$ represent the resource capacity limits within line department b_m;
- p_j , $j = 1,2,\ldots P$ represent the development projects approved for implementation;
- $a_{j,i}$, $j = 1,2,\ldots P$; $i = 1,2,\ldots N_j$ represent activity *i* of project *j*, where N_j designates the total number of tasks in the directed activity network for project p_j , and where task a_{j,N_j} represents the final task required to complete project j;
- $S_j(i)$ designate the set of all downstream activities that succeed activity $a_{j,i}$, as determined by the directed activity network for project p_j ;
- $\mathcal{K}_{j,i}$, $j = 1,2,\ldots P$; $i = 1,2,\ldots N_j$ define the cardinality of $S_j(i)$;
- $P_j(i)$ designate the prescribed set of activities that immediately precede activity $a_{j,i}$, as determined by the directed activity network for project p_j ;
- $\mathcal{L}_{j,i}$, $j = 1,2,\ldots P$; $i = 1,2,\ldots N_j$ define the cardinality of $P_j(i)$;
- $\delta_{j,i}$, $j = 1,2,\ldots P$; $i = 1,2,\ldots N_j$ represent the nominal time duration associated with activity $a_{j,i}$ (in the same units of time as *t*);
- $\overline{\delta}_j$, $j = 1,2,\ldots P$; represent the minimum time duration to complete project *P*, as determined by the activities $\overline{a}_{j,i}$ and durations $\overline{\delta}_{j,i}$ along the critical path of project *P*;
- $s_{j,i}$, $j = 1,2,\ldots P; i = 1,2,\ldots N_j$ represent the actual start time for activity $a_{j,i}$, where the abbreviated notation s_j , $j = 1,2,\ldots P$ designates the overall start time for project p_j (ie, $s_j \equiv s_{j,1}$);
- $f_{j,i}$, $j = 1,2,\ldots P$; $i = 1,2,\ldots N_j$ represent the overall finish time for activity $a_{j,i}$, where the abbreviated notation f_j , $j = 1,2,\ldots P$ designates the actual finish time for project p_j (ie, $f_j \equiv f_{j,N_j}$), noting that $f_{j,i} \triangleq s_{j,i} + \delta_{j,i}$;
- $\hat{f}_j$, $j = 1,2,\ldots P$ represent the target completion date for project p_j ;

- w_j , $j = 1, 2, \ldots P$ represent the penalty weight per unit of time (consistent with the units of measure for t) for late completion of project p_j (ie, whenever $f_j > \hat{f}_j$);
- $r_{m,j,i}$, $m = 1, 2, \ldots M$; $j = 1, 2, \ldots P$; $i = 1, 2, \ldots N_j$ represent resource requirements from department *m* for activity *i* of project j ,

Note that various types of resources (such as staff, or funding, or consumable items) can be captured within the following formulation by consistent definition of units associated with c_m and $r_{m,j,i}$ and *t*.

Let $\overline{N}_j$ designate the number of activities along the critical path of project p_j , as determined by $\overline{a}_{j,i}$ and $\overline{\delta}_{j,i}$. If necessary, a dummy activity a_{j,N_j} may be defined as a zero-duration, final project activity ($\delta_{j,N_j} = 0$) appended to the end of a project critical path, if the associated activity network would otherwise contain multiple, concurrent final project activities. It is assumed that the activity durations along the project critical path satisfy the relationship $\overline{\delta}_j = \sum_{n=1}^{\overline{N}_j} \overline{\delta}_{j,n} \leq T$ such that the project makespan is less than or equal to the time horizon T.

The problem is to find a near-optimal sequence of activity start times $s_{j,i}$ for all projects p_j such that the resource capacity limits C_m are satisfied while striving to minimize the weighted sum of project completion times f_j according to the objective function

$$J_C = \min \sum_{j}^{P} w_j \left(f_j - \hat{f}_j \right) \quad . \tag{3.1}$$

where, by definition, $f_j \equiv s_j + \delta_{j,N_j}$.

It is assumed that project activities may require resources from multiple line departments. It is also assumed that once a given activity $a_{j,i}$ starts, it is allowed to complete without interruption.

Define binary decision variables $X_{j,i,t}$ $j = 1,2,\ldots P$; $i = 1,2,\ldots N_j$; $t = 1,2,\ldots T$ such that $X_{j,i,t} = 1$ if activity *i* of project *j* has started by time *t* and $X_{j,i,t} = 0$ otherwise. The start and finish times for an activity $a_{j,i}$ are thus given by

$$s_{j,i} = (T+1) - \sum_{t=1}^{T} X_{j,i,t} \tag{3.2}$$

$$f_{j,i} = (s_{j,i} + \delta_{j,i} - 1) = \left(T + \delta_{j,i} - \sum_{t=1}^{T} X_{j,i,t} \right) \tag{3.3}$$

Note that, for any activity $a_{j,i}$, if $X_{j,i,t} = 1$ for all *t*, then $\sum_{t=1}^{T} X_{j,i,t} = T$ and $s_{j,i} = 1$; and if $X_{j,i,t} = 0$ for all *t*, then $s_{j,i} = T+1$ (ie, the activity start time is beyond the time horizon T). Equation (3.3) allows the objective function (3.1) to be re-written as

$$\begin{aligned} J_C &= \min \sum_{j=1}^{P} w_j * \left(f_j - \hat{f}_j \right) \\ &= \min \sum_{j=1}^{P} w_j * \left(\left(T + \delta_{j,N_j} - \sum_{t=1}^{T} X_{j,N_j,t} \right) - \hat{f}_j \right) \\ &= \min \sum_{j=1}^{P} w_j * \left(\left(T + \delta_{j,N_j} - \hat{f}_j \right) - \sum_{t=1}^{T} X_{j,N_j,t} \right) \end{aligned} \tag{3.4}$$

Define constants γ_j as

$$\gamma_j \triangleq \left(T + \delta_{j,N_j} - f_j \right) \tag{3.5}$$

Then

$$\begin{aligned} J_C &= \min \sum_{j=1}^{P} w_j * \left(\gamma_j - \sum_{t=1}^{T} X_{j,N_j,t} \right) \\ &= \sum_{j=1}^{P} w_j \gamma_j + \max \sum_{j=1}^{P} \sum_{t=1}^{T} w_j X_{j,N_j,t} \end{aligned} \tag{3.6}$$

Note that the first summation is a constant term that has been dropped from the optimization function. Introduce a modified penalty coefficient $w_{j,i,t}$ with the following definition:

$$w_{j,i,t} = \begin{Bmatrix} w_j \ \ when\ i = N_j \ \ \forall\ t \\ 0 \ \ otherwise \end{Bmatrix}. \tag{3.7}$$

The PCP can now be stated in terms of the following Binary Integer Linear Programming (BILP) maximization problem (equations (3.8) thru (3.12)).

PCP:

$$J_{PCP} = \max \sum_{j=1}^{P} \sum_{i=1}^{N_j} \sum_{t=1}^{T} \left(w_{j,i,t} X_{j,i,t} \right) \tag{3.8}$$

subject to the following constraints

(continuity) $$X_{j,i,t+1} \geq X_{j,i,t} \qquad 1 \leq j \leq P;\ 1 \leq i \leq N_j;\ 1 \leq t \leq T \tag{3.9}$$

(precedence) $$X_{j,i,t-\delta_{j,i}} \geq X_{j,k,t} \qquad 1 \leq j \leq P\ ;\ 1 \leq i \leq N_j\ ;\ 1 \leq t \leq T; k \subset S_j(i) \tag{3.10}$$

(resources) $$\sum_{j,i} \left(X_{j,i,t} - X_{j,i,t-\delta_{j,i}} \right) r_{m,j,i} \leq C_m \qquad 1 \leq m \leq M; 1 \leq t \leq T \tag{3.11}$$

(binary) $$X_{j,i,t} \in (0,1) \quad 1 \leq j \leq P;\ 1 \leq i \leq N_j;\ 1 \leq t \leq T \tag{3.12}$$

The above definition for $X_{j,i,t}$ leads to a somewhat larger number of decision variables than other possible formulations[15]. However, the structure of this formulation will be shown to yield advantageous decoupling properties.

Constraint (3.9) imposes the continuity requirement that once an activity starts, it must complete. Activity $a_{j,i}$ starts when decision variable $X_{j,i,t}$ transitions from 0 to 1, and completes after $\delta_{j,i}$ subsequent time steps. Constraint (3.9) requires $X_{j,i,t}$ to remain "on" (ie, $X_{j,i,t}$=1) for at all times subsequent to activation. Constraints (3.9) and (3.10) together

[15] See chapter 6 in Demeulemeester, Erik L. and Willy S. Herroelen. Project Scheduling: A Research Handbook. Boston: Kluwer Academic Publishers, 2002.

impose activity precedence relationships; any activity $a_{j,k}$ that succeeds activity $a_{j,i}$ cannot start until after activity $a_{j,i}$ has completed.

Constraints (3.11) impose line department resource constraints. Constraints (3.9) and (3.10) ensure that the term $\left(X_{j,i,t} - X_{j,i,t-\delta_{j,i}}\right)$ will equal unity for all time intervals during which activity $a_{j,i}$ is active, and will be zero otherwise. The sum of all active resource allocations from department *m* at time *t* must be less than or equal to the resources capacity limits within department *m*. Note that by convention, $X_{j,i,\tau} \triangleq 0 \ \ \forall \tau \le 0$, where $\tau = t - \delta_{j,i}$ in (3.10) and (3.11); this allows a reduction in the total number of required decision variables.

The number of required decision variables $\mathcal{N}$ is given by

$$\mathcal{N} = T * \sum_{j=1}^{P} N_j \tag{3.13}$$

and the number of constraint relationships $\mathcal{M}$ is given by

$$\mathcal{M} = (T-1) * \sum_{j=1}^{P} N_j + \mathcal{K} * T + M * T \tag{3.14}$$

where $\mathcal{K} \triangleq \sum_{j=1}^{P} \sum_{i=1}^{N_j} \mathcal{K}_{j,i}$ represents the total number of successor relationships. Although the magnitude of $\mathcal{K}$ depends on the topology of the activity networks for each project p_j, it is bounded by the relationship

$$\sum_{j=1}^{P} \left(2 * N_j - 3\right) \le \mathcal{K} \le \frac{1}{2} \sum_{j=1}^{P} \left(N_j \left(N_j - 1\right)\right)$$

The lower bound derives from 3-stage network topologies comprising single start and finish nodes with all other activity nodes in parallel between the start and finish nodes. The upper bound derives from single-string chain topologies in which all activities follow one another sequentially from start to finish.

3.1.2 *Solution methods*

3.1.2.1 *Binary Integer Linear Programming*

The above PCP formulation can be solved directly with standard Binary Integer Linear Programming algorithms, if the dimension $\mathcal{N}$ of $X_{j,i,t}$ is reasonably small. However, for problems of practical interest, the number of decision variables $\mathcal{N}$ and constraint relationships $\mathcal{M}$ tend to be very large. Numeric optimization of Resource Constrained Project Schedule Problems (RCPSP) are characterized as "NP Hard" [16], meaning that solution times cannot be bound by a polynomial function $\mathcal{N}$ and $\mathcal{M}$. Table 3.1 provides actual numerical solution times for a set of simplified PCP example problems, using the standard Excel Solver binary integer solution method[17]. These example problems were carefully constructed to expand $\mathcal{N}$, $\mathcal{M}$ and $\mathcal{K}$ while satisfying the inherent Excel SOLVER problem size limitation (ie, $\mathcal{N} \leq 200$). In addition, project late penalty weights and line department resource constraints were carefully selected to make these examples particularly difficult to solve (ie, these results approximate worst case computational burdens). Figure 3.1 shows that the resultant Central Processor Unit (CPU) times are an exponential function of the number of constraints, $\mathcal{M}$. Extrapolating these results to problems of practical interest (say, P = 20 project, N_j = 7 activities, M=10 departments and T=120 months), runtimes exceeding thousands of hours can easily be required on present day PC laptop computers (ie, 1.5 GHz clock speed). In the past, this limitation has curtailed interest and application of the PCP.

Case	N_Projects P	M_dept M	N_activity Nj	Tmax T	Successors $\mathcal{K}$	$\mathcal{N}$	$\mathcal{M}$	BILP Solution Time
1	2	2	2	4	2	16	28	0.1
2	2	2	2	8	2	32	60	0.2
3	2	2	4	8	11	64	176	0.5
4	3	4	4	10	11	120	258	1.4
5	4	2	4	8	21	128	296	1.0
6	5	4	4	9	21	180	385	2.0
7	2	2	12	7	74	168	676	6.8
8	2	3	10	10	56	200	770	6.7
9	2	2	9	10	70	180	882	23.1
10	2	2	10	10	84	200	1040	57.6

Table 3-1 Comparison of Actual Excel SOLVER CPU Times (in seconds)

[16] See chapter 6 in Demeulemeester, Erik L. and Willy S. Herroelen. Project Scheduling: A Research Handbook. Boston: Kluwer Academic Publishers, 2002.

[17] Numeric results and CPU times were obtained on a PC laptop computer with a 1.5 MHz Pentium 4 processor, using the standard SOLVER add-on in Microsoft Excel 2000 (9.0.6126 SP-3) under Windows 2000 (Version 5.0.2195).

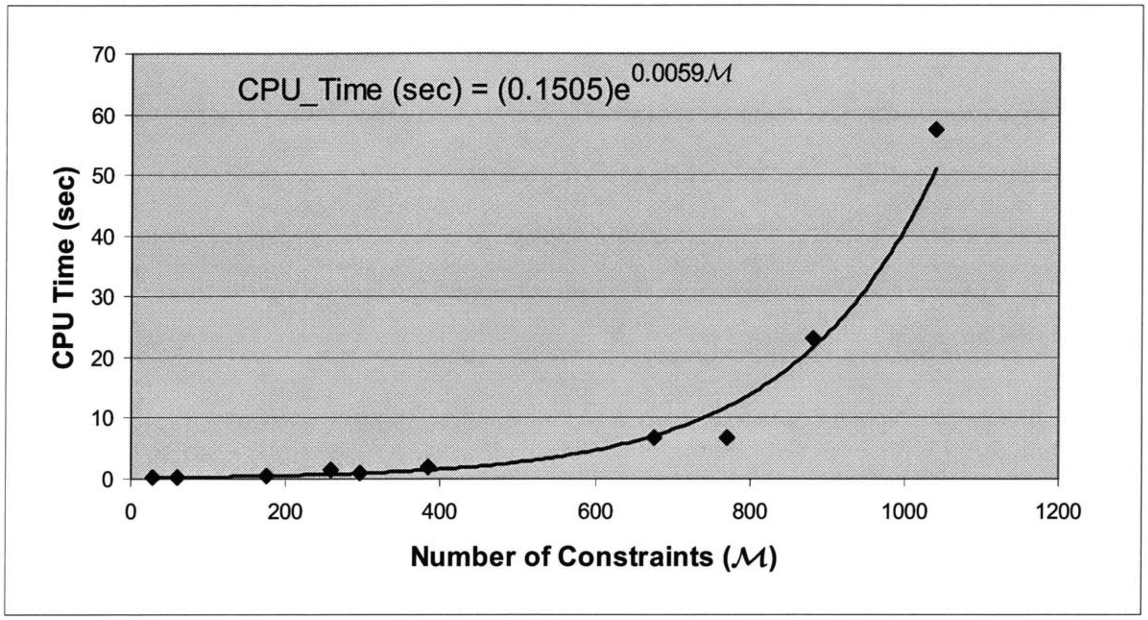

Figure 3-1 Actual EXCEL SOLVER CPU Times for Binary Integer Linear Programming Solutions

3.1.2.2 Lagrangian relaxation

To circumvent the computational obstacle, the PCP can be reformulated in terms of P separate linear programming problems by use of the Lagrangian Relaxation (LR) method[18]. Examination of the PCP constraints reveals that only resource constraint (3.11) couples the individual projects in the BILP formulation. The LR method dualizes constraint (3.11) by including a Lagrange multiplier term in a modified PCP cost function for each of the (M*T) equations comprising constraint (3.11). The method proceeds as follows. Let $\lambda_{m,t}$ be the Lagrange multiplier associated with department m at time t, and add the non-negative term $\lambda_{m,t} * \left(C_m - \sum_{j=1}^{P} \sum_{i=1}^{N_j} \left(X_{j,i,t} - X_{j,i,t-\delta_{j,i}} \right) r_{m,j,i} \right) \forall m,t$ to equation (3.8) to obtain the "LR objective function"

18 Reference: Fisher, Marshall L. "An Applications Oriented Guide to Lagrangian Relaxation." Interfaces 15:2, (March-April 1985): 10-21.

$$\begin{aligned} J_{LR} &= \max\left(\sum_{j=1}^{P}\sum_{i=1}^{N_j}\sum_{t=1}^{T}\left(w_{j,i,t}X_{j,i,t}\right)+\sum_{t=1}^{T}\sum_{m=1}^{M}\left(\lambda_{m,t}\left(C_m-\sum_{j=1}^{P}\sum_{i=1}^{N_j}\left(X_{j,i,t}-X_{j,i,t-\delta_{j,i}}\right)r_{m,j,i}\right)\right)\right) \\ &= \max\sum_{j=1}^{P}\left(\sum_{i=1}^{N_j}\sum_{t=1}^{T}\left(w_{j,i,t}X_{j,i,t}\right)+\sum_{i=1}^{N_j}\sum_{t=1}^{T}\sum_{m=1}^{M}\lambda_{m,t}\left(X_{j,i,t-\delta_{j,i}}-X_{j,i,t}\right)r_{m,j,i}\right)+\sum_{t=1}^{T}\sum_{m=1}^{M}\lambda_{m,t}C_m \end{aligned} \tag{3.15}$$

Substituting the temporary change in index $\tau = t-\delta_{j,i}$, with the understanding that $X_{j,i,\tau} \equiv 0 \ \forall \tau \le 0$, equation (3.15) becomes

$$\begin{aligned} J_{LR} = \max\sum_{j=1}^{P}&\left(\sum_{i=1}^{N_j}\sum_{t=1}^{T}\left(w_{j,i,t}X_{j,i,t}\right)+\sum_{i=1}^{N_j}\sum_{m=1}^{M}\sum_{\tau=1-\delta_{j,i}}^{T-\delta_{j,i}}\lambda_{m,\tau+\delta_{j,i}}\left(X_{j,i,\tau}-X_{j,i,\tau+\delta_{j,i}}\right)r_{m,j,i}\right) \\ &+\sum_{m=1}^{M}\sum_{\tau=1-\delta_{j,i}}^{T-\delta_{j,i}}\lambda_{m,\tau+\delta_{j,i}}C_m \end{aligned} . \tag{3.16}$$

Expanding the summation series over indices m and τ (using the notation $m_1 \equiv 1$, $m_2 \equiv 2$, $\tau_2 \triangleq 2$ for clarity)

$$\sum_{j=1}^{P}\sum_{i=1}^{N_j}\left[\sum_{m=1}^{M}\sum_{\tau=1-\delta_{j,i}}^{T-\delta_{j,i}}\lambda_{m,\tau+\delta_{j,i}}\left(X_{j,i,\tau}-X_{j,i,\tau+\delta_{j,i}}\right)r_{m,j,i}\right]=$$

$$\sum_{j=1}^{P}\sum_{i=1}^{N_j}\left[\begin{array}{l} r_{m_1,j,i}\left(\begin{array}{l}\lambda_{m_1,\tau_1+\delta_{j,i}}\left(X_{j,i,\tau_1}-X_{j,i,\tau_1+\delta_{j,i}}\right)+\lambda_{m_1,\tau_2+\delta_{j,i}}\left(X_{j,i,\tau_2}-X_{j,i,\tau_2+\delta_{j,i}}\right)+\cdots \\ +\lambda_{m_1,\tau_1+2\delta_{j,i}}\left(X_{j,i,\tau_1+\delta_{j,i}}-X_{j,i,\tau_1+2\delta_{j,i}}\right)+\lambda_{m_1,\tau_2+2\delta_{j,i}}\left(X_{j,i,\tau_2+\delta_{j,i}}-X_{j,i,\tau_2+2\delta_{j,i}}\right) \\ +\ldots\end{array}\right) \\ \qquad\qquad\vdots \\ +r_{m_2,j,i}\left(\begin{array}{l}\lambda_{m_2,\tau_1+\delta_{j,i}}\left(X_{j,i,\tau_1}-X_{j,i,\tau_1+\delta_{j,i}}\right)+\lambda_{m_2,\tau_2+\delta_{j,i}}\left(X_{j,i,\tau_2}-X_{j,i,\tau_2+\delta_{j,i}}\right)+\cdots \\ +\lambda_{m_2,\tau_1+2\delta_{j,i}}\left(X_{j,i,\tau_1+\delta_{j,i}}-X_{j,i,\tau_1+2\delta_{j,i}}\right)+\lambda_{m_2,\tau_2+2\delta_{j,i}}\left(X_{j,i,\tau_2+\delta_{j,i}}-X_{j,i,\tau_2+2\delta_{j,i}}\right) \\ +\ldots\end{array}\right) \\ \qquad\qquad\vdots \end{array}\right] \tag{3.17}$$

Regrouping in terms of $\lambda_{m,t}$ instead of $X_{j,i,t}$, the above summations take the form

$$\sum_{j=1}^{P}\sum_{i=1}^{N_j}\left[\begin{array}{l} r_{m_1,j,i}\left(\begin{array}{l}\left(\lambda_{m_1,\tau_1+2\delta_{j,i}}-\lambda_{m_1,\tau_1+\delta_{j,i}}\right)X_{j,i,\tau_1+\delta_{j,i}}+\lambda_{m_1,\tau_1+\delta_{j,i}}X_{j,i,\tau_1}-\lambda_{m_1,\tau_1+2\delta_{j,i}}X_{j,i,\tau_1+2\delta_{j,i}}+\cdots\\ +\left(\lambda_{m_1,\tau_2+2\delta_{j,i}}-\lambda_{m_1,\tau_2+\delta_{j,i}}\right)X_{j,i,\tau_2+\delta_{j,i}}+\lambda_{m_1,\tau_2+\delta_{j,i}}X_{j,i,\tau_2}-\lambda_{m_1,\tau_2+2\delta_{j,i}}X_{j,i,\tau_2+2\delta_{j,i}}\\ +\cdots\end{array}\right)\\ \vdots\\ +r_{m_2,j,i}\left(\begin{array}{l}\left(\lambda_{m_2,\tau_1+2\delta_{j,i}}-\lambda_{m_2,\tau_1+\delta_{j,i}}\right)X_{j,i,\tau_1+\delta_{j,i}}+\lambda_{m_2,\tau_1+\delta_{j,i}}X_{j,i,\tau_1}-\lambda_{m_2,\tau_1+2\delta_{j,i}}X_{j,i,\tau_1+2\delta_{j,i}}+\cdots\\ +\left(\lambda_{m_2,\tau_2+2\delta_{j,i}}-\lambda_{m_2,\tau_2+\delta_{j,i}}\right)X_{j,i,\tau_2+\delta_{j,i}}+\lambda_{m_2,\tau_2+\delta_{j,i}}X_{j,i,\tau_2}-\lambda_{m_2,\tau_2+2\delta_{j,i}}X_{j,i,\tau_2+2\delta_{j,i}}\\ +\cdots\end{array}\right)\\ \vdots\end{array}\right] \quad (3.18)$$

$$=\sum_{j=1}^{P}\sum_{i=1}^{N_j}\sum_{m=1}^{M}\sum_{\tau=1-\delta_{j,i}}^{T-\delta_{j,i}} r_{m,j,i}\left(\lambda_{m,\tau+2\delta_{j,i}}-\lambda_{m,\tau+\delta_{j,i}}\right)X_{j,i,\tau+\delta_{j,i}} \quad (3.19)$$

$$=\sum_{j=1}^{P}\sum_{i=1}^{N_j}\sum_{m=1}^{M}\sum_{t=1}^{T} r_{m,j,i}\left(\lambda_{m,t+\delta_{j,i}}-\lambda_{m,t}\right)X_{j,i,t} \quad (3.20)$$

by using the reverse substitution, $t=\tau+\delta_{j,i}$. Objective function(3.16) can now be written as

$$\begin{aligned} J_{LR}=\max\sum_{j=1}^{P}&\left(\sum_{i=1}^{N_j}\sum_{t=1}^{T}\left(w_{j,i,t}X_{j,i,t}\right)+\sum_{i=1}^{N_j}\sum_{t=1}^{T}\sum_{m=1}^{M}\left(r_{m,j,i}\left(\lambda_{m,t+\delta_{j,i}}-\lambda_{m,t}\right)X_{j,i,t}\right)\right)\\ &+\sum_{t=1}^{T}\sum_{m=1}^{M}\left(\lambda_{m,t}C_m\right)\end{aligned} \quad (3.21)$$

or

$$J_{LR}=\max\sum_{j=1}^{P}\left(\sum_{i=1}^{N_j}\sum_{t=1}^{T}\left(w_{j,i,t}+\sum_{m=1}^{M}r_{m,j,i}\left(\lambda_{m,t+\delta_{j,i}}-\lambda_{m,t}\right)\right)X_{j,i,t}\right)+\sum_{t=1}^{T}\sum_{m=1}^{M}\left(\lambda_{m,t}C_m\right) \quad (3.22)$$

Note that the final double-summation is independent of $X_{j,i,t}$ for any given set of Lagrange multiplier terms $\lambda_{m,t}$. The process of dualizing resource constraint (3.11) has transformed the single PCP optimization problem (equations (3.8) through (3.12)) into the following set of ***P*** parallel-coupled optimization problems that are individually easy to solve:

$$\textbf{PCPj}: J_{LR_j} = \max \sum_{i=1}^{N_j} \sum_{t=1}^{T} \sum_{m=1}^{M} \left(w_{j,i,t} + r_{m,j,i} \left(\lambda_{m,t+\delta_{j,i}} - \lambda_{m,t} \right) \right) X_{j,i,t} \quad \forall j = 1,2,\ldots P \quad (3.23)$$

subject to continuity, precedence and magnitude constraints

(continuity) $X_{j,i,t+1} \geq X_{j,i,t} \qquad 1 \leq i \leq N_j; \quad 1 \leq t \leq T$ (3.24)

(precedence) $X_{j,i,t-\delta_{j,i}} \geq X_{j,k,t} \qquad 1 \leq i \leq N_j;\ 1 \leq t \leq T;\ k \subset S_j(i)$ (3.25)

(Lower bound) $X_{j,i,t} \geq 0 \qquad 1 \leq i \leq N_j; \quad 1 \leq t \leq T$ (3.26)

(Upper bound) $X_{j,i,t} \leq 1 \qquad 1 \leq i \leq N_j; \quad 1 \leq t \leq T$ (3.27)

Note in particular that the binary integer constraint (3.12) has now been replaced by linear upper and lower bound constraints (3.26) and (3.27). This is due to the fact that the PCPj formulation (3.23)-(3.27) constitutes a network flow problem with integer coefficients. Therefore, if a solution does exist to each PCPj sub-problem, then integer values for $X_{j,i,t}$ will automatically be generated with standard SIMPLEX algorithms.

3.1.2.3 Heuristic solutions

The Lagrange Relaxation method above transforms the single NP-Hard PCP optimization into a set of **P** separate PCP_j problems that can be solved quickly (in polynomial time), but at the expense of:

(i) a more complicated and highly coupled LR objective function (3.22) , written in terms of constant but unknown Lagrange multiplier terms $\lambda_{m,t}$; and

(ii) a dualized resource constraint that now appears in objective function (3.22), but which will not necessarily be satisfied in the original form (equation (3.11)).

Addressing each of these concerns leads immediately to heuristic methods. First, an iteration loop is introduced to converge upon satisfactory values of Lagrange multiplier terms $\lambda_{m,t}$.

The method follows directly from Fisher[19]. A second "perturbation loop" is then utilized to adjust the locally-optimal PCP_j solutions such that the original resource constraint (3.11) is satisfied. The net result is a feasible, and often an optimal or near-optimal, solution to the project coordination problem within a reasonable amount of computational time.

3.1.2.3.1 Lagrange Multiplier Iteration Loop

The following iteration loop is used to arrive at suitable, non-negative Lagrange multiplier terms $\lambda_{m,t}$. Let l represent an iteration loop index with $l_{\max}$ designating the maximum desired number of iterations. Let $\lambda^l_{m,t}$ represent the l^{th} iteration for the Lagrange multiplier term $\lambda_{m,t}$. Let $X^l_{j,i,t}$ represent the l^{th} locally-optimal value of $X_{j,i,t}$ found by solving PCP_j (equations (3.23)-(3.27)) for a given set of Lagrange multipliers $\lambda^l_{m,t}$; and let Z^l designate the l^{th} value of LR objective function J_{LR} (3.21) associated with $\lambda^l_{m,t}$ and $X^l_{j,i,t}$. Then

$$Z^l = \sum_{j=1}^{P}\left(\sum_{i=1}^{N_j}\sum_{t=1}^{T}\left(w_{j,i,t} + \sum_{m=1}^{M} r_{m,j,i}\left(\lambda^l_{m,t+\delta_{j,i}} - \lambda^l_{m,t}\right)\right)X^l_{j,i,t}\right) + \sum_{t=1}^{T}\sum_{m=1}^{M}\left(\lambda^l_{m,t}C_m\right) \quad (3.28)$$

Let $v^l_{j,i,t}$ designate the coefficients of $X^l_{j,i,t}$ in (3.28) :

$$v^l_{j,i,t} = w_{j,i,t} + \sum_{m=1}^{M} r_{m,j,i}\left(\lambda^l_{m,t+\delta_{j,i}} - \lambda^l_{m,t}\right). \quad (3.29)$$

Decompose Z^l into components $Z^l = Z^l_C + Z^l_P$ where

$$Z^l_C \triangleq \sum_{t=1}^{T}\sum_{m=1}^{M}\left(\lambda^l_{m,t}C_m\right) \quad (3.30)$$

and

[19] Reference: Fisher, Marshall L. "The Lagrangian Relaxation Method for Solving Integer Programming Problems." Management Science, Vol. 27, No. 1 (Jan. 1981). See also Fisher, Marshall L. "A Multiplier Adjustment Methods for the Generalized Assignment Problem." Management Science, Vol. 32, No. 9 (Sept. 1986).

$$Z_P^l \triangleq \sum_{j=1}^{P}\left(Z_j^l\right)=\sum_{j=1}^{P}\left(\sum_{i=1}^{N_j}\sum_{t=1}^{T}\left(v_{j,i,t}^l\ X_{j,i,t}^l\right)\right) \tag{3.31}$$

Observe that $Z_j^l = J_{LR_j}$, the outcome of successive PCP$_j$ optimization calculations:

$$Z_j^l \triangleq \sum_{i=1}^{N_j}\sum_{t=1}^{T}\left(v_{j,i,t}^l\ X_{j,i,t}^l\right)=\sum_{i=1}^{N_j}\ \sum_{t=1}^{T}\left(w_{j,i,t}+\sum_{m=1}^{M} r_{m,j,i}\left(\lambda_{m,t+\delta_{j,i}}^l-\lambda_{m,t}^l\right)\right)X_{j,i,t}^l\ . \tag{3.32}$$

Finally, let $\overline{Z}$ represent the maximum value found for any Z^l during the iteration loop, with $\overline{X}_{j,i,t}$ designating the corresponding, locally optimal decision variables. Then a suitable set of Lagrange multipliers $\lambda_{m,t}$ can be found using the following iterative algorithm:

Step 1. Initialize parameters

$X_{j,i,t}^l = 0$	$1 \le j \le P;\ 1 \le m \le N_j\ ;\ 1 \le t \le T$	
$\lambda_{m,t}^l = 0$	$1 \le m \le M;\ 1 \le t \le T$	
$\alpha = 1.0$	(arbitrary iteration acceleration factor; typically $0.1<\alpha<20$)	
β=1.2	(arbitrary acceleration derating factor; typically $0<\beta<2$)	
$\mu_l = 0$	(scalar correction factor)	(3.33)
$r = 1$	(scalar convergence counter)	
$r_{\max} = 5$	(typical value for convergence test)	
$l = 1$	(LR iteration loop counter)	
$l_{\max} = 10$	(typical value for maximum number of iterations)	

Step 2. Iterate on l for new values of $\lambda_{m,t}^l$, $X_{j,i,t}^l$ and Z^l:

(a) Update cost coefficients: $v_{j,i,t}^l = w_{j,i,t} + \sum_{m=1}^{M}\left(\lambda_{m,t+\delta_{j,i}}^l - \lambda_{m,t}^l\right) r_{m,j,i}$; (3.34)

(b) For j = 1 to P, solve PCP$_j$ for $X^l_{j,i,t}$ using SIMPLEX for example, and then compute $Z^l_P \triangleq \sum_{j=1}^{P} \left(Z^l_j \right)$,;

(c) Update $Z^l_C \triangleq \sum_{t=1}^{T} \sum_{m=1}^{M} \left(\lambda^l_{m,t} C_m \right)$ and $Z^l = Z^l_C + Z^l_P$; (3.35)

(d) Check for new lower bound:

i. If $Z^l \leq \overline{Z}$ then $\overline{Z} = Z^l$ and r=0 (3.36)

ii. Else, $r = r+1$; if $r > r_{\max}$ then set r=0 and $\alpha = \dfrac{\alpha}{\beta^l}$; (3.37)

(e) Compute resource constraint violations $\gamma^l_{m,t}$:

$$\gamma^l_{m,t} = C_m - \sum_{j=1}^{P} \sum_{i=1}^{N_j} \left(X^l_{j,i,t} - X^l_{j,i,t-\delta_{j,i}} \right) r_{m,j,i} \tag{3.38}$$

(f) Compute scalar correction factor μ^l as follows:

If $\sum_{m=1}^{M} \sum_{t=1}^{T} \left(\gamma^l_{m,t} \right) \neq 0$,

$$\text{then set } \mu^l = \frac{\alpha \left(Z^l - Z^* \right)}{\left(\sum_{m=1}^{M} \sum_{t=1}^{T} \left(\gamma^l_{m,t} \right)^2 \right)} \leq 0 \qquad (\text{since } Z^l \leq Z^*); \tag{3.39}$$

else set $\mu^l = 0$.

(g) Update Lagrange multipliers $\lambda^{l+1}_{m,t} = \max\left(0 \, , \left(\lambda^l_{m,t} - \mu^l \gamma^l_{m,t} \right) \right)$; (3.40)

(h) If $l < l_{\max}$, then increment $l = l+1$ and repeat Step 2; else, exit the Lagrange multiplier iteration loop and set $\overline{J}_{LR_j} = Z^l_j$, $X^*_{j,i,t} = X^l_{j,i,t}$ and $\lambda^*_{m,t} = \lambda^l_{m,t}$.

Fisher has shown that the convergence properties of the above iteration loop yield successively lower bounds for the optimal PCP$_j$ solution. Fisher notes that the selection of the acceleration parameter α is crucial yet arbitrary, and recommends an initial value of $\alpha = 2$ with a constant de-rating factor of $\beta = 2$. However in this application, an exponential derating factor of β^l, with $\beta^0 = 1.2$, has been observed to be much more effective.

Experience with this modification to Fisher's iteration algorithm has shown fast convergence, typically in less than 10 iterations and often in just two or three steps.

3.1.2.3.2 Perturbations to the PCP_j Solution

Since (3.38) - (3.40) tend to increase the magnitude of cost coefficients $v^{l}_{j,i,t}$, the Lagrange Relaxation loop Step 2(a) does penalize violations of resource constraint (3.11). However, the PCP_j formulation only guarantees compliance with constraints (3.9) and (3.10). An additional heuristic algorithm is required to perturb the PCP_j solutions $X^{*}_{j,i,t}$ whenever constraint (3.11) is violated at the completion of the LR iteration loop. This section describes a "brute force" heuristic method to ensure PCP_j compliance with all four constraints, (3.9) through (3.12). Assuming that a given Lagrange Relaxation solution $X^{*}_{j,i,t}$ to a PCP_j problem is "near-optimal" and satisfies the continuity and precedence constraints, the heuristic seeks a "nearby" solution $\tilde{X}_{j,i,t}$ that also satisfies the resource constraints. The method comprises five sequential steps:

Step 1. Assign a non-increasing numerical score $n_{j,i}$ to each project activity $a_{j,i}$ along the directed activity network. Note that this step need only be performed once during the problem initialize stage. A suitable scoring scheme is the inclusive sum of downstream activity durations, or downstream resource requirements, or downstream budgeted costs, etc. For the present purposes, let $n_{j,i} \triangleq \sum_{j=1}^{P}\sum_{i=1}^{N_j}\delta_{j,i} * w_j \quad , \qquad t = 1,2,\ldots T$.

Step 2a Solve the PCP_j problem for $X^{*}_{j,i,t}$ and $\lambda^{*}_{m,t}$.

Step 2b If constraint (3.11) is satisfied, then $X^{*}_{j,i,t}$ is a feasible solution and no further effort is required (i.e., set $\tilde{X}_{j,i,t} \equiv X^{*}_{j,i,t}$); otherwise, remove all "backward schedule slack" as follows:

i) Initially, set $\tilde{X}^*_{j,i,t} \equiv X^*_{j,i,t}$. Compute the activity start times, $s^*_{j,i}$, and finish times, $f^*_{j,i}$ for the Lagrange Relaxation solution $X^*_{j,i,t}$:

$$s^*_{j,i} = \left(T + 1 - \sum_{t=1}^{T} X^*_{j,i,t} \right)$$

$$f^*_{j,i} = \left(T + \delta_{j,i} - \sum_{t=1}^{T} X^*_{j,i,t} \right)$$

ii) Compute the activity "backward slack" times for the Lagrange Relaxation solution:

For $j = 1$ to P
  If $s^*_{j,1} > 1$ then set **backward_slack(*j*, 1)** = $(s^*_{j,1} - 1)$.
  For $i = 2$ to N_j
    Set $T_{prior} = 0$
    For $k = 1$ to $L_{j,i}$ (ie, the number of precedents for $a_{j,i}$)
      Set $m = k \in P_j(i)$ (ie, the kth precedent of $a_{j,i}$)
      If $m > 0$ and $f^*_{j,m} > T_{prior}$ then set $T_{prior} = f^*_{j,m}$
    Next k
  Set **backward_slack(*j*, *i*)** = $\max\left[\left(s^*_{j,i} - T_{prior} - 1\right), 0\right]$
  Next i
Next j

iii) Remove activity "backward slack" times from the Lagrange Relaxation solution:

For $j = 1$ to P
  For $i = 1$ to N_j
  If **backward_slack(*j*, *i*)** >0 then
    For $t = (s^*_{j,i}$ - **backward_slack(*j*, *i*)**) to $s^*_{j,i}$, set $\tilde{X}^*_{j,i,t} = 1$
    Next t
  Next i
Next j

This step is necessary, since the perturbation heuristic will only step forward in time, and can easily miss near-by optimal solutions that allow activities to start at times earlier than those given by $X^{*}_{j,i,t}$.

Step 3a. Assemble the ordered set $A_0(j,i,t,n_{j,i})$ for which $X^{*}_{j,i,t} = 1$;

Step 3b. Let $q_{\max}$ = number of entries in $A_0(j,i,t,n_{j,i})$ and let q be an index for A_0 such that

$\left\{ j_q, i_q, t_q, n_{j_q,i_q} \right\} = A_0(q)$;

Step 4. Sort $A_0(q)$, first according to decreasing n_{j_q,i_q} and then by increasing t_q. For convenience, save results in the re-ordered set $A_1(q) = \left\{ j_q, i_q, t_q, n_{j_q,i_q} \right\}$, initially setting feasible solutions $\tilde{X}_{j,i,t}$ to zero;

Step 5. For $q = 1$ to $q_{\max}$, if $\tilde{X}_{j_q,i_q,t_q} = 0$, then

If the activity finish times for every activity that succeeds a_{j_q,i_q} satisfies

$$\tilde{f}_{j_q,k} < t_q \qquad \forall k \subset S_{j_q}(i_q) \text{, where } \tilde{f}_{j_q,k} = \left(T + \delta_{j_q,k} - \sum_{t=1}^{T} \tilde{X}_{j_q,k,t} \right) \qquad (3.41)$$

$$\text{and if } \sum_{j=1}^{P} \sum_{i=1}^{N_j} \left(\tilde{X}_{j,i,t} - \tilde{X}_{j,i,t-\delta_{j,i}} \right) r_{m,j,i} \le \left(C_m - r_{m,j_q,i_q} \right), \qquad (3.42)$$

$$\text{then set } \tilde{X}_{j_q,i_q,t} = 1 \qquad \forall t:\ t_q \le t \le T \ . \qquad (3.43)$$

Note that in order to start an activity, Step 5 first ensures that precedence constraint (3.10) and resource constraint (3.11) are satisfied, and then enforces the continuity constraint (3.9).

3.2 Illustrative Examples

3.2.1 A Two-Project Example

Consider the example shown in Figure 3.2, comprising $P = 2$ concurrent projects (P_1 and P_2), with four activities per project (i.e., $N_1 = N_2 = 4$), staffed by $M = 2$ line departments. The available capacity of each department is limited to a maximum of 2 resources. The activity networks in the figure convey the precedence relationships, along with activity resource requirements and durations. Note that the topology of project P_1 represents the minimum number of successor relationships for a 4-activity network $\left(\sum_{i=1}^{N_1} \mathcal{K}_{1,i} = (2*N_1 - 3) = (2*4-3) = 5\right)$; the topology of project P_2 represents the maximum number of successor relationships for a 4-activity network $\left(\sum_{i=1}^{N_2} \mathcal{K}_{2,i} = \frac{1}{2}\left(N_2\left(N_2 - 1\right)\right) = \frac{1}{2}\left(4(3)\right) = 6\right)$. As an aside, note that if activity $a_{1,4}$ in project P_1 required zero resources and zero duration, then it would constitute a "dummy" activity to ensure completion of activities $a_{1,2}$ and $a_{1,3}$.

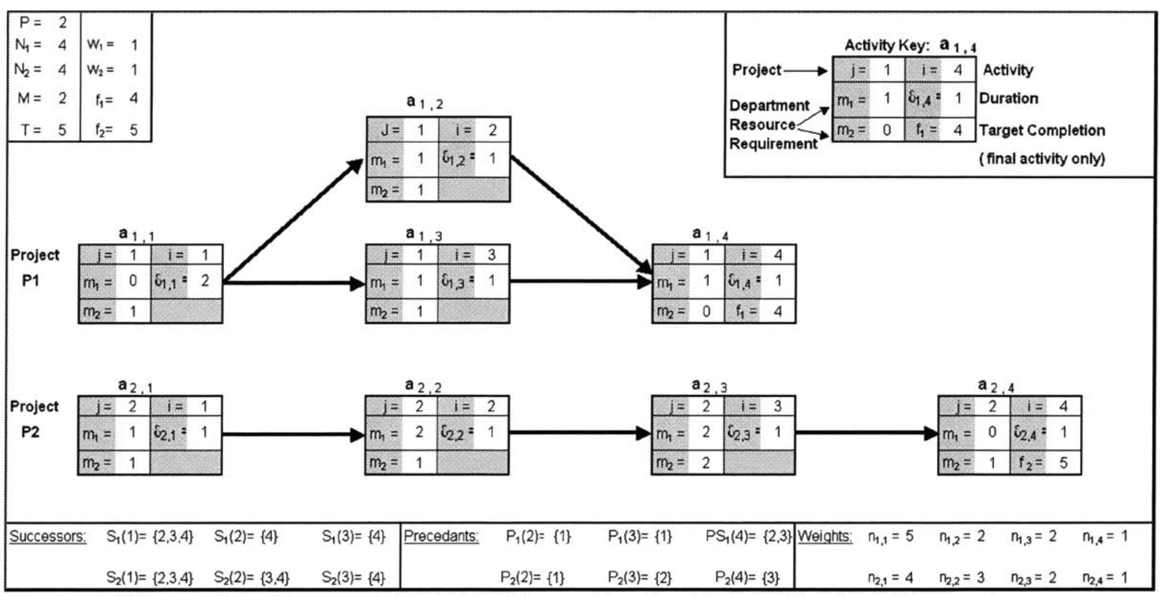

Figure 3-2 Directed Activity Networks for A Two-Project Example

For this example, each department has a maximum resource capacity of 2. Setting the time horizon to $T = 5$, the optimal BILP solution for the PCP formulation (equations (3.8) through

(3.12)) obtained with Excel Solver yields an objective function value of $J_{PCP} = 2$, corresponding to a total penalty cost of $J_C = 5$ (equation(3.6)). Figure 3-3 illustrates the resultant project activity schedule, and Figure 3-4 illustrates the resultant resource utilization, as determined by the optimal BILP solution. The triangular "milestone markers" in Figure 3-3 indicate the targeted completion time period for each project.

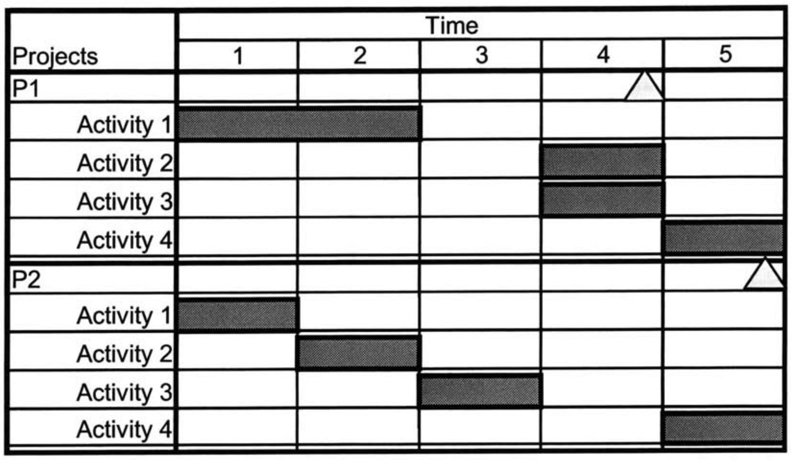

Figure 3-3 Project Activity Gantt Schedule for BILP Solution

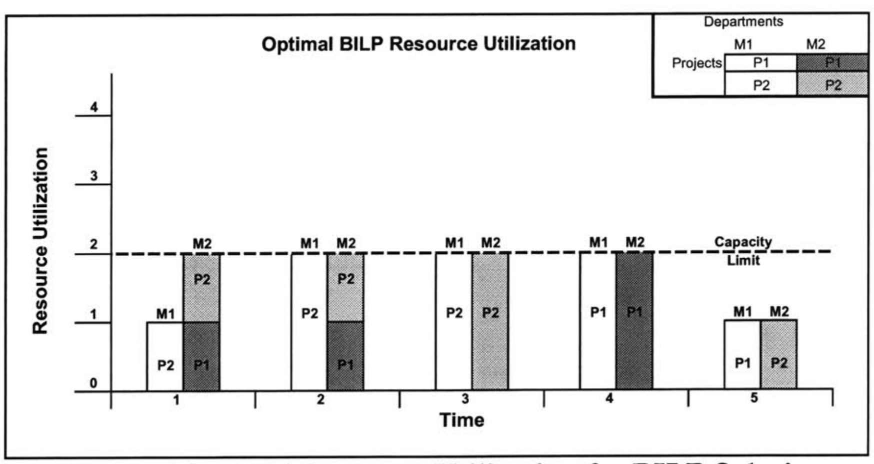

Figure 3-4 Optimal Resource Utilization for BILP Solution

These optimal BILP results will be compared to PCP_j results for various values of the acceleration factors α, both with and without the heuristic perturbation loop. Figure 3-5 shows the activity schedule, and Figure 3-6 the corresponding resource utilization, obtained from the Lagrange Relaxation solution to the PCP_j formulation after 20 iterations, with $\alpha = 1.0$ and without using the perturbation heuristic. Clearly, this solution is infeasible, since the resource utilization for both departments is 100% over-subscribed at t = 4. The difference between the optimal BILP solution and this LR solution is the start time for activity 3 in project 2. Note that this LR solution produces "backward slack" of one time unit for activities $a_{1,2}, a_{1,3}$, and $a_{2,3}$; removing the "backward slack" for $a_{2,3}$ renders the optimal BILP solution.

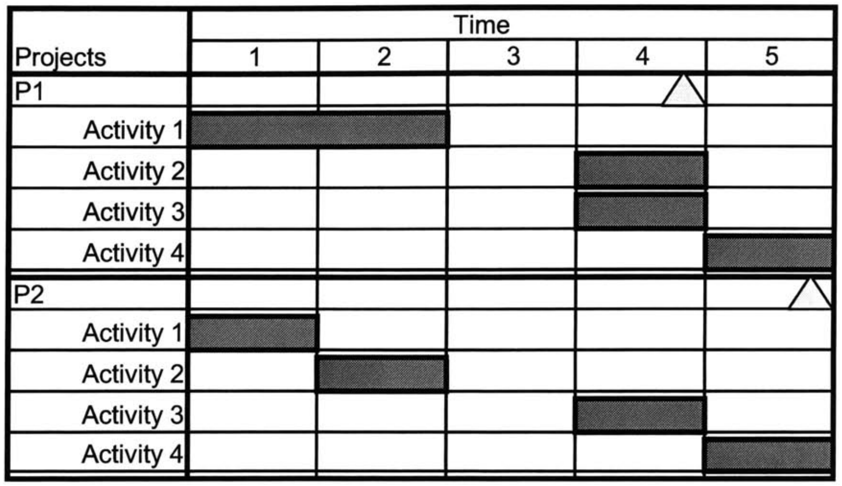

Figure 3-5 Infeasible Project Activity Schedule for α = 1

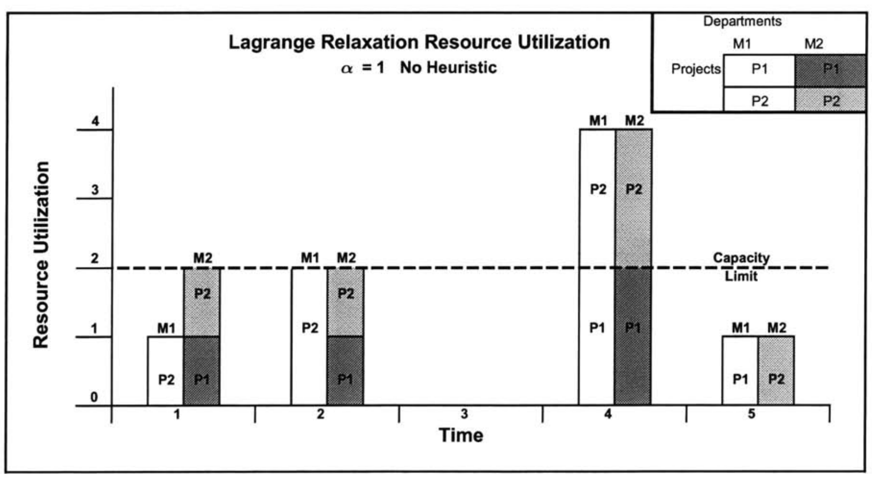

Figure 3-6 Infeasible Project Resource Utilization for α=1

Now, for this particular example, the perturbation heuristic applied to the LR solution after 20 iterations with α = 1.0 yields the feasible solution shown in Figure 3-7 and Figure 3-8. Since the project completion times in Figure 3-3 and Figure 3-7 are identical, the resultant objective function $J_C = 5$ is identical to that obtained with the BILP solution. The perturbation heuristic applied to the LR solution in this case thus yields an alternative, optimal solution.

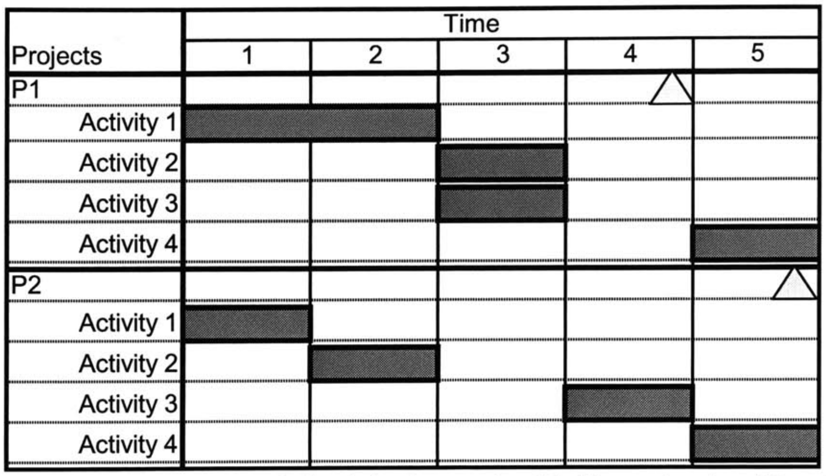

Figure 3-7 Feasible Activity Schedule for α=1 with Perturbation Heuristic

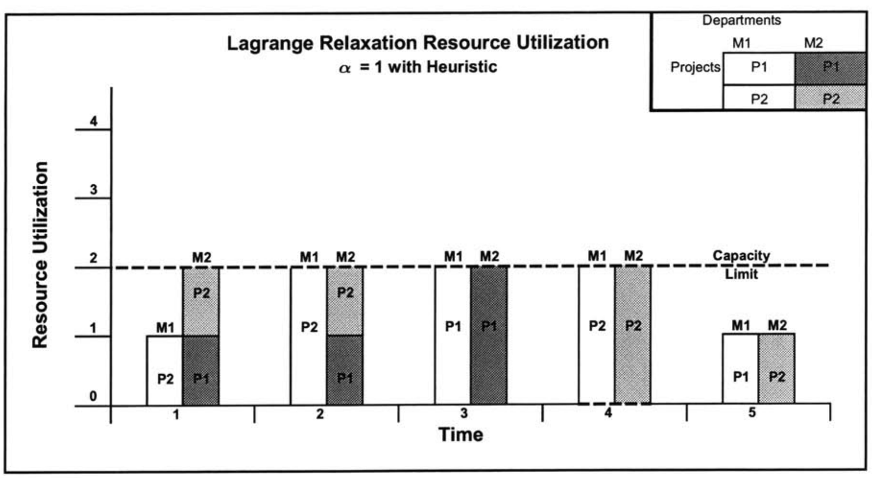

Figure 3-8 Feasible Resource Utilization for α=1 with Perturbation Heuristic

Figure 3-9 shows the convergence behavior of cost functions J_{PCP} and J_{LR} versus iteration number with $\alpha = 1$, along with the number of violations of constraint (3.11), for this example problem. During iterations 8 through 11, it can be seen that, in striving to meet constraint (3.11), neither project completes ($J_{PCP} = 0$). The cost function discontinuities in Figure 3.7

can be attributed to the convergence behavior of the Lagrange multipliers, as demonstrated by $\lambda_{1,3}$ and $\lambda_{1,4}$ in Figure 3-10.

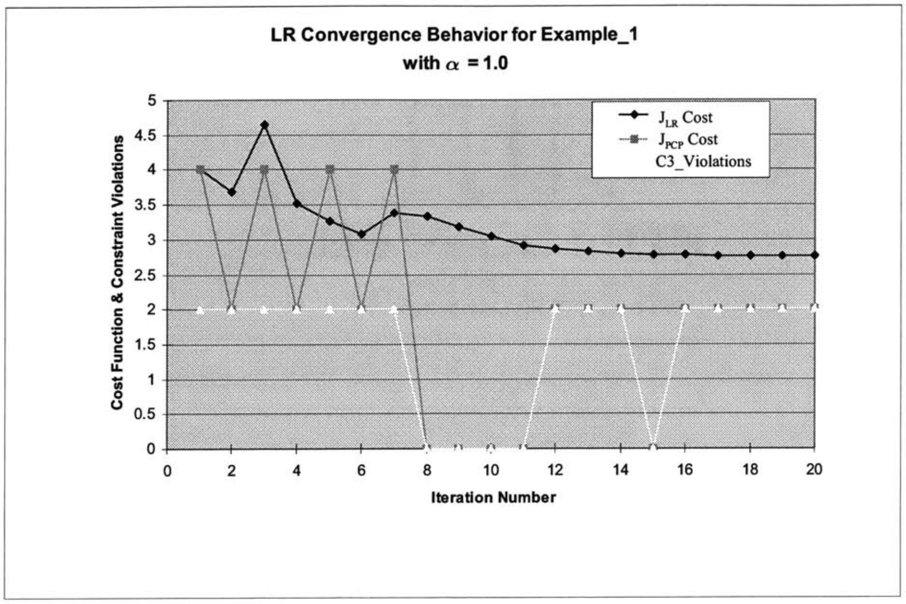

Figure 3-9 Convergence of Cost Function and Constraint Violations for $\alpha = 1$

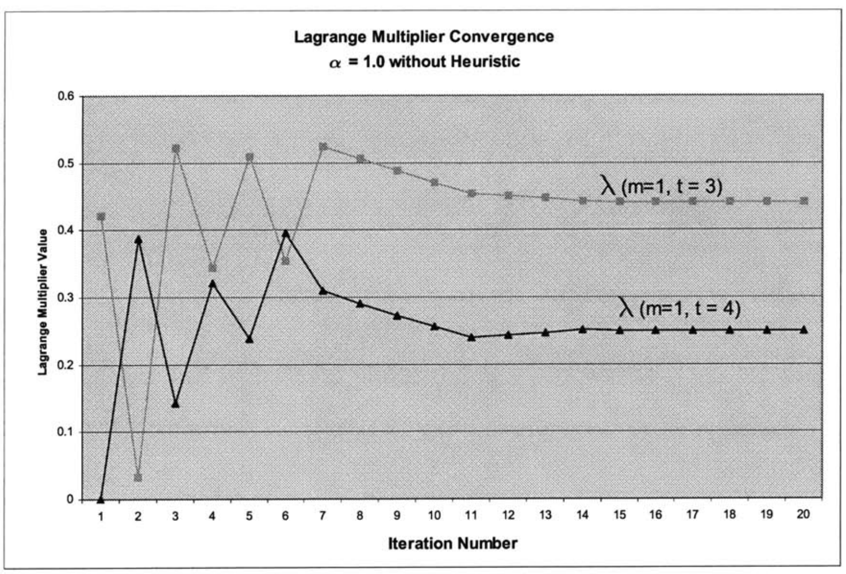

Figure 3-10 Lagrange Multiplier Convergence for $\alpha = 1$

For this particular example, the LR convergence behavior is strongly influenced by the selection of α. For comparison, the cost function behavior with α=0.5 is shown in Figure 3-11, and the cost function behavior with α=3.0 is shown in Figure 3-12. With α=0.5, the Lagrange multipliers, and the resultant decision variables and cost functions, exhibit small variations about the initial values. With α=3.0, the Lagrange multipliers, and resultant cost functions, exhibit large amplitude variations about the initial value, driving the steady-state solution to $X^*_{j,i,t} = 0$. Experience with multiple example problems has shown that the LR sensitivity to α is closely related to the ratio of the number of decision variables $\mathcal{N}$ to the initial number of constraint (3.11) violations. This ratio is an indirect measure of the degree of "tightness" of constraint (3.11). The following empirical relationship has been shown by example to determine an effective initial value of α, after the first iteration loop has been completed. Let γ_0 equal to the number of violations to constraint (3.11) after the first iteration loop; then set $\alpha = \frac{\mathcal{N}^{1/3}}{\gamma_0}$. (3.44).

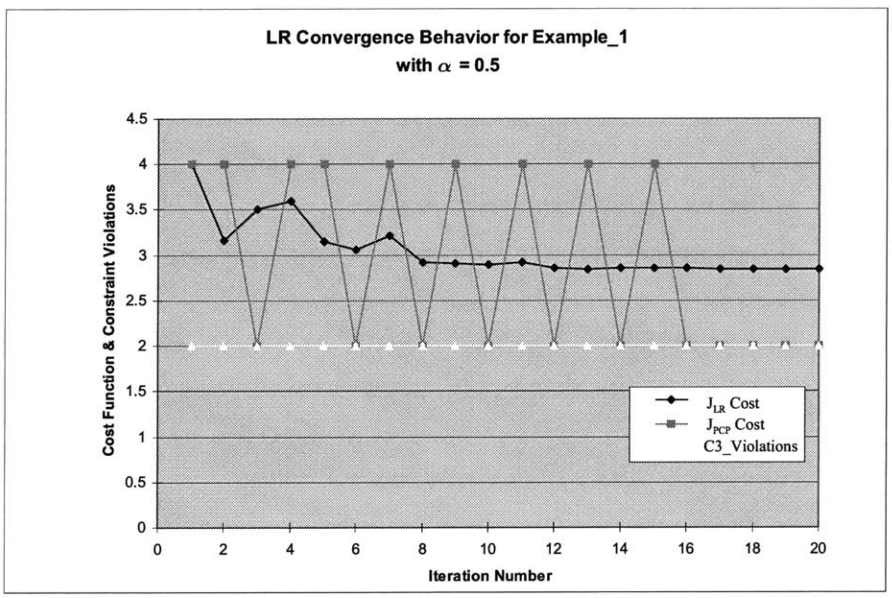

Figure 3-11 Lagrange Relaxation Convergence Behavior with α = 0.5

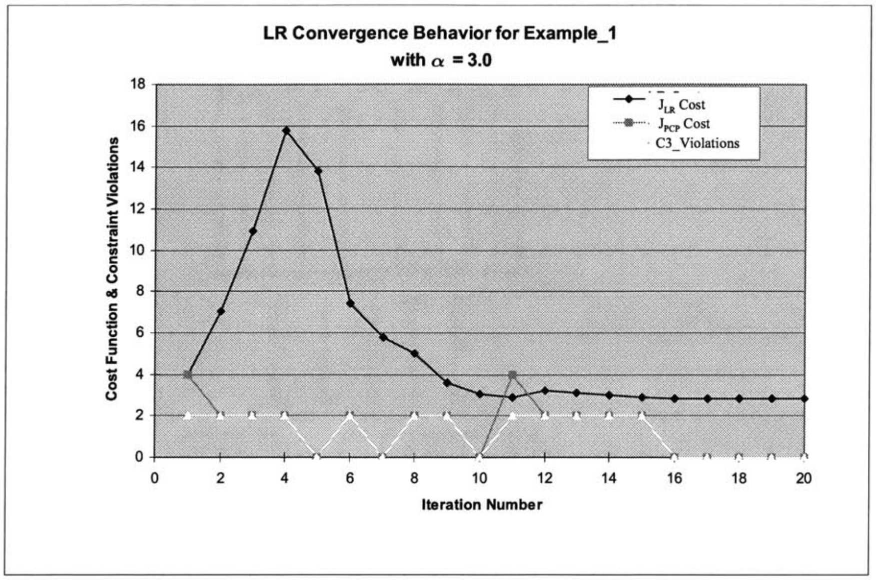

Figure 3-12 Lagrange Relaxation Convergence Behavior with α = 3.0

3.2.2 Computational Results

The 10-problem example set used to generate Table 3-1 and Figure 3-1 was also used to assess the computational burden for two variations of the Lagrange Relaxation and Perturbation Heuristic method. The first variation (designated LR#1):

(a) uses equation (3.44) to determine the value of the LR acceleration factor α;

(b) terminates the Lagrange Relaxation loop either after 20 iterations or when successive values of the cost function J_{PCP} converge within 2.5% of each other;

(c) then implements the perturbation heuristic as described in Section 3.1.2.3.2.

The second method (designated LR#2):

(a) also establishes α using equation (3.44),

(b) but terminates the Lagrange Relaxation loop after exactly 4 iterations;

(c) and then implements the perturbation heuristic.

Results are provided in Table 3-2 as an extension of Table 3-1. Figure 3-13 plots CPU times for the BILP, LR#1 and LR#2 solutions versus the number of constraints $\mathcal{M}$. The data suggest that the Lagrange Relaxation solution methods are nearly linear functions of the number of constraints, whereas the BILP solutions are clearly non-linear and non-polynomial functions of $\mathcal{M}$. For this set of data, the slopes of the LR#1 and LR#2 linear curve fits are determined largely by the Excel SOLVER numerical pre-conditioning algorithms. In practice, far superior results will be obtained by tailoring linear programming network flow solution methods to the PCP_j formulation, resulting in a substantial reduction in pre-conditioning time.

Case	N_Projects P	M_dept M	N_activity Nj	Tmax T	Successors $\mathcal{K}$	$\mathcal{N}$	$\mathcal{M}$	BILP Solution Time	LR#1 Solution Time	LR#2 Solution Time
1	2	2	2	4	2	16	28	0.1	1.3	0.7
2	2	2	2	8	2	32	60	0.2	1.8	1.2
3	2	2	4	8	11	64	176	0.5	6.9	2.1
4	3	4	4	10	11	120	258	1.4	10.2	4.6
5	4	2	4	8	21	128	296	1.0	17.1	5.1
6	5	4	4	9	21	180	385	2.0	20.1	8.3
7	2	2	12	7	74	168	676	6.8	24.7	10.8
8	2	3	10	10	56	200	770	6.7	45.2	17.6
9	2	2	9	10	70	180	882	23.1	52.0	15.8
10	2	2	10	10	84	200	1040	57.6	52.3	20.9

Table 3-2 Computational Burden for the BILP, LR#1 and LR#2 Methods

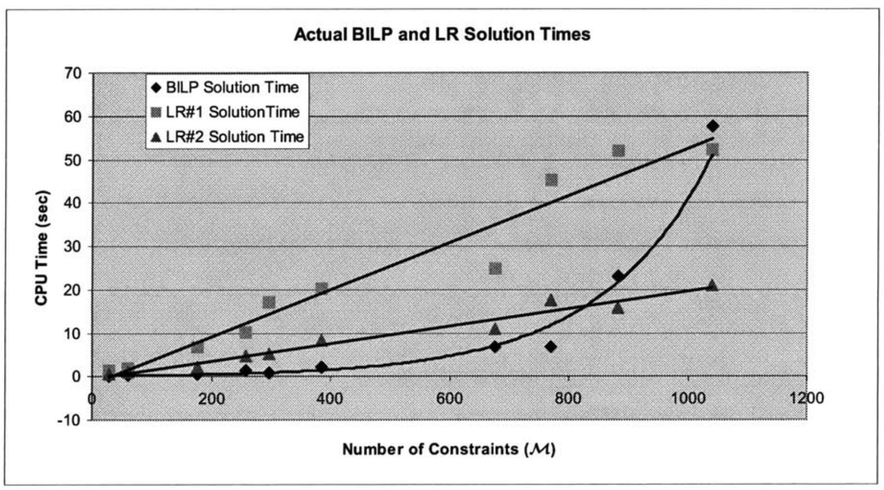

Figure 3-13 Curve Fit Comparison of BILP, LR#1 and LR#2 CPU Times

For this set of problems, the accuracy of the Lagrange Relaxation methods is adequate, but not particularly impressive. Figure 3-14 provides a side-by-side comparison of the J_{PCP} cost function results, as a percentage of the optimal BILP cost function value, for the LR#1 and LR#2 methods. Overall, the LR#1 method averaged 85.3% of the BILP cost function value, whereas the LR#2 method only achieved an accuracy of 70.5%. It must be noted, however, that this set of example problems were contrived to represent "near-worst-case conditions" with very tight constraint bounds. Under less severe conditions, the accuracy and computation effort of either method is much improved.

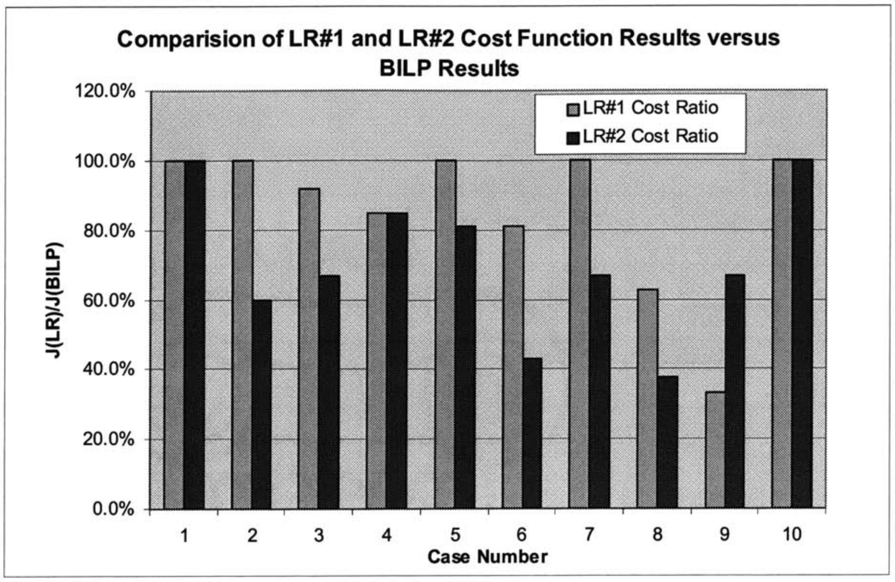

Figure 3-14 Comparison of LR#1 and LR#2 Solution Accuracies as a Percentage of BILP Cost Function Values

3.3 Extensions

3.3.1 Activity Start, Finish and Continuity Constraints

In practice, it is often necessary to prescribe minimum acceptable project start times, maximum acceptable project completion times, or a maximum acceptable time interval between project phases. Each of these additional constraints apply to individual projects. As shown below, it is easy to accommodate these additional requirements in the PCP_j formulation. However, doing so may invalidate the standard network flow construction for PCP_j, such that the integrality constraint (3.12) must be used in lieu of (3.26) and (3.27).

To prescribe project start times, $s_j = \left(T + 1 - \sum_{t=1}^{T} X_{j,1,t} \right) \geq \hat{s}_j$, where $\hat{s}_j$ is a minimum acceptable project start time, impose the condition

$$\sum_{t=1}^{T} X_{j,1,t} \leq \left(T + 1 - \hat{s}_j \right). \tag{3.45}$$

For maximum acceptable project completion times, $f_j = \left(T + \delta_{j,N_j} - \sum_{t=1}^{T} X_{j,N_j,t} \right) \leq \hat{f}_j$ impose the constraint

$$\sum_{t=1}^{T} X_{j,N_j,t} \geq \left(T + \delta_{j,N_j} - \hat{f}_j\right). \qquad (3.46)$$

Finally, to impose a maximum acceptable time interval, $\xi_{\max}$, between successive project activities, require $\Delta\tau_{j,\rho} \triangleq \left(s_{j,\rho} - f_{j,k}\right) \leq \xi_{\max} \quad \forall k \subset P_j(\rho)$ (3.47)

where $k \subset P_j(\rho)$ designates the set of activities *k* which immediately precede activity $a_{j,\rho}$.

3.3.2 Time-Varying Resource Limits

The previous formulation of the PCP and PCP_j problems assumed that line department resource limits C_m were constant over time. However, when using the Project Coordination Problem from a strategic planning perspective, it is essential to accommodate time-varying resource limits. This is easily done by introducing a modified line department resource limit parameter, $C_{m,t}$, in constraint (3.11):

$$\sum_{j=1}^{P}\sum_{i=1}^{N_j}\left(X_{j,i,t} - X_{j,i,t-\delta_{j,i}}\right) r_{m,j,i} \leq C_{m,t}\,, \qquad 1 \leq m \leq M;\, 1 \leq t \leq T \qquad (3.48)$$

3.3.3 Project Selection Problem

The optimal BILP solution to over-constrained Project Coordination Problems will set decision variables $X_{j,\rho,t} = 0$, $\forall \rho \geq k$ for the lowest priority projects (smallest w_j) which demand excessive resources for activity k. In these instances, the BILP PCP solution often starts activities that precede activity k (i.e., sets $X_{j,\zeta,t} = 1$, $\zeta < k$) even though the project "does not complete". Formal proof of this observation is beyond the scope of this thesis.

To avoid this inconsistency, consider a modified objective function J_S which captures the net earned value for project *j* only if the project completion time $f_j \leq T$. Here, the net earned value for project *j* is defined as the earned value[20], e_j, less the cost of all resources consumed

[20] Earned value is a cumulative performance measure frequently used in government development projects, and equates roughly to the sale price for a completed service or delivered product. Here, the earned value for a

and less the penalty cost for late completion. Let ϕ_m designate the cost incurred per unit of time t for use of department m resources. The objective function J_S can then be written as:

$$J_S = \max\left(\sum_{j=1,P} \left(e_j * X_{j,N_j,T}\right) - \sum_{j=1}^{P}\sum_{i=1}^{N_j}\sum_{m=1}^{M} \left(X_{j,i,T} * r_{m,j,i} * \delta_{j,i} * \phi_m\right) - \sum_{j=1}^{P} w_j \left(f_j - \hat{f}_j\right)\right) \quad (3.49)$$

Cost function (3.49) takes advantage of the observation that, by virtue of continuity constraint (3.9),

$$\sum_{t=1}^{T}\left(X_{j,i,t} - X_{j,i,t-\delta_{j,i}}\right) r_{m,j,i} = X_{j,i,T} * r_{m,j,i} * \delta_{j,i} \quad (3.50)$$

Let $F_{j,i} \triangleq \sum_{m=1}^{M}\left(r_{m,j,i} * \delta_{j,i} * \phi_m\right)$ represent the cost coefficient for activity i on project j; substitution into (3.49) yields,

$$J_S = \max \sum_{j=1}^{P}\left(e_j * X_{j,N_j,T} - \sum_{i=1}^{N_j}\left(X_{j,i,T} * F_{j,i}\right) + \sum_{t=1}^{T} w_j * X_{j,N_j,t} \right) - \sum_{j=1}^{P} w_j \gamma_j \quad (3.51)$$

with $\gamma_j \triangleq \left(T + \delta_{j,N_j} - f_j\right)$ as in equation (3.5). Ignoring the last summation as a constant term, and defining cost coefficient $u_{j,i,t}$ as

$$u_{j,i,t} = \begin{cases} e_j - F_{j,i} + w_j & \text{if } i = N_j \text{ and } t = T \\ -F_{j,i} & \text{if } i \neq N_j \text{ and } t = T \\ w_j & \text{if } i \neq N_j \text{ and } t \neq T \end{cases} \quad (3.52)$$

the Project Selection Problem (**PSP**) BILP formulation is given by:

PSP:

$$J_{PSP} = \max \sum_{j=1}^{P}\sum_{i=1}^{N_j}\sum_{t=1}^{T}\left(u_{j,i,t}\ X_{j,i,t}\right) \quad (3.53)$$

subject to the constraints

---

completed project, e_{V_j}, is equated to the Budgeted Cost of Work Scheduled (BCWS) for the entire project. Reference: NASA Policy Directive NPD 9501.3A, Earned Value Management at http://evm.nasa.gov.

(continuity) $$X_{j,i,t+1} \geq X_{j,i,t} \qquad 1 \leq j \leq P;\ 1 \leq i \leq N_j;\ 1 \leq t \leq T \tag{3.54}$$

(successors) $$X_{j,i,t-\delta_{j,i}} \geq X_{j,k,t} \qquad 1 \leq j \leq P\ ;\ 1 \leq i \leq N_j\ ;\ 1 \leq t \leq T; k \subset S_j(i) \tag{3.55}$$

(resources) $$\sum_{j,i} \left(X_{j,i,t} - X_{j,i,t-\delta_{j,i}} \right) r_{m,j,i} \leq C_{m,t} \qquad 1 \leq m \leq M; 1 \leq t \leq T \tag{3.56}$$

(start time) $$\sum_{t=1}^{T} X_{j,1,t} \leq \left(T + 1 - \hat{s}_j \right) \tag{3.57}$$

(binary) $$X_{j,i,t} \in (0,1) \quad 1 \leq j \leq P;\ 1 \leq i \leq N_j;\ 1 \leq t \leq T \tag{3.58}$$

For low order problems, global optimum solutions to the PSP can be readily obtained using convention Binary Integer Programming (BIP) algorithms, such as that provided by Excel SOLVER. In these instances, project activities are activated only for those projects selected for completion. However, the set of constraints for the PSP increase the computational burden beyond that required for the PCP. This significantly limits the use of the PSP in practical applications. Moreover, experience with the Lagrange relaxation method on high-order PSP examples has provided inconsistent project selection results, in which projects are often "started" but fail to "complete". Therefore, an alternative, low-order BIP approach is required to provide the project selection capability needed within SEMPRO.

3.3.4 An Aggregate Project Selection Problem (APSP)

This section describes an alternative approach for the Project Selection Problem that significantly reduces the BILP computational burden by treating each project as a contiguous, aggregate activity with time varying resource requirements. The method will be developed in reference to the example problem shown in Figure 3-15. This is a variation of the two-project example described in Section 3.2.1, but here with only three activities required for project P1. The critical path duration for project P1 is $\overline{\delta}_1 = 3$, and for project P2 is $\overline{\delta}_2 = 4$. For a time horizon of T = 5, the requirement to execute each project contiguously once it has started implies only 3 feasible start times for project P1 ($s_1 = 1, 2$ or 3) and only 2 feasible start times for project P2 ($s_2 = 1$ or 2).

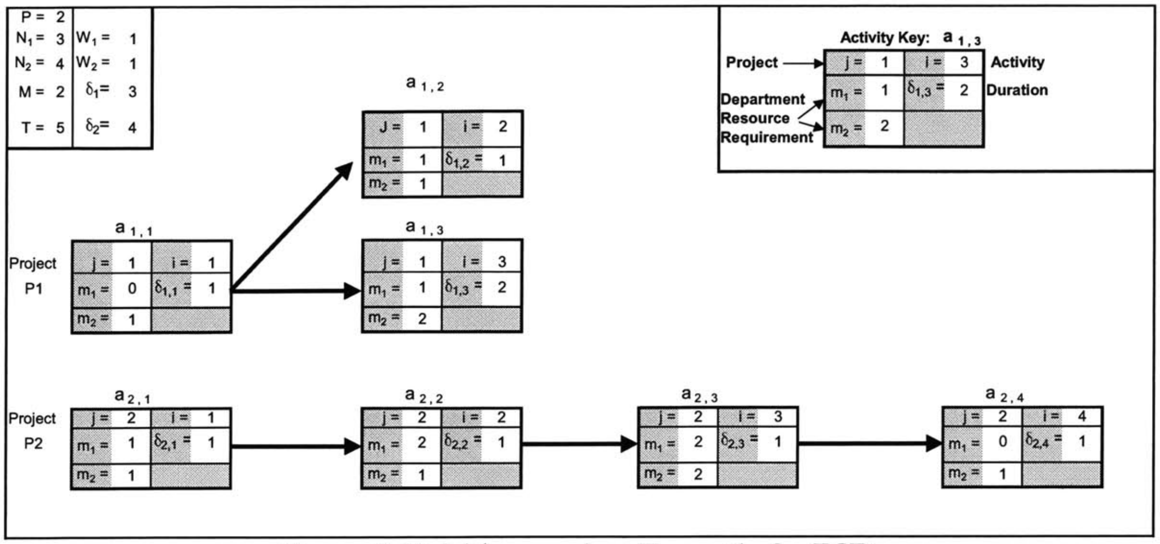

Figure 3-15 A Two-project Example for PSP

Recall that $\overline{\delta}_j$, j = 1,2,…P; designates the time duration for the critical path of project *j*, and $t = 1,2,\ldots T$ represents the planning time horizon with uniform time increments. Consider the following definitions of decision variables and design parameters. Let:

$\hat{\Gamma}_j \triangleq (\text{T-}\overline{\delta}_j + 1)$, j = 1,2,…P; designate the total slack time for project j; this requires a priori decisions on the utilization of individual activity slack times.

τ =1,2,…$\hat{\Gamma}_j$; designate a dummy time index variable;

$\hat{r}_{m,j,\tau}$, m=1,2,…M; j = 1,2,…P; τ = 1,2,…$\hat{\Gamma}_j$; designate resource requirements from department *m* during the τ^{th} time interval after project *j* has started;

$\hat{X}_{j,\tau}$, j = 1,2,…P; τ=1,2,…$\hat{\Gamma}_j$ designate the APSP decision variables such that $\hat{X}_{j,\tau} = 1$ if project j is active at or before time τ; and $\hat{X}_{j,\tau} = 0$ otherwise.

The dimensionality of the APSP decision variables is thus

$$\hat{\mathcal{N}} = \sum_{j=1}^{P} \hat{\Gamma}_j \tag{3.59}$$

instead of that given by equation (3.13).

Consider the case in which both projects arbitrarily start at time $t = \tau$. Then the associated time-varying resource constraint can be written as:

$$\sum_{j=1}^{P}\left(X_{j,t}\right)r_{m,j,\,t-\tau+1} \le C_{m,t} \quad \forall \;\; m=1,2,\ldots M;\;\; t=1,2,\ldots T \tag{3.60}$$

Now, to accommodate all feasible project start times, let the dummy time index τ vary from 1 to $\hat{\Gamma}_j$. Then constraint (3.60) takes the form:

$$\sum_{j=1}^{P}\sum_{\tau=t}^{\hat{\Gamma}_j}\left(\hat{X}_{j,t-\tau+1} - \hat{X}_{j,t-\tau}\right)\hat{r}_{m,j,\tau} \le C_{m,t} \quad \forall \;\; m=1,2,\ldots M;\;\; t=1,2,\ldots T \;. \tag{3.61}$$

Re-arranging equation (3.61) by collecting terms associated with $\hat{X}_{j,\tau}$, the constraint becomes

$$\sum_{j=1}^{P}\sum_{\tau=1}^{\hat{\Gamma}_j}\left(\hat{r}_{m,j,t} - \hat{r}_{m,j,t-\tau}\right)\hat{X}_{j,\tau} \le C_{m,t} \quad \forall \;\; m=1,2,\ldots M;\;\; t=1,2,\ldots T \tag{3.62}$$

where, by definition, $$\hat{r}_{m,j,\tau} \triangleq 0 \text{ if } \tau > \overline{\delta}_j \;. \tag{3.63}$$

For illustrative purposes, constraint (3.62) for the example problem takes the matrix form

$$\begin{bmatrix} C_{m,1} \\ C_{m,2} \\ C_{m,3} \\ C_{m,4} \\ C_{m,5} \end{bmatrix} \geq \begin{bmatrix} \hat{r}_{m,1,1} & 0 & 0 \\ \hat{r}_{m,1,2} - \hat{r}_{m,1,1} & \hat{r}_{m,1,1} & 0 \\ \hat{r}_{m,1,3} - \hat{r}_{m,1,2} & \hat{r}_{m,1,2} - \hat{r}_{m,1,1} & \hat{r}_{m,1,1} \\ -\hat{r}_{m,1,3} & \hat{r}_{m,1,3} - \hat{r}_{m,1,2} & \hat{r}_{m,1,2} \\ 0 & -\hat{r}_{m,1,3} & \hat{r}_{m,1,3} \end{bmatrix} \begin{bmatrix} \hat{X}_{1,1} \\ \hat{X}_{1,2} \\ \hat{X}_{1,3} \end{bmatrix}$$

$$+ \begin{bmatrix} \hat{r}_{m,2,1} & 0 \\ \hat{r}_{m,2,2} - \hat{r}_{m,2,1} & \hat{r}_{m,2,1} \\ \hat{r}_{m,2,3} - \hat{r}_{m,2,2} & \hat{r}_{m,2,2} \\ \hat{r}_{m,2,4} - \hat{r}_{m,2,4} & \hat{r}_{m,2,3} \\ -\hat{r}_{m,2,4} & \hat{r}_{m,2,4} \end{bmatrix} \begin{bmatrix} \hat{X}_{2,1} \\ \hat{X}_{2,2} \end{bmatrix} \tag{3.64}$$

Note also that the associated slack times are given by $\hat{\Gamma}_1 = 3$ and $\hat{\Gamma}_2 = 2$ such that the dimensionality of the APSP decision variables is given by $\hat{\mathcal{N}} = \sum_{j=1}^{P} \hat{\Gamma}_j = 5$; the corresponding dimensionality for the PSP is given by $\mathcal{N} = T * \sum_{j=1}^{P} N_j = 35$.

Redefining the PSP cost coefficients for the APSP formulation, let

$$\hat{u}_{j,\tau} = \begin{cases} 0 & \text{if } \tau < \hat{\Gamma}_j \\ e_j - \hat{F}_j + w_j & \text{if } \tau = \hat{\Gamma}_j \end{cases} \tag{3.65}$$

where
$$\hat{F}_j \triangleq \sum_{m=1}^{M} \sum_{\tau=1}^{\hat{\Gamma}_j} \left(\hat{r}_{m,j,\tau} * \phi_m \right) .$$

The Aggregate Project Selection Problem (APSP) binary integer linear programming formulation can now be written as:

APSP:
$$J_{APSP} = \max \sum_{j=1}^{P} \sum_{\tau=1}^{\hat{\Gamma}_j} \left(\hat{u}_{j,\tau} \ \hat{X}_{j,\tau} \right) \tag{3.66}$$

subject to the constraints

(continuity) $$\hat{X}_{j,\tau+1} \geq \hat{X}_{j,\tau} \quad 1 \leq j \leq P; \;\; 1 \leq \tau \leq \hat{\Gamma}_j \tag{3.67}$$

(start time) $$\sum_{\tau=1}^{\hat{\Gamma}_j} \hat{X}_{j,\tau} \leq \left(T+1-\hat{s}_j\right) \tag{3.68}$$

(resources) $$\sum_{j=1}^{P} \sum_{\tau=1}^{\hat{\Gamma}_j} \left(\hat{r}_{m,j,t} - \hat{r}_{m,j,t-\tau}\right) \hat{X}_{j,\tau} \leq C_{m,t} \quad \forall \;\; m = 1,2,\ldots M; \;\; t = 1,2,\ldots T \tag{3.69}$$

(binary) $$\hat{X}_{j,\tau} \in (0,1) \quad 1 \leq j \leq P; \;\; 1 \leq \tau \leq \hat{\Gamma}_j \tag{3.70}$$

For the above example problem, with the following time-dependent capacity limits,

Department Capacity	Time				
	1	2	3	4	5
M1	2	2	2	3	3
M2	2	2	3	4	4

the optimal BILP solution is to start project P1at t = 3, and start project P2 at t= 1. Section 5.5 illustrates an APSP application for a candidate project portfolio comprising 18-projects over a 10 year time horizon.

4 SEMPRO: An Operational Model for DFRC Project Portfolio Management

This section provides a functional description of the SEMPRO program structure, with particular emphasis on the discrete event simulation elements. The presentation is not intended as a software requirements document or users manual, but does pertain directly to the SEMPRO prototype version as implemented in the Microsoft Excel Visual Basic Application (VBA) programming language. While the SEMPRO input and output data structure is capable of supporting a wide range of functional capabilities, this section only covers those features incorporated in the prototype version at the time of this writing. Potential enhancements and follow-on developments are discussed in subsequent sections.

4.1 SEMPRO Overview

4.1.1 Model purpose and description

The primary functions of the SEMPRO prototype are to:

(a) Load project attribute information from a candidate project portfolio database;

(b) Generate resource-loaded WBS Level 2/3 activity networks for each project in the portfolio;

(c) Select a feasible sub-set of executable projects using the APSP algorithm;

(d) Determine a feasible time-phased execution sequence of WBS Level 2 activities using the PCP_j algorithm;

(e) Validate the project activity execution sequence generated by the PCP_j algorithm against WBS Level 3 task flow, using a non-linear, stochastic, discrete event simulation model of the research center's project management and implementation processes;

(f) Generate graphical outputs of APSP, PCP_j and simulation results.

4.1.2 SEMPRO System Architecture

Figure 4-1 illustrates the overall framework used to develop the SEMPRO system architecture. The left side of the figure captures the project attribute, selection and coordination elements, as described in Sections 2.0 and 3.0. Elements in the center of the figure represent the primary functional modules comprising the SEMPRO discrete event simulation capability. The output of the Project Coordination Problem (PCP) module, along with the project WBS database and the Executive Management decision rules, are the primary inputs to the simulation module. The main simulation objects are the individual projects, individual project tasks, individual line organizations (branches), and overall center management objects. Figure 4-2 conveys the software program structure used to implement the SEMPRO system architecture. The remainder of this section provides detail on each of these structural elements, with the exception of the SEMPRO Main Executive, data declaration and the utilities modules. These latter modules deal mainly with Excel VBA programming details and are of little interest in the present context.

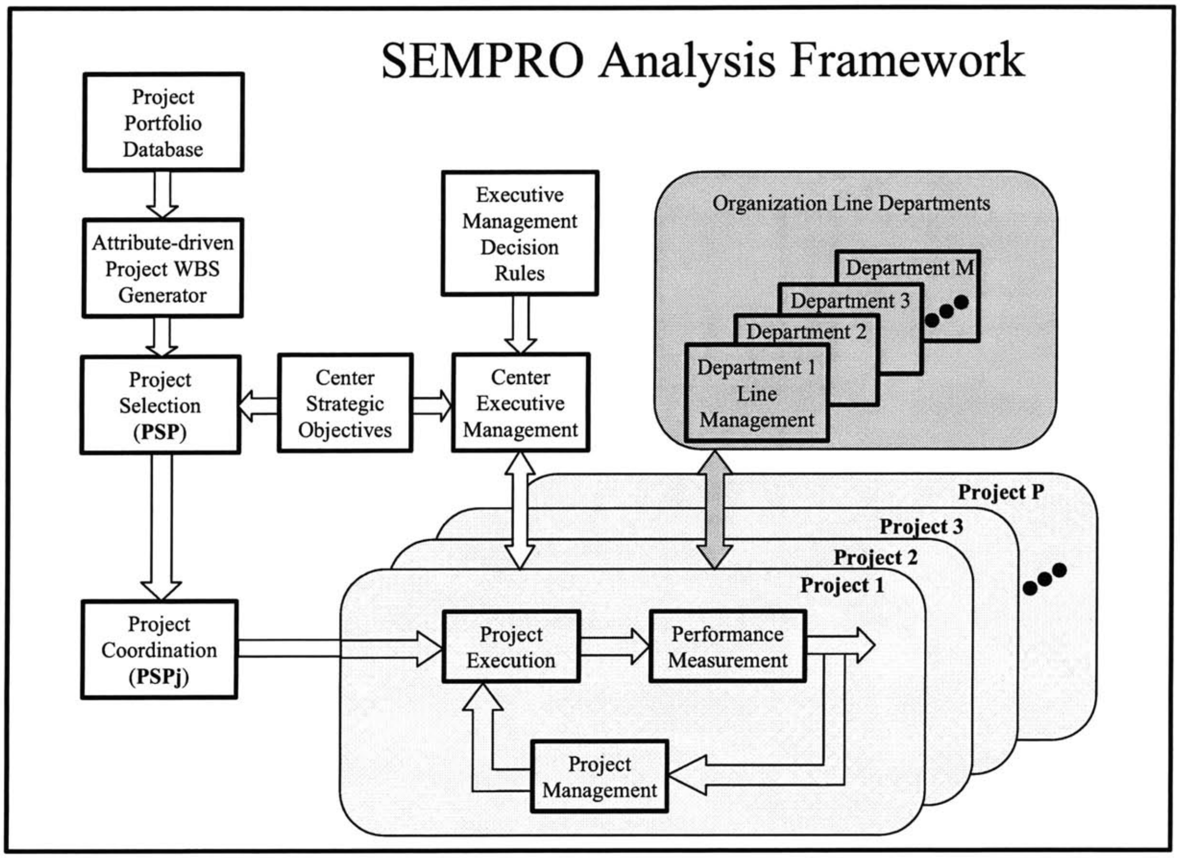

Figure 4-1 SEMPRO Overall System Architecture

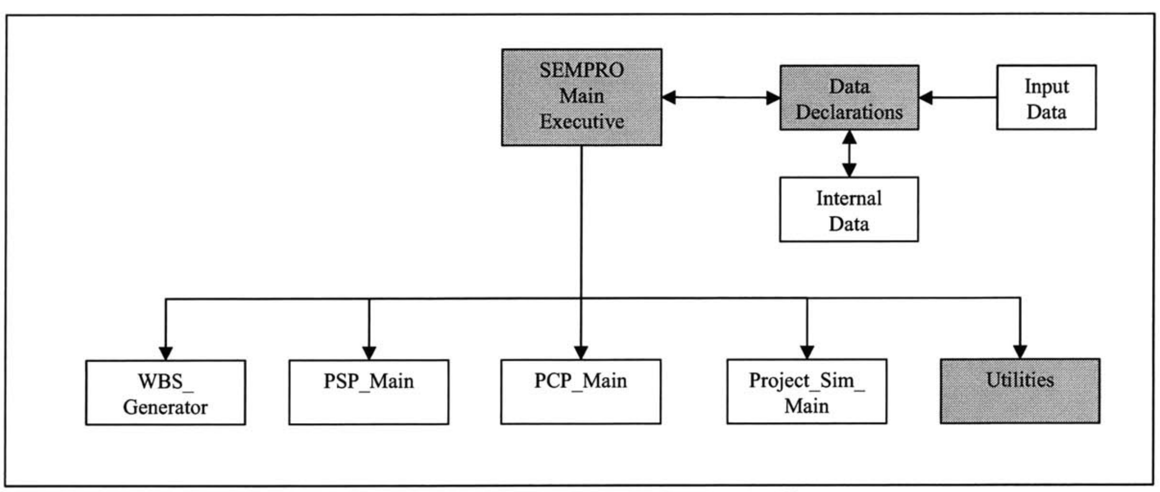

Figure 4-2 SEMPRO Software Program Structure

4.1.3 *Selection of Programming Environment*

Several factors contributed to the selection of the Microsoft VBA programming environment for SEMPRO development. Other programming languages evaluated during this thesis research include MATLAB[21] Simulink/Stateflow© (student version R12) with the Optimization Toolbox; the Extend[22] discrete event simulation language (student-version); and the AMPL[23] mathematical programming language (student version). The Excel VBA environment presented the best compromise of programming flexibility and utility, capable of hosting the entire SEMPRO software code within a single application program. The other programming options required manual user intervention to access intermediate results across one or more additional application programs. As part of the Microsoft Office© suite, the Excel VBA environment is also highly portable to other interested users or downstream developers. In addition, the direct linkage between Excel spreadsheets and VBA macros was especially helpful in the early algorithm development stage. For example, SEMPRO input, output and internal data structures were first constructed manually on spreadsheets as a visualization aid, and then coded in VBA to replicate the desired formats. The primary disadvantages of the Excel VBA environment are: (i) significant additional coding burden due to the low-level programming language; (ii) slower execution speeds due to "in-line compiling" and embedded spreadsheet maintenance routines; and (iii) inherent problem size limitations associated with Excel SOLVER, as noted below. It would be expected that subsequent beta-versions of SEMPRO would migrate to high-level programming languages such as AMPL.

4.1.4 *Limitations*

The SEMPRO prototype has inherent data variable size limitations imposed by the Microsoft Excel VBA programming environment. The Excel Solver module used to solve the PCP, PCP_j and APSP formulations are limited to no more than 200 decision variables; this limits SEMPRO applicability to cases where $\mathcal{N} \leq 200$. [The corresponding size limit in the AMPL Student Version is 300 decision variables. The MATLAB Optimization Toolbox does not

[21] MATLAB, Simulink and Stateflow are copyrighted by The MathWorks, Inc.

[22] Extend is copyrighted by Imagine That, Inc.

[23] The AMPL Modeling System software is copyrighted by Bell Laboratories

restrict the size of the decision variable.] For programming convenience, the SEMPRO prototype also includes several "hardwired" limitations, including:

- P_{max} = Max_Projects = 20
- N_Activity = 6 (fixed number of "phases" per DFRC project)
- Max_EP = 20 (maximum number of employees per department)
- M_{max} = M_dept $\leq$ 10 (maximum number of departments)

4.1.5 Definitions:

4.1.5.1 Terms of Reference

In the following sub-sections, SEMPRO terminology is focused on the DFRC operating model, as explained under Section 2.0. Key terms of reference used to describe the SEMPRO programming conventions are listed below.

A project "**phase**" is synonymous with a PCP "activity"; these are WBS Level 2 elements, each comprising 10-12 networked "tasks"

A project "**task**" is synonymous with a project WBS Level 3 element, each comprising 10 to 1000 lower level sub-tasks.

A project "**sub-task**" is the basic unit of measurable work output, representing a completed product (hardware item, software item, or service provided such as test objective completion).

An organizational "**branch**" is equivalent to a "line department" as used in Section 3.0, typically comprising 10-30 full-time employees.

Project **productivity** (**K_p**) is defined in terms of nominal workforce hours per task. SEMPRO defines **productivity** as the staffing requirement associated with each task in a project WBS under nominal conditions, assuming journeyman level workforce skills with adequate project experience for the given task. Off nominal workforce conditions are taken into account by workforce "**efficiency**" and "**quality**" coefficients for each task, as explained below. Figure 4-3 depicts the relationship between project task requirements, productivity and efficiency.

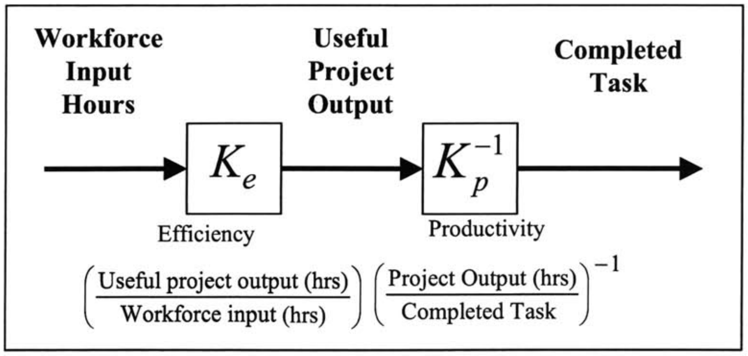

Figure 4-3 Simplified Definitions of Project Proficiency and Efficiency

Workforce **efficiency** (**K_e**) converts workforce effort, measured in terms of workforce input hours applied to a task, into project output, measured in terms of useful output hours per task. With a task efficiency coefficient of **K_e**=1, a project team produces a completed task after expending the number of workforce hours prescribed by the associated project WBS Level 3 element. However, efficiency coefficients will almost always be less than unity, as determined by a "user-defined" non-linear functional relationship that accounts for recent project experience and skill level for individual team members. Figure 4-4 illustrates the non-linear relationship between workforce efficiency, project experience and Civil Service General Schedule pay level (GS Level)[24] as used in the SEMPRO prototype for DFRC projects. The non-linear workforce efficiency function also accounts for project schedule pressure and workforce morale.

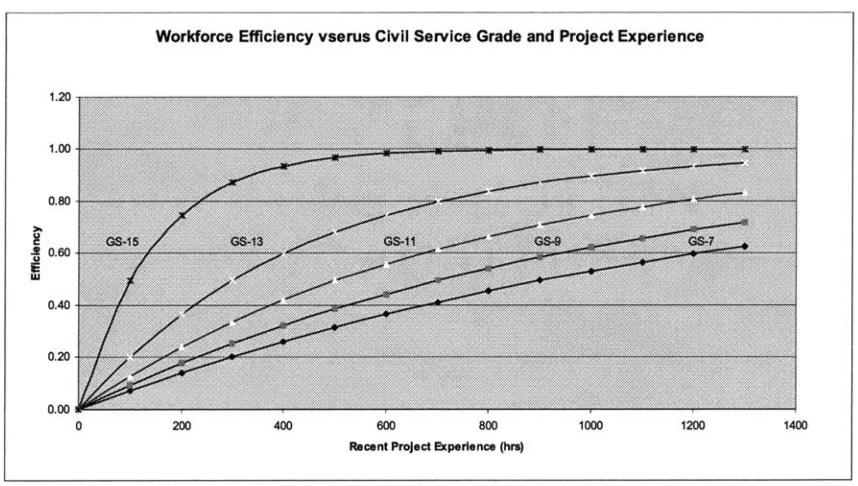

Figure 4-4 SEMPRO Model for Efficiency versus Skill and Experience

24 The General Schedule is the pay scale used within the U.S. Civil Service workforce, consisting of pay grades ranging from GS3 to GS15, with each GS pay grade containing 10 graduated steps. For convenience, practitioners often refer to **GS Levels** when referring to "General Schedule pay grade levels".

Project **quality** is defined in terms of usable project output tasks, as measured on a scale of percentage of requirements met (note that this definition allows quality to exceed 100%, at the expense of additional, extraneous workforce effort). SEMPRO determines the quality of a completed project task using a combination of a scalar output coefficient ($\mathbf{K_q}$) and additive measurement noise. The scalar output coefficient ($\mathbf{K_q}$) is determined by a non-linear functional dependency on project uncertainty and workforce morale. Additive measurement noise is determined by the level of safety risk (high safety risk translates into high quality requirements). SEMPRO assigns a random numeric quality value to each completed task.

Project **rework** is defined in terms of both discovered rework and undiscovered rework. Discovered rework is modeled as low quality work that is discovered within the project team prior to task completion, allowing for immediate corrective action. Undiscovered rework comprises low quality tasks that escape detection within a given project phase, and propagate into downstream activities.

Project **visibility** is a non-linear function of management overhead in terms of reporting hours per quarter. SEMPRO determines visibility as a quadratic function of the project Schedule Performance Index (SPI), as shown in Figure 4-5. (SPI is a standard Earned Value performance metric, defined in terms of Actual Cost of Work Scheduled divided by Budgeted Cost of Work Performed).

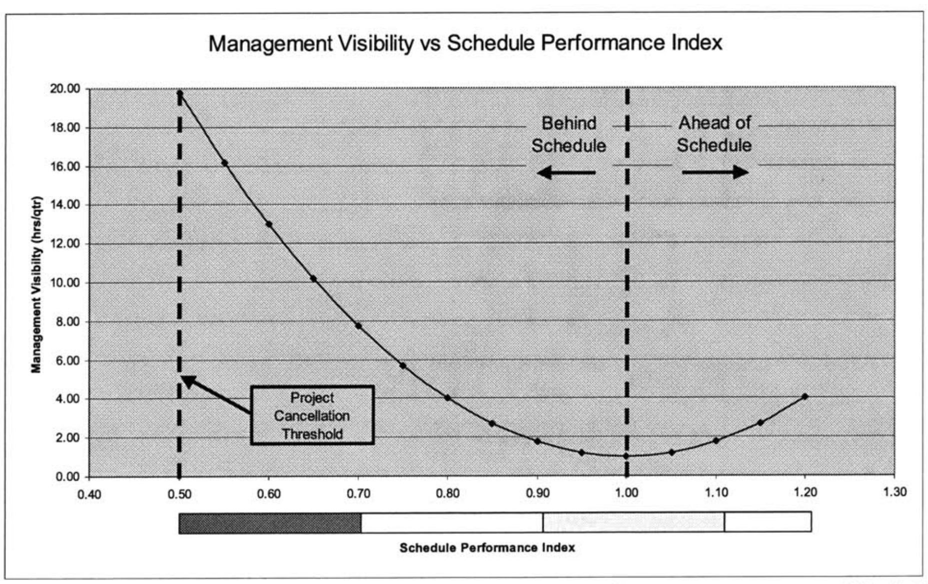

Figure 4-5 SEMPRO Functional Relationship for Management Visibility

4.1.5.2 Discrete event states

The execution of a SEMPRO simulation model is governed by a set of discrete, allowable, operating **states** for individual projects, project phases, project tasks, and organizational branches as listed in Table 4-1. The discrete states of each grouping in Table 4-1 are mutually exclusive, with a prescribed sequence governing the transition between states. State transitions are a subset of SEMPRO **actions** taken in response to a finite set of **events**; SEMPRO **actions** can also trigger additional **events**.

Project State	Excel Value
Failed	-3
Suspended	-2
Cancelled	-1
Wait	0
Enabled	1
Active	2
Complete	3

Project Phase	Excel Value
SR	1
PD	2
CD	3
FAB	4
T&V	5
FLT	6

Phase State	Excel Value
Wait	0
Enabled	1
Active	2
Complete	3

Task State	Excel Value
Failed	-3
Suspended	-2
Starved	-1
Wait	0
Enabled	1
Active	2
Complete	3

Branch Demand	Excel Value
Empty	0
Nominal	1
Saturated	2

Table 4-1 Definition of SEMPRO Discrete States

4.1.5.3 Discrete Health Status Indicators

SEMPRO also utilizes a set of discrete status indicators to measure project and branch health. The status indicators listed in Table 4.2 influence the output of specialized functions. For example, the output of the non-linear project efficiency function is influenced by the state of the Schedule_Status project metric. Figure 4.2 (above) illustrates the "stop light" indicator states for the Schedule_Status health metric.

Health Metric	Indicator State			Determined by
Project Status				
Schedule_Status	Red	Yellow	Green	Schedule Performance Index
Cost_Status	Red	Yellow	Green	Cost Performance Index
Staffing_Status	Red	Yellow	Green	Task_Queue.Status
Project_Morale	Low	Normal	High	Overtime, SPI, and Momentum
Project_Momentum	Low	Medium	High	Phase and Task-Hrs/Week
Project_Visibility	Low	Medium	High	Center Management
Project_Priority	Low	Medium	High	Center Management
Branch Status				
Branch_Morale	Low	Normal	High	Demand + OT + Project Type
OT_Authorization	TRUE	FALSE		Branch_Task_Request

Table 4-2 SEMPRO Definition of Health Status Indicators

4.1.5.4 *Discrete Events and Actions*

Table 4-3 lists the set of SEMPRO discrete events and actions that control state transitions. Events are treated as binary (True/False) variables that are reset each simulation cycle.

Event	Action
Project_Start	Transition from Project_State=Wait to Project_State=Enabled
Project_Activated	Transition from Project_State=Enabled to Project_State=Active
Project_Suspended	Transition from Project_State=Active to Project_State=Suspended
Project_Reactivated	Transition from Project_State=Suspended to Project_State=Active
Project_Complete	Transition from Project_State=Active to Project_State=Complete
Project_Failed	Transition from Project_State=Active to Project_State=Failed
Project_Cancelled	Transition from Project_State=Active to Project_State=Cancelled
Phase_Start	Increment Active_Phase; Load Task_Wait_Queue
Phase_Complete	If Active_Phase = FLT, then trigger Project_Completion
	Else, trigger Next_Phase
Task_Start	Trigger Branch_Resource_Request
Task_Completion	Determine Task_Quality
	Trigger Branch_Resource_Release;
	If N_starved > 0, trigger Starved_Task_Request
Task_Failed	Increment Task_Failure_Counter
	If N_failed > Max_Failures, then trigger Project_Cancelled
	Else, re-insert task into Task_Enabled_Queue
Monthly_Event	Update Center performance metrics
QTRLY_Event	Trigger Branch_Quarterly_Assignments;
	Cancel Projects with SPI < 0.50 (or other value set by management)
	Enable new projects with start times within next quarter
Annual_Event	Adjust project priorities;

Table 4-3 SEMPRO Definition of Discrete Events and Actions

4.2 SEMPRO Software Module Descriptions

The next six sub-sections provide functional descriptions of each of the main software modules shown in Figure 4-2 SEMPRO Software Program Structure.

4.2.1 Input data structure

The SEMPRO input data structure is illustrated in Figure 4-6. The current SEMPRO prototype version employs Excel spreadsheets to load the Project Attributes and Branch Data information; the remaining input data elements are "hard wired" into the SEMPRO Data Declaration section of the program code. These "hard wired" parameters will be replaced by interactive dropdown-menus in subsequent versions of SEMPRO. An example of the Project Attribute input data was provided previously in Table 2-1, Table 2-2 and Table 2-3 of Section 2.4. An example of a Branch Data input spreadsheet is provided in Table 4-4 in Section 4.2.6.1. Branch input data is required for each full-time employee in a given branch to define current skill level (i.e., GS Level), full cost burden per work-hour, and allocations of quarterly annual leave, administrative and training burdens. These quarterly allocations are updated during the simulation by the **Center_Mgt** and **Branch_Update** subroutines. Subtracting the quarterly burdens from a default value of 440 work-hours per quarter per employee establishes the maximum quarterly availability of each employee to perform project tasks. The project experience columns in Table 4-4 provide the initial conditions for determining each employee's project efficiency, based upon recent project experience over the prior three quarters. A total of six projects are represented in Table 4-4. Employee project experience is updated during each cycle of a SEMPRO simulation run.

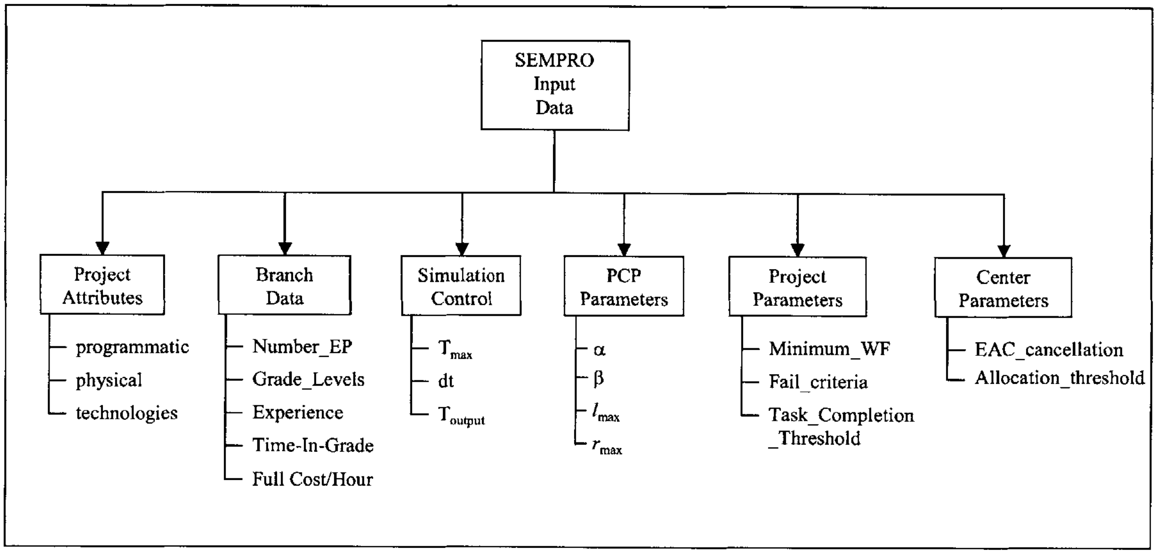

Figure 4-6 SEMPRO Input Data Structure

4.2.2 Internal data structure

Figure 4-7 depicts the basic internal data structure associated with the SEMPRO simulation capabilities. Additional internal data objects associated with simulation control, mathematical programming elements, and Excel VBA code requirements are also required but not shown. In some cases, the data structure sub-elements in Figure 4.6 are aggregate representations of lower-level details. Figure 8-14 through Figure 8-18 in Appendix 8.4 provide actual Excel VBA data type declarations for each of the five internal SEMPRO data structure elements.

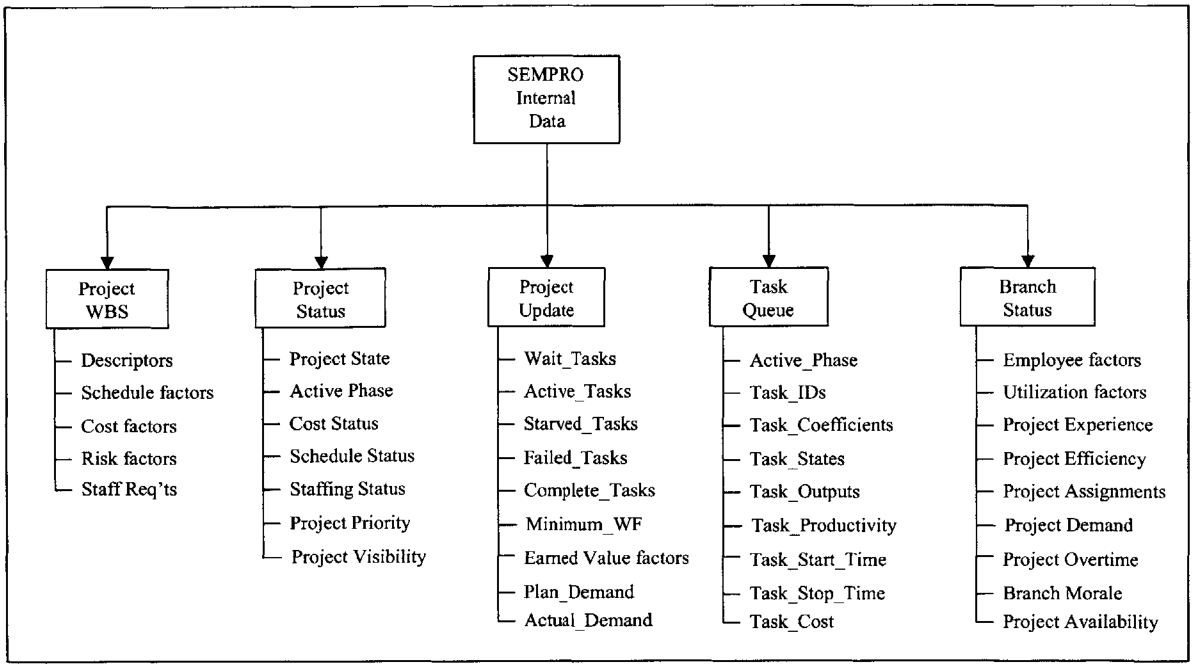

Figure 4-7 SEMPRO Internal Data Structure

4.2.3 Attribute-Driven WBS Generator

To satisfy the prototype demonstration objectives of SEMPRO, the current version of the WBS generator uses a simple scaling algorithm governed by a project category, cost estimate, technology readiness level (TRL) and program risk entries in the project attribute tables (reference Section 2.3 and Figure 2-7). Figure 8-5 and Figure 8-6 in Appendix 8.1 provide a reference WBS for the Category I/Internal X-plane projects. Reference WBS models for the other project categories have identical structure, but different task resource requirements and task durations. These reference-category Work Breakdown Schedules were based, in part, on actual data associated with current DFRC projects. The WBS generator creates a new WBS table for each entry in the project portfolio by scaling the task durations and resource requirements from the reference category WBS, using a linear interpolation algorithm that accounts for project cost estimates, risk factors and Technology Readiness Levels. Future versions of SEMPRO would be expected to employ more sophisticated WBS generation algorithms.

Figure 4-8 outlines the hierarchy and general process flow of SEMPRO software modules that generate project WBS objects. Each line entry in the figure represents a software subroutine called by the WBS_Generator module. The WBS_Generator module produces three outputs:

(i) an Excel spreadsheet WBS table created within the "Project_WBS" worksheet of the active SEMPRO workbook for each entry in the project portfolio (e.g., Figure 8-5 and Figure 8-6 in Appendix 8.1); (ii) an internal RAM (random access memory) image of each project WBS table loaded into the SEMPRO Project_WBS data type variable (as listed in Figure 8-14 through Figure 8-18 in Appendix 8.4); and (iii) Excel spreadsheet tables created within the "PSP_Data" worksheet of the active SEMPRO workbook to provide the input data required by the PSP_Main module.

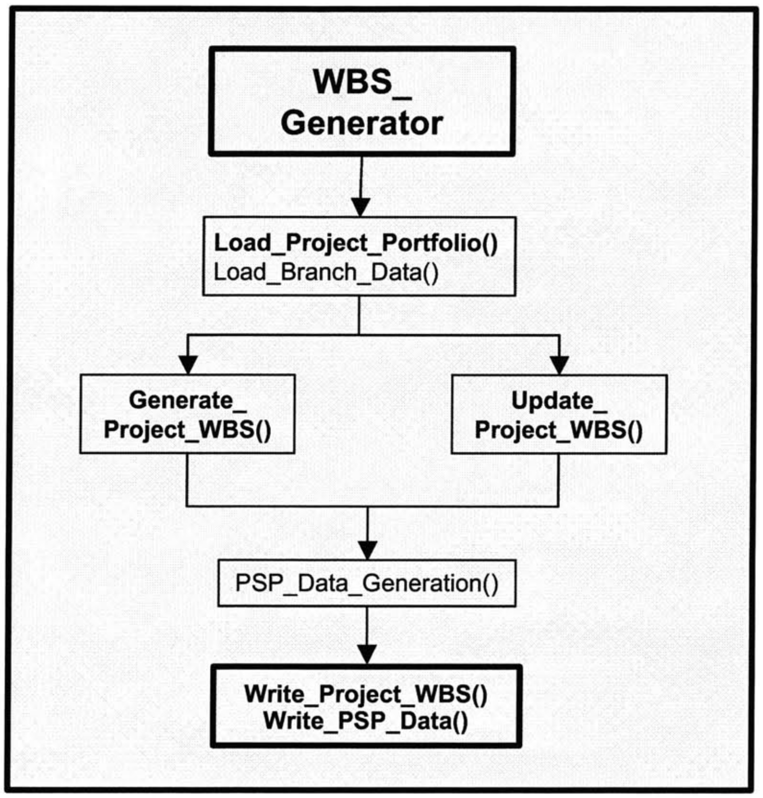

Figure 4-8 Structure of SEMPRO WBS Generator Module

4.2.4 Project Selection Module (PSP_Main)

Figure 4-9 outlines the SEMPRO program structure for execution of the Aggregate Project Selection Problem algorithm. The figure identifies the APSP equations from Section 3.3.3 that are implemented within subroutines in the PSP_Main module. Input data for the PSP_Main module is loaded from the "PSP_Data" worksheet of the active SEMPRO workbook. Whenever changes are made to the project portfolio database, the **WBS_Generator** must be called prior execution of the **PSP_Main** module to update the table entries within the "PSP_Data" worksheet.

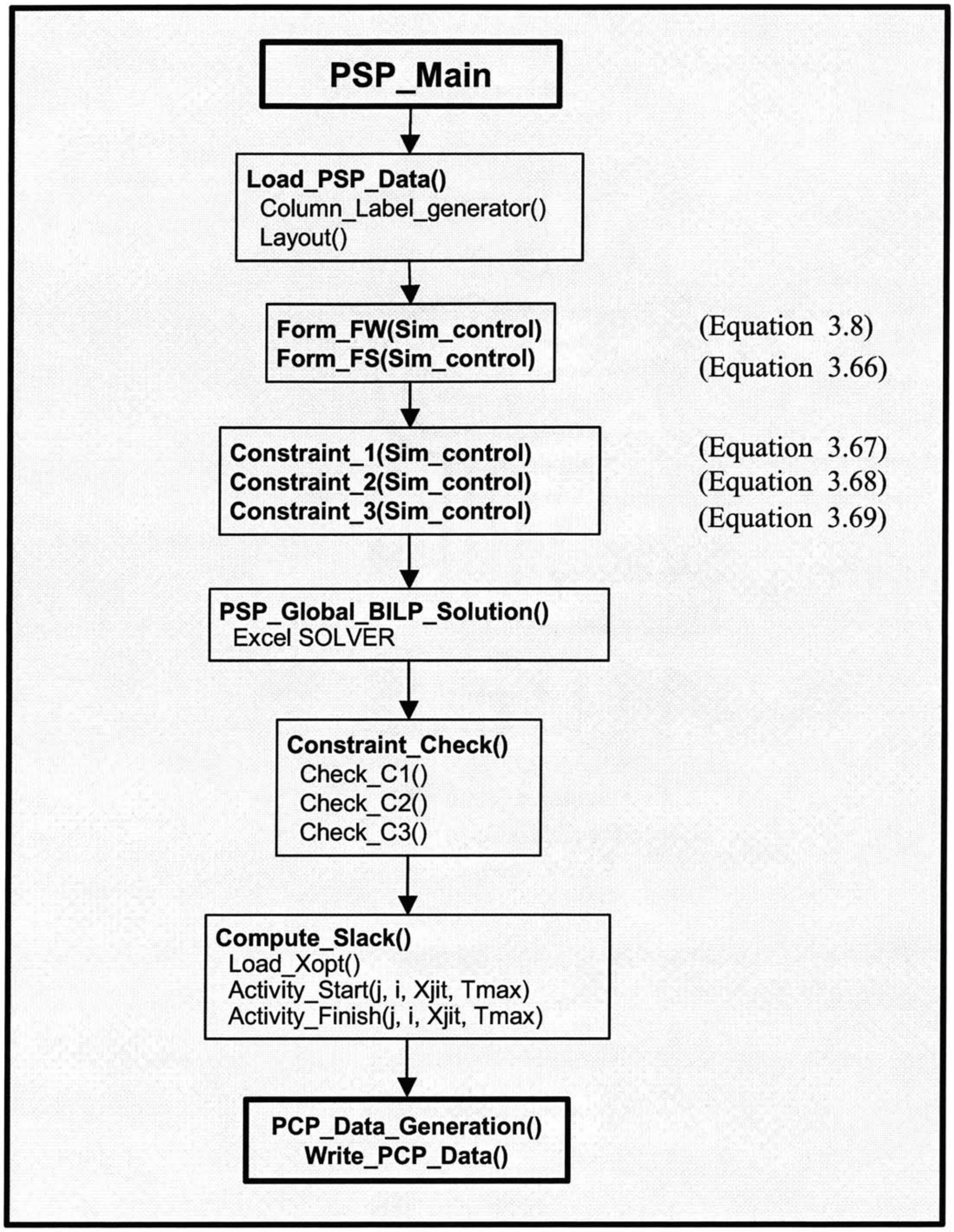

Figure 4-9 Structure of the Project Selection Module (PSP_Main)

Due to the inherent size limitation with Excel SOLVER, project selections within the SEMPRO prototype are determined by WBS Level 1 project representations. The primary output of the **PSP_Main** module is the corresponding WBS Level 2 information for the selected projects as required for input data to the project coordination module. This information is stored as Excel tables within the "LR1" worksheet of the active SEMPRO workbook. **Figure 4-10** illustrates an integrated project schedule output from **PSP_Main**.

Solid green bars indicate projects selected from the project portfolio described in Section 2.4; the remaining projects (with yellow hash-line bars) were not selected for implementation.

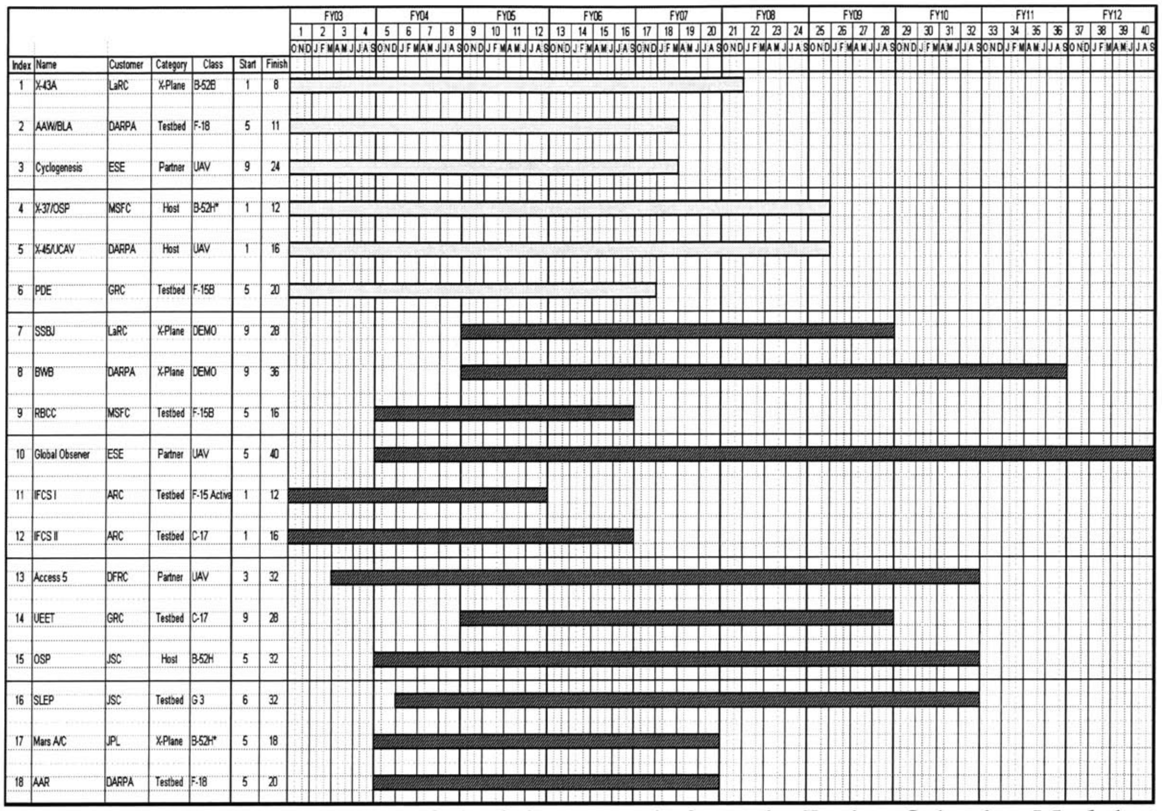

Figure 4-10 Integrated Project Schedule Example from the Project Selection Module

4.2.5 Project Coordination Module (PCP_Main)

Figure 4-11 outlines the SEMPRO program structure for execution of the Project Coordination Problem algorithm described in Section 3.1. Input data for **PCP_Main** is obtained from the "LR1" worksheet as provided by the **PSP_Main** module. Whenever changes are made to the project portfolio database, both the **WBS_Generator** and the **PSP_Main** modules must be called prior to execution of the **PCP_Main** module. For practical problems of interest, project selections within the SEMPRO prototype are constrained to WBS Level 2 project representations in which the product of $T * N_j \leq 200$. For DFRC project models, N_j is "hardwired" to 6 activities or phases per project; therefore, T <= 33 time increments. The primary output of the PCP_Main module is the list of WBS Level 2 activity start and finish times, as determined by subroutine **Schedule_Results**. The

PCP_Main module also produces activity schedule graphics (as shown in Figure 3-3) and line department staffing allocations (as shown in Figure 3-4).

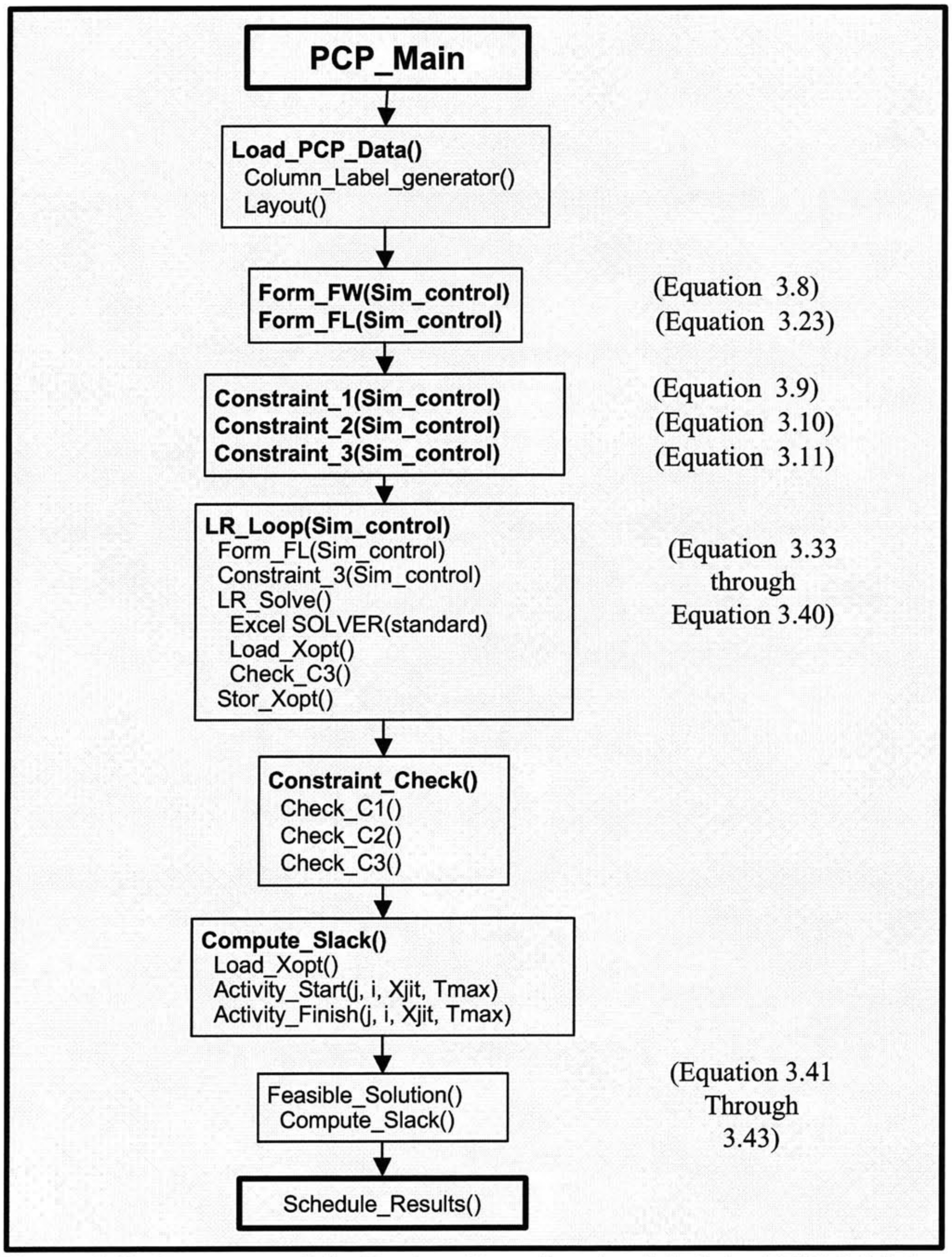

Figure 4-11 Structure of the Project Coordination Module (PCP_Main)

4.2.6 Project Simulation Module (Project_Sim_Main)

SEMPRO information flow is relatively straightforward for the WBS_Generator, PSP_Main and PCP_Main modules. In contrast, the Project_Sim_Main module involves complex interactions between multiple software subroutines. Figure 4-12 provides a schematic representation of these interactions for a single project and line department (or branch management) and the executive (Center) management. Typical SEMPRO simulations will entail multiple projects and branches in parallel to those shown. Key features of this schematic include: (i) project and task state transitions driven by discrete events and action message flow; (ii) WBS task flow processing through a sequence of discrete task queues; (iii) simulated task execution dynamics; (iv) allocation and release of line department staff in response to project task requests; and (v) Center-wide quarterly staff allocation plans.

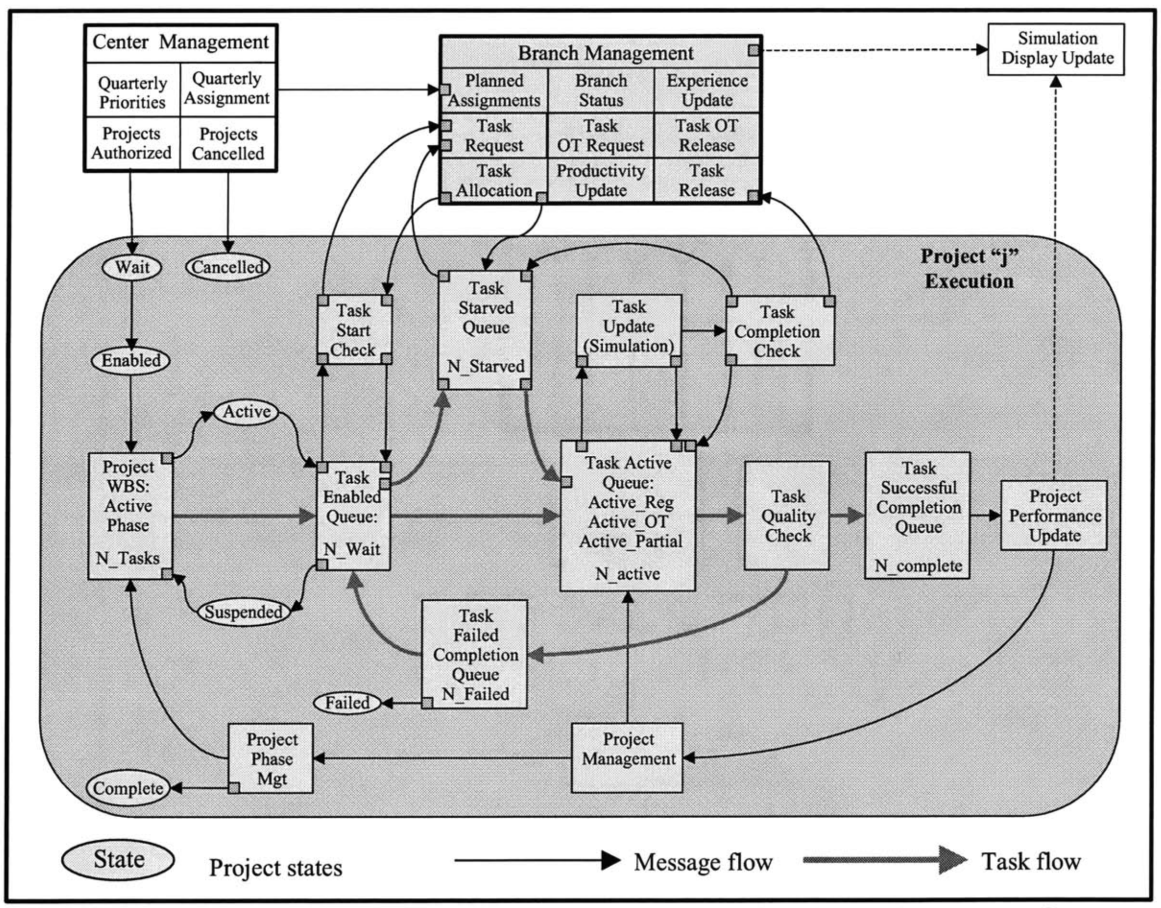

Figure 4-12 Discrete Event Simulation Schematic for Single Project Execution

The schematic also captures the top-level functional requirements for the Project_Sim_Main software module. Projects are initialized in the **Wait** state, transition to the **Enabled** state when authorized by Center management, and then transition to the **Active** state when the WBS tasks for the first phase are loaded into the **Task_Enabled_Queue**. During every simulation time increment, the **Task_Start_Check** routine will "push" a task from the **Task_Enabled_Queue** into the **Task_Active_Queue** when all predecessors for that task have been successfully completed, and when sufficient resources have been allocated by the line departments. If sufficient resources cannot be allocated, then the task moves into the **Task_Starved_Queue** to await release or replenishment of department resources as other tasks are completed. When a task enters the **Task_Active_Queue**, a linear systems dynamic model is initiated to simulate task execution and progress towards completion. When the simulation dynamics indicate that the task is complete, the **Task_Quality_Check** determines the Pass/Fail outcome based on a randomly assigned quality metric for that task; the stochastic properties (mean and variance) of the quality random variable are determined by the task uncertainty and technical risk factors. Successful task completion leads to project performance updates and earned value increase. On the other hand, failed tasks are recycled through the **Task_Enabled_Queue**, provided that the maximum number of failures has not been exceeded for that task. If the maximum number of task failures is exceeded, then the project transitions to the **Failed** state, and execution for that project comes to a halt. The task flow shown in Figure 4-12 adheres to a "conservation of tasks principle" by ensuring during every simulation time step that the total number of tasks (N_Tasks) defined in a project WBS for the currently active phase equals the combined number of tasks in each of the task queues. In particular,

$$N\_Tasks = N\_Wait + N\_Active + N\_Starved + N\_Complete + N\_Failed \quad (4.1)$$

where

$$N\_Active = N\_Active\_Regular + N\_Active\_Overtime + N\_Active\_Partial \quad (4.2)$$

N_Active_Regular tracks the number of **Active** tasks for which line department staff are allocated using normal workhours in accordance with the quarterly project assignment plan. N_Active_Overtime tracks the number of **Active** tasks for which additional overtime hours for at least one line department employee are required to complete task execution in the timeframe set by the Center quarterly plan. N_Active_Partial tracks the number of **Active** tasks for which insufficient regular and overtime time work hours are available in one or more line departments to complete the task in the planned timeframe; but sufficient staff are nonetheless allocated to allow task completion in a reasonably longer timeframe. A **Minimum_Workforce** parameter is defined by each project to control the minimum acceptable percentage of planned line department workforce per task for which execution is allowed to proceed as an **Active_Partial** task. If the available workforce is insufficient to meet the **Minimum_Workforce** parameter, the task enters the **Task_Starved_Queue** to await additional resource availability.

Figure 4-13 outlines the software program structure for implementing the SEMPRO discrete event simulation functions within the **Project_Sim_Main** module. After loading the project portfolio and branch data input data files, and the PSP and PCP output data files, **Project_Sim_Main** first reconstructs the planned sequence of project resource demands on each of the line organizations as determined by the PCP_j solution and then initializes the simulation loop. Then, for each time step in the simulation loop, SEMPRO repeats the following update sequence:

(1) Reset all event triggers to **FALSE**;

(2) Update the simulation clock counters; and take the following actions if the controlling events are true:

   a. If **annual_event = TRUE**, enable project execution for those projects scheduled to start within the next fiscal year; and update the Center prioritization list for all enabled and active projects;

   b. If **QTRLY_Event=True**, cancel any active project for which the Estimate_At_Completion (EAC) exceeds the EAC_Cancellation threshold; and update the Branch_Quarterly_Assignment plan for all remaining enabled or active projects;

   c. If **Monthly_event = True**, update the Center performance metrics based on the status of all active projects;

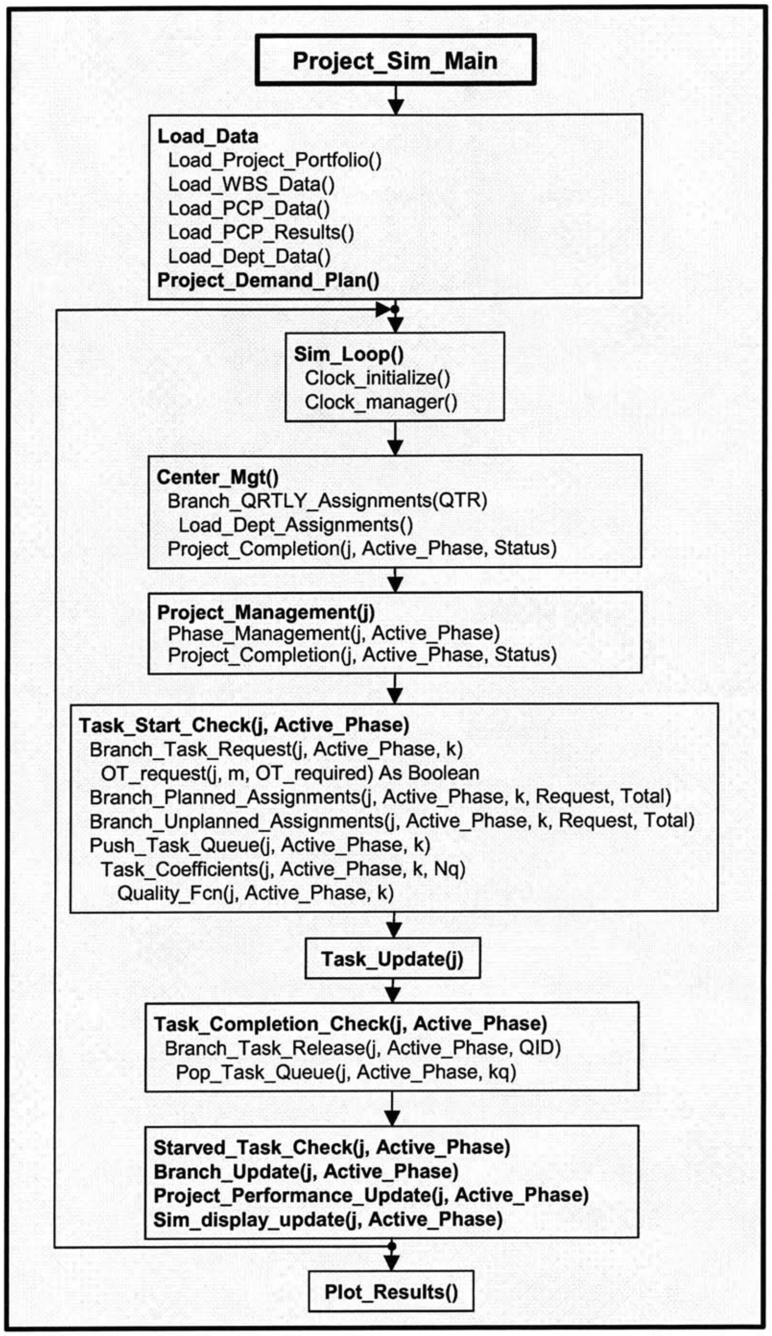

Figure 4-13 SEMPRO Structure for Discrete Event Simulation Module

(3) For each project selected for implementation:

a. Activate any enabled project "*j*" when the simulation time satisfies $t_{sim} \geq s_j$

b. For each active project, in priority order,

i. If the current project phase has completed, then either transition to the project complete state or initialize the next project phase, as appropriate;

ii. Update management control parameters for project visibility, schedule and budget pressure based upon the project health status indicators;

iii. Check the **Task_Enabled_Queue** for task start conditions ($t_{sim} \geq s_{j,i}$ and task $a_{j,k}$ completion status $\forall k \subset P_j(i)$); if the task start conditions are true, then

   1. Initiate a **Branch_Task_Request** to each line department for the necessary resources; if adequate resources are allocated, then "push" the new task into the **Task_Active_Queue**, else, "push" the new task into the **Task_Starved_Queue**;

iv. Update the linear, stochastic system dynamics models for each active task (as described below in Section 4.2.6.2);

v. Check the **Task_Active_Queue** for any completed tasks; if a task has completed then:

   1. Release the line department resources allocated to the completed task, and "pop" the task out of the **Task_Active_Queue**;

   2. Determine the quality metric for the finished task; if the task fails to meet the quality threshold for that project, then recycle it back into the **Task_Enabled_Queue** if the maximum number of task failures has not been exceeded, else transition to the project failed state;

   3. Check the **Task_Starved_Queue** to see if the released resources are sufficient to start any starved tasks for the current project;

vi. Update the Branch quarterly experience and overtime metrics;

vii. Update project performance metrics; and

viii. Update the SEMPRO simulation display indicators with the current project and branch health status information;

c. Repeat (i) – (viii) for the next active project

(4) Repeat (1) – (3) for the next simulation time step.

The SEMPRO prototype uses a time step default value of one day per simulation loop. The above description captures the key aspects of the information flow within the SEMPRO discrete event simulation module. However, the **Branch_Quarterly_Assignments** and the **Task_Update** subroutines require additional explanation.

4.2.6.1 *Branch Quarterly Assignments*

The Branch_Quarterly_Assignment module allocates individual line department staff to the active projects on a quarterly basis to satisfy forecasts of project resource demand for the ensuing quarterly period. These allocations are determined by solving a standard linear programming assignment problem defined as follows.

Let τ represent a given quarterly time period of interest.

Let
$$X_j^\tau = \begin{cases} 1 \text{ if project } j \text{ is active during quarterly period } \tau \\ 0 \text{ otherwise} \end{cases} \tag{4.3}$$

Let $U^\tau_{m,n,j}$ designate the positive, real valued decision variables for the staff assignment problem, with $U^\tau_{m,n,j}$ specifying the number of work hours assigned to the n^{th} member of department *m* to work on project *j* during quarterly period τ.

Let $D^\tau_{j,m}$ represent the staff resource demand on department *m* from project *j* during quarterly period τ ; then $D^\tau_{j,m}$ is given by

$$D^\tau_{j,m} \triangleq \sum_{k=1}^{\kappa_{j,\tau}} r_{j,k,m} * \left(1 - \xi^\tau_{j,k}\right) * X^\tau_j \qquad \forall\ j = 1,2,\ldots P;\ m = 1,2,\ldots M \tag{4.4}$$

where $k = 1,2,\ldots\kappa_{j,\tau}$ designates the set of tasks for project *j* that are expected to be active during quarterly period τ , and where $\xi^\tau_{j,k}$ represents the percent completion of task *k* of project *j* at the start of quarterly period τ .

Let $\rho^\tau_{j,m}$ represent the overall workforce efficiency of personnel assigned to project *j* from department *m* during quarterly period τ, such that

$$\rho^\tau_{j,m} = \sum_{n=1}^{N_m} \eta^\tau_{m,n,j} U^\tau_{m,n,j} \tag{4.5}$$

where N_m represents the number of available personnel in department *m*, and $\eta^{\tau}_{m,n,j}$ represents the efficiency of the n^{th} member of department *m* on project *j* during quarterly period τ. Workforce efficiency is determined by a non-linear functional relationship between employee skill level, recent project experience, schedule pressure and morale, as described in Section 4.1.5.1. This implies the following relationship between individual workforce efficiency as used in (4.5) and the effective project efficiency during quarterly period τ as shown in Figure 4-3:

$$K^{\tau}_{e_j} = \frac{\sum_{m=1}^{M}\sum_{n=1}^{N_m}\eta^{\tau}_{m,n,j}\,U^{\tau}_{m,n,j}}{\sum_{m=1}^{M}\sum_{n=1}^{N_m}U^{\tau}_{m,n,j}} \tag{4.6}$$

Finally, let $Q^{\tau}_{m,n}$ designate the maximum availability of the n^{th} member of department *m* during quarterly period τ to perform project work; nominally,

$$Q^{\tau}_{m,n} \triangleq Q_{\max} - \text{Annual Leave}(\tau)_{m,n} - \text{Administrative burden}(\tau)_{m,n} - \text{Training}(\tau)_{m,n} \tag{4.7}$$

where $Q_{\max}$ represents the maximum possible workforce availability in a quarterly period. A default value of $Q_{\max} = 440 \text{ (hours)}$ is used in the SEMPRO prototype.

The quarterly workforce assignment problem seeks to maximize each department's workforce efficiency for the active projects during the ensuing quarterly period, while satisfying the project resource demand and workforce availability constraints. Using the above definitions, the problem can be stated as follows:

For each department $m = 1, 2, \ldots M$,

$$\text{maximize } J^{\tau}_{m} = \sum_{j=1}^{P}\left(X^{\tau}_{j}\rho^{\tau}_{j,m}\right) = \sum_{j=1}^{P}\sum_{n=1}^{N_m}\left(X^{\tau}_{j}\,\eta^{\tau}_{m,n,j}\,U^{\tau}_{m,n,j}\right) \tag{4.8}$$

subject to:

$$\text{(project demand)} \qquad \sum_{n=1}^{N_m} \eta^{\tau}_{m,n,j} \, U^{\tau}_{m,n,j} \geq D^{\tau}_{j,m} \qquad \forall \; j = 1,2,\ldots P \tag{4.9}$$

$$\text{(availability)} \quad \sum_{j=1}^{P} X^{\tau}_{j} * U^{\tau}_{m,n,j} \leq Q^{\tau}_{m,n} \quad \forall m = 1,2,\ldots M; \; n = 1,2,\ldots N_m \tag{4.10}$$

Branch: RF		Project	Time In	Full Cost	Quarterly Availability				Recent Project Experience							Project Efficiency						
Employee		GS/Level	Grade	per hr	AL	Admin	TRG	Avail	1	2	3	4	5	6	Total	1	2	3	4	5	6	Avg
EP	1	13	5	$108	40	24	16	360	100	100	50	1100	100	200	1650	0.33	0.33	0.33	0.73	0.33	0.33	0.39
	2	13	4	$108	20	24	8	388			1500			100	1600	0.33	0.33	0.77	0.33	0.33	0.33	0.40
	3	14	3	$120	8	24	0	408		1300	200	100		0	1600	0.35	0.89	0.44	0.35	0.35	0.35	0.46
	4	15	6	$132	8	24	8	400	500	600	100	500		0	1700	0.97	0.98	0.49	0.97	0.38	0.38	0.69
	5	12	2	$96	16	24	40	360	1700					50	1750	0.66	0.30	0.30	0.30	0.30	0.30	0.36
	6	13	3	$108	0	24	24	392		1700				50	1750	0.33	0.78	0.33	0.33	0.33	0.33	0.40
	7	14	4	$120	0	24	8	408			1700			50	1750	0.35	0.35	0.90	0.35	0.35	0.35	0.44
	8	14	3	$120	0	24	0	416				1700		50	1750	0.35	0.35	0.35	0.90	0.35	0.35	0.44
	9	15	2	$132	0	24	8	408		100	150	100	700	600	1650	0.38	0.49	0.64	0.49	0.99	0.98	0.66
	10	12	3	$96	0	24	80	336					0	1750	1750	0.30	0.30	0.30	0.30	0.30	0.66	0.36
	11	13	4	$108	8	24	40	368					1700	0	1700	0.33	0.33	0.33	0.33	0.78	0.33	0.40
	12	14	5	$120	8	24	8	400	200	200	200	200	200	650	1650	0.44	0.44	0.44	0.44	0.44	0.80	0.50
	13	14	4	$120	8	24	0	408	350		750	500		50	1650	0.63	0.35	0.83	0.74	0.35	0.35	0.54
	14	13	5	$108	24	24	0	392		750		900			1650	0.33	0.65	0.33	0.70	0.33	0.33	0.44
	15	9	2	$60	32	24	80	304	600	600	100	100	100	100	1600	0.23	0.23	0.23	0.23	0.23	0.23	0.23
	16	11	2	$84	24	24	40	352	400	200	600	250	100	100	1650	0.28	0.28	0.34	0.28	0.28	0.28	0.29
	17	13	4	$108	8	24	0	408	400	150	900	100	100	100	1750	0.48	0.33	0.70	0.33	0.33	0.33	0.41
	18	13	5	$108	8	24	0	408	400	150	100	900	100	100	1750	0.48	0.33	0.33	0.70	0.33	0.33	0.41
	19	14	6	$120	8	24	0	408	400	150	100	100	900	100	1750	0.67	0.36	0.35	0.35	0.86	0.35	0.49
	20	14	7	$120	0	24	0	416	400	150	100	100	100	900	1750	0.67	0.36	0.35	0.35	0.35	0.86	0.49

Table 4-4 Example of SEMPRO Line Department Input Data for the DFRC Flight Systems Branch (Code RF)

Branch: RF	Project QTRLY Assignments						Total	Product-	Unused	Project Daily Assignments						Total
Employee	1	2	3	4	5	6	Hours	ivity	Capacity	1	2	3	4	5	6	Hours
EP 1	0	0	0	0	0	0	0	0	360	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	388	0	0	0	0	0	0	0
3	0	408	0	0	0	0	408	363	0	0	0	0	0	0	0	0
4	400	0	0	0	0	0	400	387	0	0.2685	0	0	0	0	0	0.2685
5	0	0	0	0	0	0	0	0	360	0	0	0	0	0	0	0
6	0	25.75	0	0	0	0	25.75	20	366	0	16.343	0	0	0	0	16.343
7	0	0	0	0	0	0	0	0	408	0	0	0	0	0	0	0
8	0	0	0	416	0	0	416	373	0	0	0	0	6.2761	0	0	6.2761
9	0	0	0	0	362.1	0	362.1	359	46	0	0	0	0	5.1435	0	5.1435
10	0	0	0	0	0	0	0	0	336	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	368	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	400	0	0	0	0	0	0	0
13	0	0	0	5.077	0	0	5.077	4	403	0	0	0	17.46	0	0	17.46
14	0	0	0	0	0	0	0	0	392	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	304	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	352	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	408	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	408	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	408	0	0	0	0	14.77	0	14.77
20	10.79	0	0	0	0	0	10.79	7	405	0.0105	0	0	0	0	0	0.0105
Effective Total	394	383	0	377	359	0	1513	1513	6112	0.279	16.343	0	23.737	19.914	0	60.272
Project Demand	394	383	0	377	359	0	1513		21.03%							
Total Allocation	410.8	433.7	0	421.1	362.1	0	1628			0.2667	12.8	0	18.488	17.775	0	49.33
Eff. Productivity	0.959	0.883	0	0.895	0.992	0	0.93			0.9558	0.7832	0	0.7789	0.8926	0	0.8184
Avg Cost Coefficient	$132	$119	$0	$120	$132	$0										

Table 4-5 Example of SEMPRO Quarterly and Daily Project Assignment Data for the DFRC Flight Systems Branch

4.2.6.2 Task Update Simulation

Whenever a task enters the **Task_Active_Queue**, a linear, discrete time simulation is initiated within the **Task_Update** subroutine to model task execution dynamics in the presence of requirements uncertainty, random disturbances and measurement noise. Coefficients of the task dynamics model are determined within subroutine **Task_Coefficients.** These coefficients are based upon the nominal task duration and workforce effort values prescribed by the associated WBS Level 3 element, while also taking into account the net workforce efficiency, project schedule pressure, technical risk, etc. For each active task, the SEMPRO prototype employs a state-space description of the linear, discrete-time model illustrated in Figure 4-13. This model is an adaptation at the project task level of the highly aggregate project management model described by Sterman.[25] From a control system perspective, this highly simplified model has infinite gain and phase margin, which allows arbitrarily large gains in the project management feedback loop without driving the SEMPRO simulation computations unstable. The structure of the SEMPRO prototype software code can accommodate a wide spectrum of higher fidelity task simulation models by making appropriate changes to the **Task_Coefficients** subroutine, so long as the dynamics are captured by the following discrete-time, state-space model:

$$\begin{aligned} x_{t_{i+1}} &= A_t x_{t_i} + B_t u_{c_i} + D_t w_{d_i} \\ y_{t_i} &= C_t x_{t_i} + v_{d_i} \end{aligned} \tag{4.11}$$

where state variables x_{t_i} represent both task dynamics and management feedback control law states at the i^{th} simulation time increment (i.e., $t_i \triangleq t_{start} + (i-1) * dt$; SEMPRO uses a default value of dt = 1 workday); u_{C_i} represents the number of sub-task requirements issued at t_i; w_{d_i} represents unproductive task disturbances encountered at t_i; y_{t_i} represents task outputs as measured at t_i; and v_{t_i} represents task measurement noise introduced at t_i. In particular, the task output vector y_{t_i} is required to take the form

$$y_{t_i} = \begin{bmatrix} y_{r_i} \\ y_{f_i} \\ y_{p_i} \\ y_{c_i} \end{bmatrix} = \begin{bmatrix} \text{Rework tasks at } t_i \\ \text{Workforce effort at } t_i \\ \text{Completed tasks at } t_i \\ \text{Management control at } t_i \end{bmatrix} \tag{4.12}$$

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[25] Reference: Sterman, John D. Business Dynamics, Systems Thinking and Modeling for a Complex World. Boston: Irwin McGraw Hill, 2000: pages 55-61. The task update model also derives from the unpublished MIT white paper by John D. Sterman, "System Dynamics Modeling for Project Management," 1992 (from graduate course readings in MIT 15.983/Systems and Project Management).

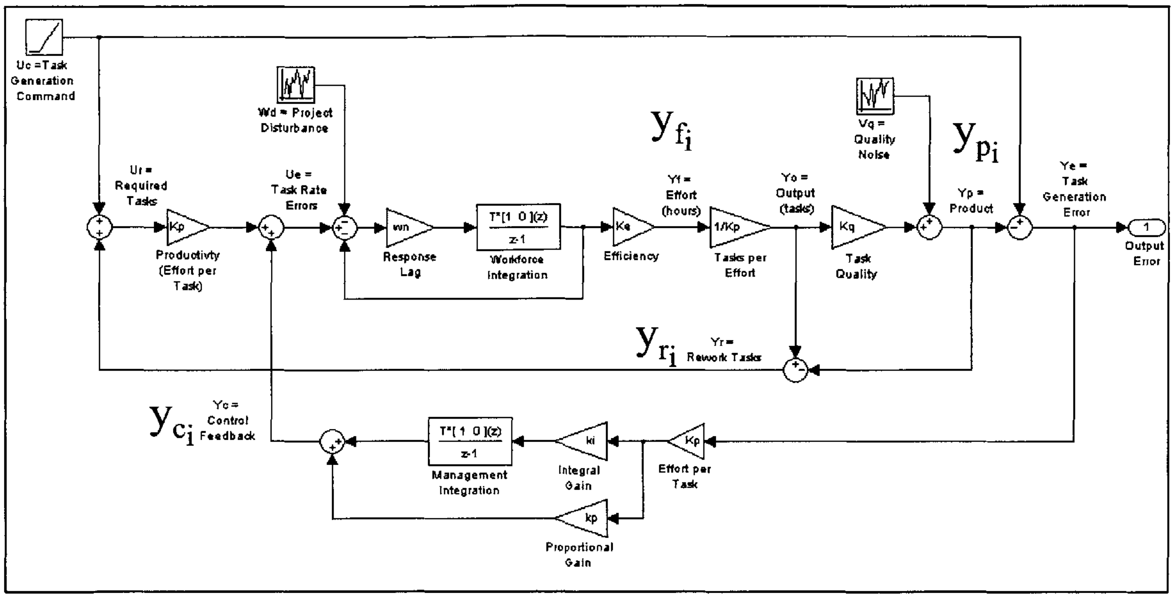

Figure 4-14 Task Update Simulation Dynamics

For the simplified task dynamics model shown in Figure 4-14, the required state space representation takes the form of equation (4.13).

$$\begin{bmatrix} x_{f_{i+1}} \\ x_{c_{i+1}} \\ x_{r_{i+1}} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_{f_i} \\ x_{c_i} \\ x_{r_i} \end{bmatrix} + \begin{bmatrix} b_f \\ b_c \\ 1 \end{bmatrix} \begin{bmatrix} u_{C_i} \end{bmatrix} + \begin{bmatrix} d_f \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} w_{d_i} \end{bmatrix}$$

$$\begin{bmatrix} y_{r_i} \\ y_{f_i} \\ y_{p_i} \\ y_{C_i} \end{bmatrix} = \begin{bmatrix} (1-K_q) & 0 & 0 \\ K_e & 0 & 0 \\ K_p K_e & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_{f_i} \\ x_{c_i} \\ x_{r_i} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} v_{q_i} \end{bmatrix} \qquad (4.13)$$

The cumulative sub-task completion shown in Figure 4-15, and cumulative workforce effort shown in Figure 4-16, illustrate the effect of the project management feedback loop on the task completion dynamics. For this example, the task generation command requires 10 sub-tasks to be completed within 3 days of task start-up. The effective workforce efficiency is set to $K_e = 0.9$ and task quality to $K_q = 0.9$. The management feedback loop is recognized as a "Proportional + Integral" control law; here the feedback gains are set to $k_p = 2.5$ and $k_i = 1.0$. The task completion performance without management feedback, indicated in

Figure 4-15 by the line labeled "Open loop response", fails to meet either the desired time or magnitude requirements. Performance with management feedback, indicated by the line labeled "Closed loop response", precisely tracks the commanded completion rate. Figure 4-16 indicates that the improved performance under tightly controlled management supervision requires roughly 15% more workforce effort on average, with roughly double the effort required during the first three days as compared to the open loop response. During SEMPRO simulations, feedback gains for each task are initially set to zero, and are progressively increased whenever the project's Schedule Performance Index (SPI) begins to deteriorate.

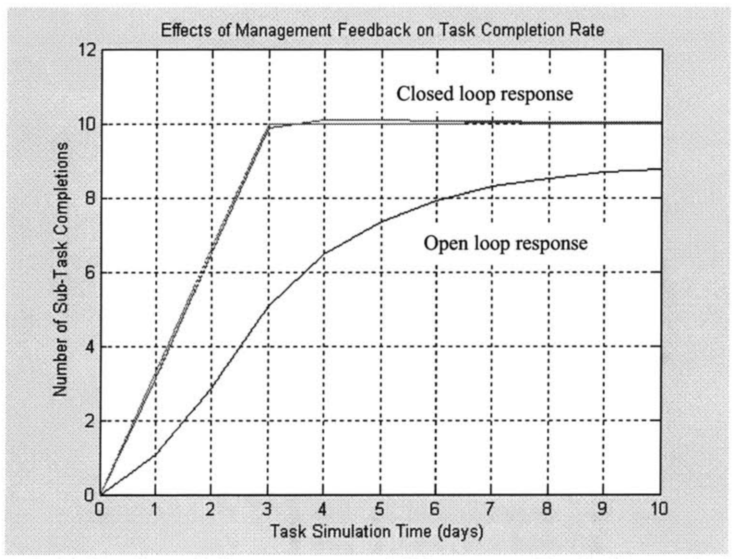

Figure 4-15 Project Management Effects on Task Completion Rate

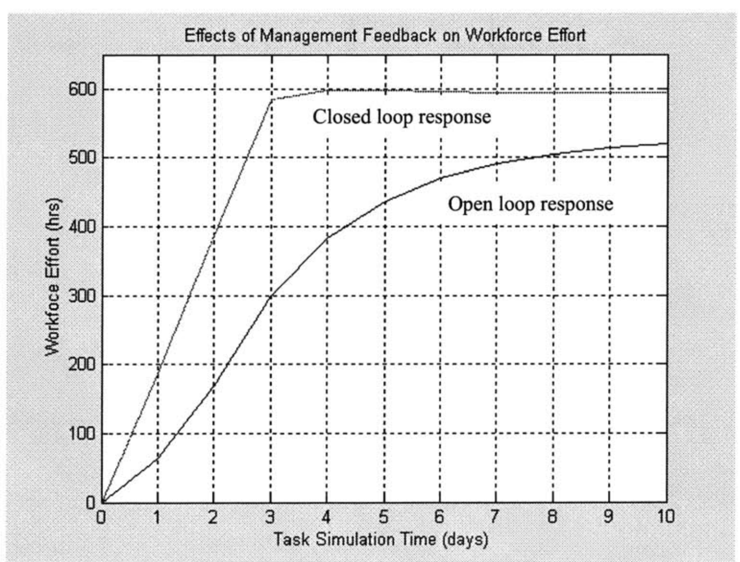

Figure 4-16 Project Management Effects on Effort

5 SEMPRO Applications

This section provides a high level overview of potential applications for SEMPRO. Applications described in the first four sections would require some modifications to the current SEMPRO prototype software code. However, the SEMPRO basic formulation and structure would readily accommodate these modifications. The fifth sub-section summarizes a test case application of SEMPRO to the DFRC candidate project portfolio described in Section 2.4. This example ties together all the major elements of SEMPRO, including the WBS generation as described in Section 2.3 and Section 4.2.3, the Project Selection and Project Coordination Problems as described in Section 3.0, and the discrete event simulation as described in Section 4.2.6.

5.1 Project Throughput and Capacity Models

The Aggregate Project Selection Problem can be utilized to determine the maximum number of projects of a given category (e.g., as defined in Section 2.3) that can be accommodated within a given time horizon and for a given projection of resource capacity limits. This determination is made by first generating the Level 1 resource requirements for a given project category using the WBS Generator Module with a typical set of project attributes; then replicating these project requirements multiple times to arrive at a maximum number of projects known to exceed the organization capacity limits; and finally using the APSP algorithm (e.g., as provided within the **PSP_Main** module) with all project target start times set to $s_j = 1$, $j = 1, 2, \ldots P$. The APSP solution will identify and sequence the maximum sub-set of projects that can be completed within the prescribed time horizon. This approach can also be used to determine the optimal mix of project categories for a given time horizon and capacity limits. In either case, the APSP objective function should be modified to maximize the resource utilization, rather than maximize net earned value. Recall, however, that the APSP algorithm requires each project to be executed contiguously, without interruption from start to finish. Solutions to the PSP formulation will always yield equivalent or superior results, provided that the number of decision variables is computationally amenable to solution.

5.2 Program Formulation Trade Studies

The capabilities of SEMPRO can also be used during the early formulation stage of major R&D programs comprised of multiple projects and sub-projects. This capability would be especially useful in those frequent instances in which the program budget and staffing limits are prescribed a priori, and the program formulation team is faced with the challenge of down-selecting multiple, candidate approaches with various risk-to-benefit attributes to arrive at an feasible program structure. In these instances, both the project throughput analyses (described above) and SEMPRO Monte-Carlo simulation results can be used to establish a locally optimal sub-set of projects with relatively high probabilities of success. This same approach can be used to support major program restructuring studies, in response, for example, to unforeseen budget cuts. SEMPRO can also be used effectively to conduct programmatic trade studies and "what if" scenarios.

5.3 Project Management Training Simulators

SEMPRO can also be used as an educational tool and training simulator for project managers. For a given project work breakdown structure, SEMPRO can demonstrate the effects of requirements uncertainty and technical risk (e.g., component test failures) on project evolution and performance. Students can gain insight into the leading indicators of project cost and schedule problems, including staffing conflicts with other projects, R&D process bottlenecks, project staff experience and training trade-offs, and quality assurance. Ancillary software support modules can be added to simulate annual budget cycle processes. Interactive, run-time menus can also be employed to develop project management decision-making proficiency; for example, students can define dual-source development paths as a mitigation strategy for high risk tasks.

An intriguing possibility, with suitable structural changes to the SEMPRO software code, would be using SEMPRO as training aid in the development of suitable, realistic work breakdown structures, project schedules and budget requirements for example case studies. This can be done by first embedding a known, detailed project solution into the simulation environment, and then comparing the student's proposed approach against the known solution during simulation run-time. Most likely, the first two levels of the student's proposed work breakdown structure would have to be prescribed in order for this training method to be practical.

5.4 Performance Metrics, Decision Criteria and Scenario Planning

The SEMPRO system architecture is tailored specifically as a decision support tool for senior management to: (i) assess potential impacts of·operational and programmatic decisions on the probability of success in pursuing a candidate portfolio of R&D projects; (ii) to aid in the development effective performance metrics for R&D project portfolios; and (iii) to study the impacts of various planning scenarios on future staffing requirements and market share. Conducting these assessments in a simulation environment prior to actual implementation can help identify the major obstacles to success and help refine specific implementation details without adversely affecting workforce performance or morale.

5.5 Case Study: DFRC 10 Year Strategic Planning

This section summarizes results obtained with SEMPRO in the context of the candidate DFRC project portfolio described Section 2.4. The primary purpose of this test case is to demonstrate the correct functional operation of the integrated suite of SEMPRO of software modules. Although the SEMPRO capabilities described in Section 4.0 have been thoroughly tested at the module level, research time limitations did not allow for a thorough case study analysis of the DFRC candidate project portfolio. Instead, the DFRC portfolio is used here to sequentially illustrate actual SEMPRO inputs and outputs for a realistic set of input data.

Table 2-1 Programmatic Attributes for a Candidate Project Portfolio, Table 2-2 Flight Vehicle Attributes for a Candidate Project Portfolio, and Table 2-3 Technology Readiness Levels for a Candidate Project Portfolio in Section 2.4 provided the primary project input data. Line department data, analogous to that provided in Table 4-4 Example of SEMPRO Line Department Input Data for the DFRC Flight Systems Branch (Code RF), was manually created within the "Branch" worksheet, as SEMPRO input data for each of the ten organizational branches used to model the DFRC operational processes.

For each of the projects listed in Table 2-1, the **WBS_Generator** module created resource loaded, Level 2/3 work breakdown structures, analogous to that shown in Figure 8-5 and Figure 8-6 for the X-43A project, and saved the results in the "Project_WBS" worksheet.

Using the sub-total cost, duration (in years) and line department staff requirements for each project phase, the **PSP_Main** module then used the APSP algorithm to select the six projects identified in **Figure 4-10 Integrated Project Schedule Example from the Project Selection Module.** Since Excel SOLVER limits the APSP size to a maximum of 200 decision variables, the cost coefficients provided to the **PSP_Main** module were artificially adjusted to ensure that at most, only six projects that could be completed within 8 years (or 32 quarters) would be selected (6 activities per project times 32 quarters leads to 192 decision variables for each project in the PCP_j Lagrange Relaxation loop).

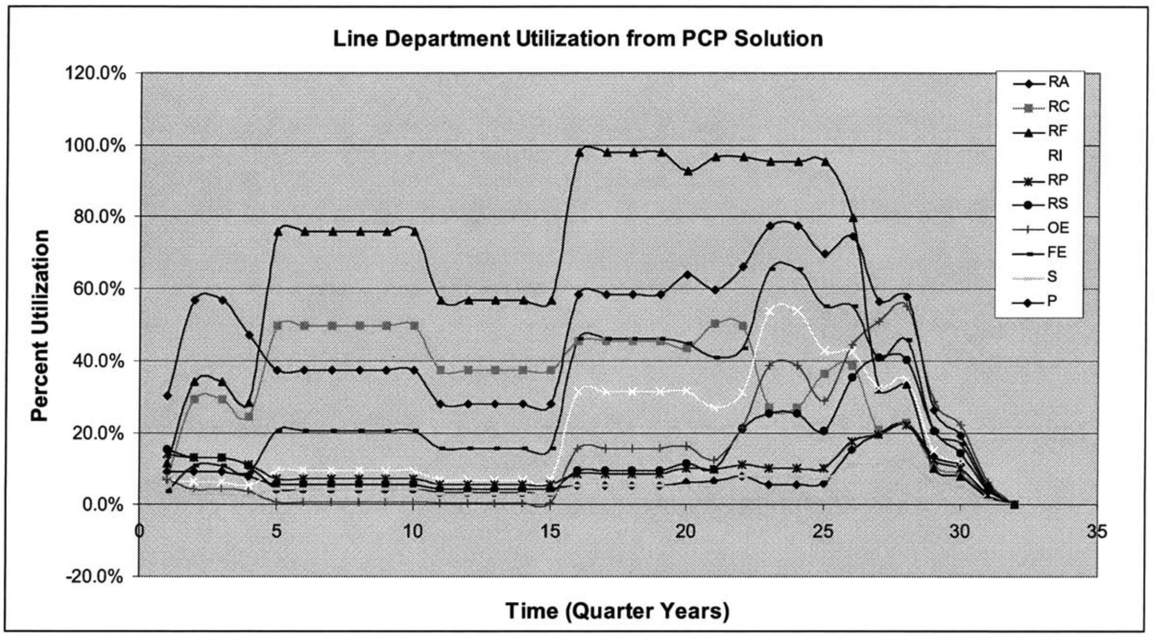

Figure 5-1 Line Department Capacity Utilization Based Upon PCP Solution

For the six selected projects, the **PCP_Main** module then established the line department capacity utilization projections shown below in **Figure 5-1 Line Department Capacity Utilization Based Upon PCP Solution.** The line department utilization shown in Figure 5-1 indicates that the project execution sequence was dictated by the capacity limits within a single branch (i.e., Code RF). The associated project Level 2 execution sequence shown in **Figure 5-2 Comparison of PCP Activity Schedules with SEMPRO Simulation Results.** The planned project execution sequence, as determined by the **PCP_Main** module, is shown on the upper row for each project in Figure 5-2. Together, the two figures indicate that the Critical Design (CD) phases are the pacing items in sequencing this particular set of projects.

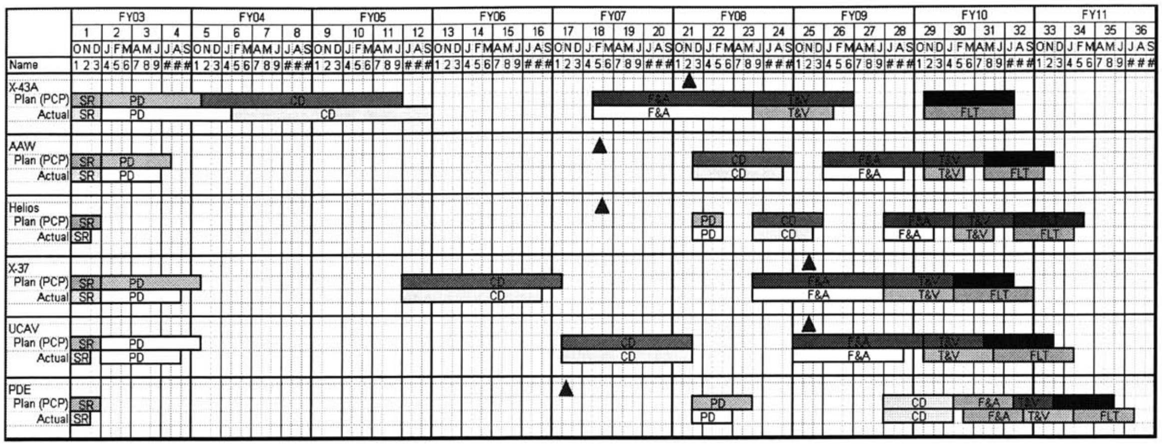

Figure 5-2 Comparison of PCP Activity Schedules with SEMPRO Simulation Results

The output of the **PCP_Main** module, in terms of planned start and stop dates for each phase of the six selected projects along with the associated project WBS Level 3 task data, provided the input data to the **Project_Sim_Main** module. The lower row for each project shown in Figure 5-2 shows the actual project activity start and completion times as determined by the SEMPRO discrete event simulation run. For this case, nominal run-time parameters were used, with no quality measurement noise or external disturbances applied. The figure shows close correlation between the project portfolio schedule plan developed by the **PCP_Main** module and the simulation results. The minor phase completion differences can be attributed to variations in work force efficiency, as governed by the individual staff allocated to each project, and to differences in time scales (i.e., quarter-year periods for **PCP_Main** versus single work days for **PCP_Sim_Main**). **Figure 5-3 SEMPRO Time Histories of Project Task Completions** illustrates the actual rate of completion of project WBS Level 3 tasks over the 1950-day simulation run. It is seen that all projects successfully completed each WBS Level 3 task. The actual run-time required to complete this simulation was approximately 55 minutes, using a PC laptop computer.

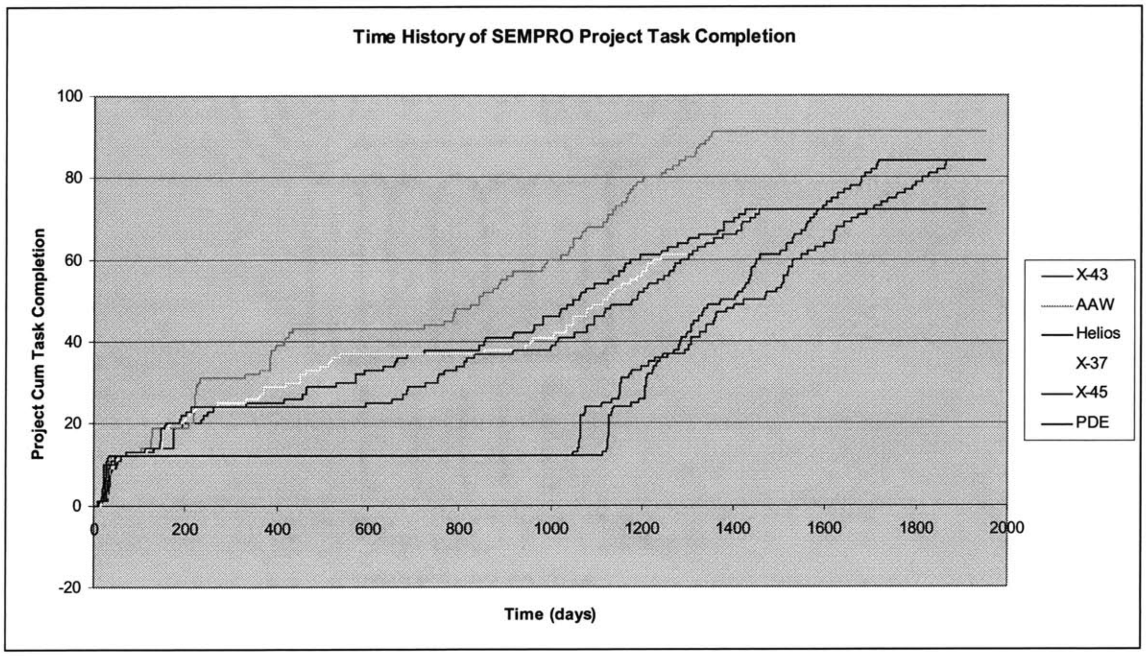

Figure 5-3 SEMPRO Time Histories of Project Task Completions

6 Conclusions and Recommendations

6.1 Summary of Research Contributions

The main contributions of this research thesis can be summarized in both academic and operational terms. The primary academic contributions are threefold. First, this thesis developed a comprehensive software system architecture that integrates elements of project portfolio management with elements of mathematical programming and discrete event simulation. The approach developed to simulate the execution of multiple, concurrent projects in a resource constrained environment is completely original to this thesis. In particular, this method as described in Section 4 introduces dynamic simulation capabilities to the traditional, static Work Breakdown Schedules used throughout the aerospace industry. Second, this thesis refined the formulation and algorithmic solution to the Project Coordination Problem first defined by Roemer. In particular, the perturbation heuristic algorithm described in Section 3.1.2.3.2 is an original development of this thesis. The details provided in the thesis on the basic PCP formulation and the heuristic solution methodology may facilitate subsequent follow-on research. Third, the formulation of the Aggregate Project Selection Problem in Section 3.3.4 comprises an original contribution of the thesis.

These same academic contributions present tangible operational benefits to the authors' employer and sponsoring organization at the NASA Dryden Flight Research Center (DFRC). In particular, the creation of an operational prototype of the Simulation Environment for Multiple Project Resource Optimization (SEMPRO) in the Microsoft Excel Visual Basic Application environment allows for immediate knowledge transfer and operational assessments at NASA DFRC. Subsequent revisions and enhancements to the SEMPRO prototype are anticipated over the next few years as the DFRC Planning Office evaluates the utility and effectiveness of this new management support tool.

6.2 Recommendations for Follow-on Research and Development

This section provides recommendations for potential follow-on research and development efforts, first in terms of theoretical and algorithm enhancements from an academic perspective, then in terms of operational improvements from a DFRC users perspective.

6.2.1 Follow-on Academic Research

6.2.1.1 Alternative Heuristic Solutions to the Project Coordination Problem

The perturbation heuristic in Section 3.1.2.3.2 may be described as a robust "brute force" method of finding a feasible solution to the Project Coordination Problem, but is computationally inefficient and often highly sub-optimal. Development of alternative, computationally efficient heuristic methods that reliably yield near-optimal solutions to the Lagrange Relaxation solution to the Project Coordination Problem is a rich area that is strongly recommended for follow-on research. Other alternative methods worth considering include: (i) Binary Integer Linear Programming sub-problems that identify the optimal PCP_j solution from the subspace of all possible forward and backward slack times associated with a given Lagrangian Relaxation solution; and (ii) formulation and solution of PCP_j sub-problems comprising all projects, if any, which contribute towards violation of the resource capacity constraints for a given Lagrangian Relaxation solution. There are undoubtedly other alternative and more elegant candidate heuristic methods worthy of investigation.

6.2.1.2 Advanced Dynamic Simulation Models for Project Task Execution

The linear, discrete time dynamic simulation model described in Section 4.2.6.2 for updating project task state variables is a highly simplified and idealized approach. This model was selected for the SEMPRO prototype based upon the inherent properties of infinite gain and phase margins associated with the project management feedback loop. However, examination of other more interesting and perhaps more accurate project management and task execution models would make an interesting research study. This can be easily accommodated within the SEMPRO prototype by substitution of alternative Excel Visual Basic Application modules for the **Task_Update** and **Task_Coefficients** subroutines.

One particular alternative modeling approach worth noting here is potential development and application of an "entropy theory of project management" based upon analogies with the discipline of statistical thermodynamics. This is an emergent theory of project management in which the primary objective is to reduce the inherent chaos and uncertainty associated with a project at the conceptual design stage, by the transformation of information into highly structured (i.e., low entropy) products or services. See, for example, the recent work by Bushuyev and Sochev[26].

6.2.1.3 Object-oriented User Interface for Organizational and Operational Studies

In order to use the SEMPRO framework for subsequent organizational and operations research studies, the development and integration of an object-oriented Graphical User Interface (GUI) module is strongly recommended. The present version of SEMPRO is tailored specifically towards an operational model of the NASA Dryden Flight Research Center. However, the underlying SEMPRO programming structure readily lends itself to a more generic graphical "point and click" interface. This capability would provide users with the ability to model alternative organizational structures without having to re-write any of the SEMPRO source code.

6.2.1.4 SEMPRO Case Studies

Practical time limits on this thesis research precluded the ability to perform detailed case studies with the SEMPRO prototype. This presents the opportunity to conduct a well-designed series of case studies as a research project for the purpose of investigating the relationship between linear programming models used for project scheduling, such as PCP and APSP, and the non-linear, stochastic discrete event simulation models used within SEMPRO. In particular, investigation into an algorithmic feedback loop between the **PCP_Main** and the **Project_Sim_Main** modules within SEMPRO may provide interesting insights regarding the use of conservative project scheduling parameters, such as inherent slack time and probabilistic task duration times. An additional academic research study worth considering is the use of alterative task estimation algorithms within the SEMPRO **WBS_Generator** module. For example, M. J. Lanigan[27] has developed an interesting, non-linear task estimation model that adjusts an "optimal" baseline task workforce and duration estimate for non-optimal workforce allocations (either larger or small project task team sizes).

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[26] Bushuyev, Sergey D and Sergey V Sochnev. "Entropy Measurement as a project control tool." International Journal of Project Management, Vol. 17, No. 6 (1999): 343-350.

[27] Lanigan, M. J. "Task Estimating: completion time versus team size." Engineering Management Journal, October, 1994: 212-218.

6.2.2 Recommended SEMPRO Operational Improvements

The following improvements to the SEMPRO prototype software code are recommended in order to make the program suitable for operational use at NASA/DFRC.

6.2.2.1 Improved User Interface

In addition to the Graphical User Interface described above (Section 6.2.1.3) for enabling rapid model development of alternative organizational structures, the existing SEMPRO prototype code requires a user-friendly graphical "point and click" interface to simplify and automate execution across each of the primary modules described in Section 4.1.1. The existing SEMPRO prototype requires manual user intervention within the Excel VBA environment when progressing through a complete project portfolio analysis, stepping sequentially through the **WBS_Generation**, **PSP_Main**, **PCP_Main** and **Project_Sim_Main** modules. Incorporating drop-down user menus to facilitate this process would be required for users not familiar with the details of the VBA programming environment. In addition, drop down user menus are recommended to facilitate SEMPRO users in the data entry for candidate project portfolios, as described in Section 4.2.1.

6.2.2.2 Embedded Linear Programming Solvers

The inherent software limitations imposed by the Excel SOLVER linear programming algorithms, as described in Section 4.1.4, constitute a major obstacle in the practical application of SEMPRO to real-world problems. The recommended approach to alleviate these limitations is to embed within SEMPRO alternative, computationally efficient network flow solution algorithms to solve the Lagrange Relaxation formulation of the Project Coordination Problem, and efficient Binary Integer Linear Programming algorithms to solve the Aggregate Project Selection Problem. An alternative approach would be to incorporate database interface capabilities within SEMPRO to allow use of commercially available linear programming software packages. This approach, however, is not recommended unless the interface to, and real-time execution of, the linear programming algorithms can be completely automated without user intervention. In either case, the programming should take advantage of the sparse data structure of the PCP_j and APSP formulations.

6.2.2.3 Calibrated WBS Generators

The functional capability of the existing **WBS_Generator** module as described in Section 4.2.3 is inadequate for practical applications. Additional work is required to calibrate the WBS generation for each project category against historical data at NASA DFRC. An enhancement to the SEMPRO software code is also recommended to allow use of actual, detailed project WBS descriptions, whenever available, instead of those provided by the SEMPRO **WBS_Generator** module.

6.2.2.4 Software Requirements Document and Users Manual

Finally, creation of a SEMPRO software systems requirement document and a SEMPRO Users Manual will be required to support development of a SEMPRO beta-type version suitable for widespread user evaluations and practical applications. Each of the above operational enhancements should be included in any subsequent beta-type or production version of SEMPRO.

7 References

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8 Appendices

Appendix 1: Project Category Examples

Appendix 2: Default WBS Level 2 Activity Networks for DFRC Projects

Appendix 3: Definition of NASA Technology Readiness Level

Appendix 4: SEMPRO Internal Data Structures

8.1 Appendix 1: Reference Activity Networks for Project Categories

8.1.1 Category 1: Internal X-Plane Project with X-43 Example

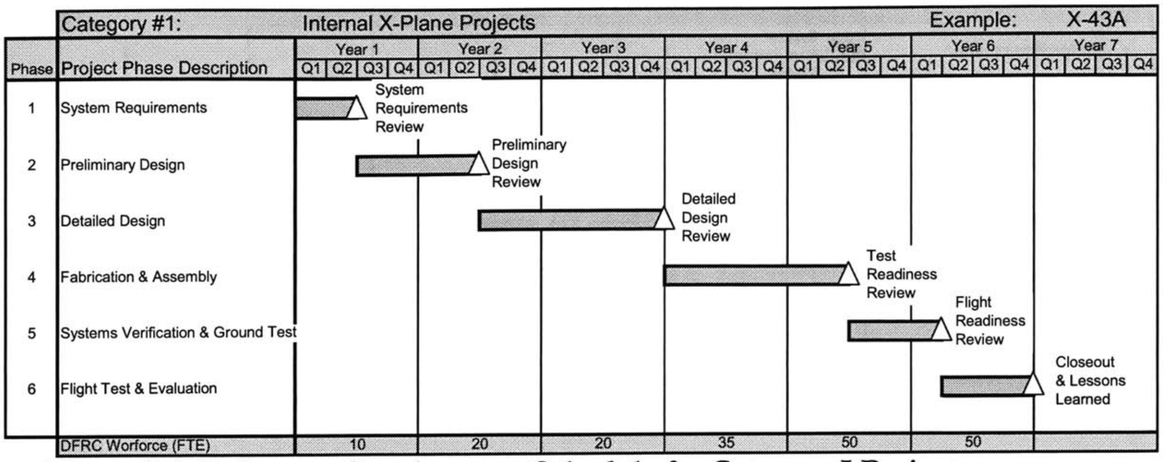

Figure 8-1 Reference Development Schedule for Category I Projects

8.1.2 Category 2: Testbed Project with AAW/SRA Example

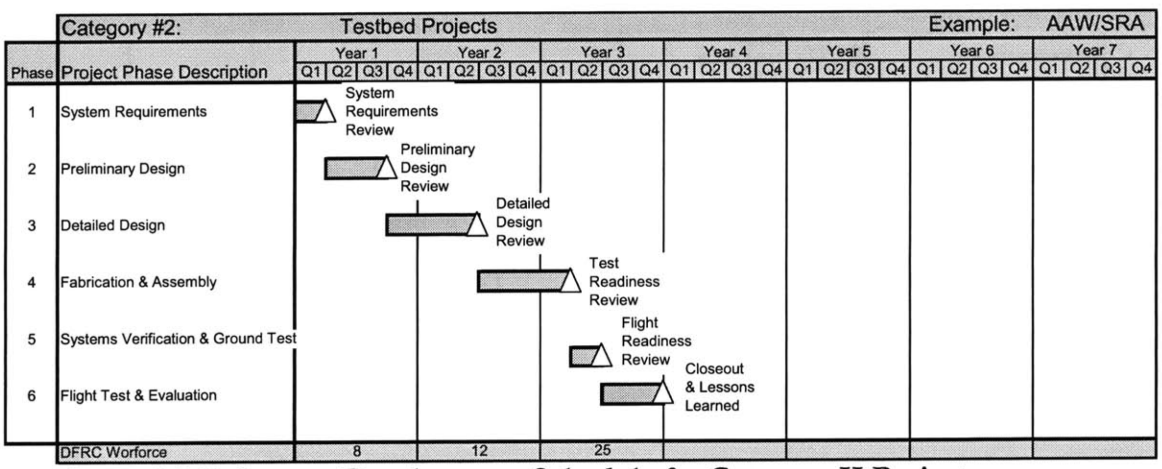

Figure 8-2 Reference Development Schedule for Category II Projects

8.1.3 Category 3: Partnership Project with Helios Example

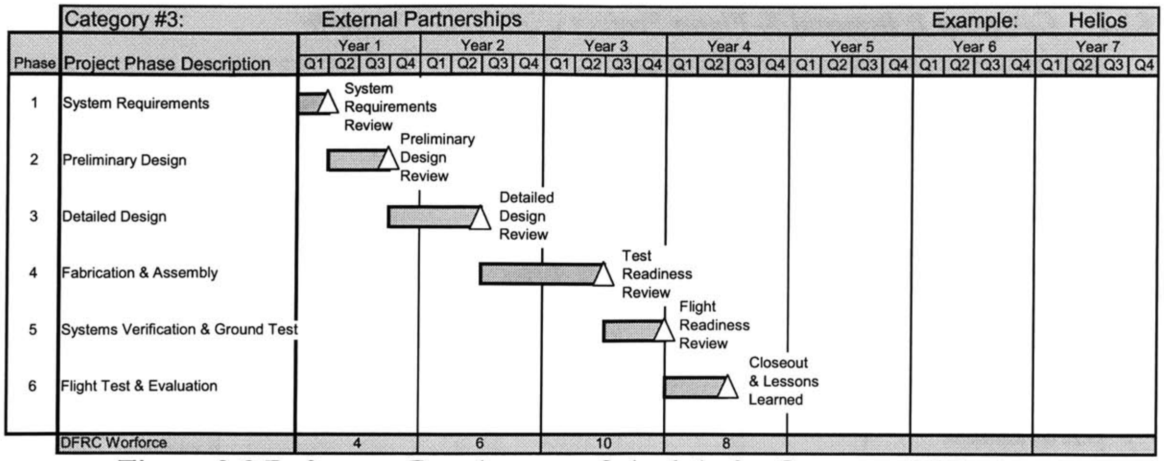

Figure 8-3 Reference Development Schedule for Category III Projects

8.1.4 Category 4: Host Mode Project with X-45 Example

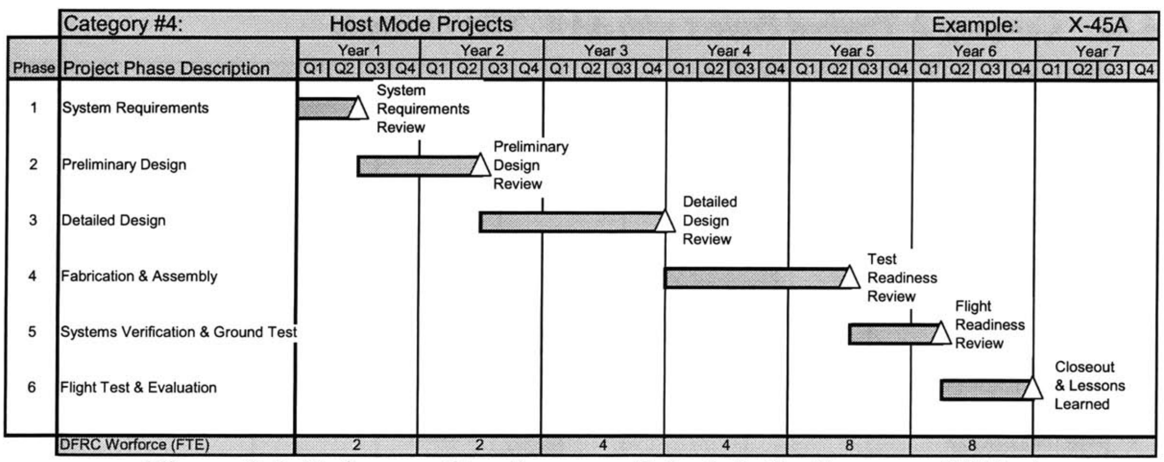

Figure 8-4 Reference Development Schedule for Category IV Projects

Project: X-43A			Schedule Factors						Cost Factors			Risk Factors				
WBS	Phase	Description	OPR	Task ID	#Sub-tasks	P1	Plan Duration (wks)	Plan Effort (hrs)	Material Cost	Labor Cost	Budgeted Cost	Uncertainty	Technical Risk	Safety Risk	Complexity	f-factor
1.010	1.000	Mission Requirements	0	1	10	0	4	928	0	92800	92800	0.870	0.837	0.830	0.983	1.847
1.020	1.000	System Architecture	0	2	10	1	6	106	0	15900	15900	0.766	0.907	0.981	0.885	1.759
1.030	1.000	Systems Engineering Reqt	0	3	12	2	3	140	0	14000	14000	0.964	0.788	0.834	0.889	1.759
1.040	1.000	Software Requirements	1	4	8	2	3	161	0	16100	16100	0.754	0.793	0.972	0.933	1.276
1.050	1.000	T&V Plan	0	5	6	2	2	171	0	17100	17100	0.959	0.896	0.976	0.961	1.759
1.060	1.000	Conceptual Design	1	6	6	2	4	102	0	10200	10200	0.829	0.759	0.895	0.808	1.407
1.070	1.000	System Safety Plan	1	7	5	2	1	136	0	13600	13600	0.907	0.891	0.968	0.791	1.407
1.080	1.000	Configuration Control Plan	0	8	4	2	1	58	0	5800	5800	0.897	0.801	0.973	0.871	1.759
1.090	1.000	Acquisition Plan	0	9	10	2	1	97	0	9700	9700	0.784	0.825	0.940	0.780	1.759
1.100	1.000	Project Plan	0	10	5	6	4	126	0	12600	12600	0.829	0.852	0.857	0.876	1.759
1.110	1.000	Project Management 1	1	11	5	0	18	540	0	108000	108000	0.830	0.902	0.928	0.844	1.000
1.120	1.000	Systems Requirement Review	0	12	81	2	2	1200	0	120000	120000	0.810	0.864	0.980	0.804	1.847
		Sub-Total_1	0	0	0	0	20.0	3765			435800					
						QTR =	2	6								
2.010	2.000	Kickoff & Orientation	0	1	5	0	1	212	0	21200	21200	0.892	0.873	0.967	0.804	1.847
2.020	2.000	Airframe Layouts	0	2	15	1	16	1392	0	139200	139200	0.987	0.890	0.900	0.962	1.847
2.030	2.000	Prelim Aero Model	0	3	8	2	12	352	0	35200	35200	0.896	0.771	0.900	0.829	1.759
2.040	2.000	Prelim GN&C Design	1	4	5	2	10	988	0	98800	98800	0.843	0.779	0.789	0.980	1.340
2.050	2.000	Prelim Propulsion Design	0	5	5	2	8	143	0	14300	14300	0.761	0.994	0.924	0.815	1.759
2.060	2.000	Prelim Avionics Design	0	6	5	2	8	312	0	31200	31200	0.775	0.797	0.847	0.820	1.519
2.070	2.000	Software Alpha Version	1	7	5	2	12	1176	0	117600	117600	0.809	0.868	0.899	0.968	1.340
2.080	2.000	Prelim Sim Models	1	8	7	2	8	496	0	49600	49600	0.941	0.887	0.835	0.968	1.477
2.090	2.000	Interface Control Dwgs	0	9	10	7	8	592	0	59200	59200	0.786	0.902	0.759	0.874	1.759
2.100	2.000	Update Requirements & Plans	0	10	7	7	3	150	0	15000	15000	0.832	0.758	0.828	0.824	1.847
2.110	2.000	Project Management 2	1	11	5	0	37	1480	0	296000	296000	0.867	0.963	0.999	0.969	1.000
2.120	2.000	PDR	0	12	77	9	2	1200	0	120000	120000	0.783	0.868	0.898	0.881	1.847
		Sub-Total_2	0	0	0	0	42	8493			997300					
						QTR =	4	10								
3.010	3.000	Detailed Design Planning	0	1	10	0	1	212	0	21200	21200	0.834	0.807	0.844	0.933	1.847
3.020	3.000	Structural Drawings	0	2	75	1	52	64	0	6400	6400	0.786	0.900	0.887	0.778	1.378
3.030	3.000	CFD Model	0	3	20	1	26	84	0	8400	8400	0.933	0.791	0.997	0.945	1.447
3.040	3.000	GN&C Design	1	4	20	1	39	4800	0	480000	480000	0.903	0.807	0.870	0.821	1.276
3.050	3.000	Propulsion Design	0	5	30	1	48	200	0	20000	20000	0.988	0.849	0.818	0.857	1.595
3.060	3.000	Avionics Design	0	6	50	1	48	264	0	26400	26400	0.874	0.769	0.827	0.886	1.519
3.070	3.000	Software Beta Version	1	7	50	1	60	6560	0	656000	656000	0.950	0.906	0.775	0.849	1.216
3.080	3.000	Real Time Sim/Bench Design	1	8	50	1	24	1480	0	148000	148000	0.830	0.988	0.987	0.760	1.340
3.090	3.000	Instrumentation	1	9	30	1	16	632	0	63200	63200	0.779	0.799	0.774	0.966	1.340
3.100	3.000	Mechanisms Designs	0	10	25	1	26	128	0	12800	12800	0.956	0.804	0.800	0.755	1.519
3.110	3.000	Procurement release	0	11	5	7	6	88	0	8800	8800	0.864	0.760	0.869	0.956	1.519
3.120	3.000	Project Management 3	1	12	5	0	67	2680	0	536000	536000	0.886	0.900	0.817	0.912	1.000
3.130	3.000	CDR	0	13	370	11	4	2400	0	240000	240000	0.830	0.992	0.874	0.912	1.847
		Sub-Total_3	0	0	0	0	71	19592			2227200					
						QTR =	6	7								
4.010	4.000	Build Plan	0	1	10	0	2	528	0	52800	52800	0.770	0.783	0.803	0.815	1.847
4.020	4.000	Airframe fab	0	2	500	1	48	2160	0	216000	216000	0.875	0.947	0.934	0.876	1.447
4.030	4.000	Support Structure fab	1	3	250	1	24	768	0	76800	76800	0.929	0.834	0.758	0.779	1.216
4.040	4.000	Avionics Fab/Procure	0	4	150	1	52	3812	0	381200	381200	0.811	0.986	0.909	0.879	1.519
4.050	4.000	Propulsion Fab/Procure	0	5	50	1	52	1560	0	156000	156000	0.805	0.933	0.932	0.905	1.378
4.060	4.000	Flight Software V&V	1	6	1000	1	52	3952	0	395200	395200	0.968	0.965	0.961	0.877	1.216
4.070	4.000	HIL Development	1	7	100	1	48	5184	0	518400	518400	0.882	0.756	0.778	0.971	1.216
4.080	4.000	Electrical Fabrication	1	8	75	1	26	1144	0	114400	114400	0.983	0.993	0.927	0.984	1.158
4.090	4.000	Mechanical fab/procure	0	9	75	1	39	616	0	61600	61600	0.783	0.825	0.878	0.858	1.519
4.100	4.000	Subsystems Integration	1	10	100	5	16	2512	0	251200	251200	0.867	0.928	0.932	0.891	1.340
4.110	4.000	GSE/FSE Fab	0	11	100	1	26	1730	0	173000	173000	0.936	0.815	0.918	0.950	1.675
4.120	4.000	Project Management 4	1	12	5	0	70	2800	0	560000	560000	0.958	0.985	0.847	0.847	1.000
4.130	4.000	Test Readiness Review	0	13	2415	6	2	1280	0	128000	128000	0.797	0.768	0.967	0.869	1.847
							72	28046								
						QTR =	6	6								
5.010	5.000	Test Readiness Review	1	1	5	0	2	800	0	80000	80000	0.816	0.822	0.941	0.794	1.477
5.020	5.000	Vehicle Delivery/Release	1	2	3	1	3	12	0	1200	1200	0.931	0.766	0.856	0.944	1.103
5.030	5.000	Software Installation	1	3	20	2	4	104	0	10400	10400	0.762	0.984	0.876	0.953	1.158
5.040	5.000	Instrumentation calibration	1	4	50	2	12	280	0	28000	28000	0.853	0.979	0.847	0.948	1.407
5.050	5.000	Ground Vibration Test	1	5	50	2	12	672	0	67200	67200	0.915	0.862	0.791	0.766	1.276
5.060	5.000	Combined Radiation Test	1	6	25	5	2	184	0	18400	18400	0.824	0.922	0.756	0.769	1.477
5.070	5.000	Combined Systems Test	1	7	25	6	3	208	0	20800	20800	0.984	0.756	0.914	0.994	1.477
5.080	5.000	Control Room Simulations	1	8	20	1	3	216	0	21600	21600	0.960	0.976	0.900	0.877	1.477
5.090	5.000	Engine Runup Tests	1	9	15	7	3	88	0	8800	8800	0.796	0.933	0.924	0.796	1.407
5.100	5.000	Taxi Tests	1	10	25	9	3	128	0	12800	12800	0.908	0.964	0.971	0.996	1.276
5.110	5.000	Project Management 6	1	11	5	0	28	1120	0	224000	224000	0.791	0.990	0.846	0.995	1.000
5.120	5.000	Flight Readiness Review	1	12	243	10	4	640	0	64000	64000	0.905	0.758	0.897	0.960	1.477
							32	4452								
						QTR =	3	7								
6.010	6.000	Tech Brief & Crew Brief	1	1	2	0	1	400	0	40000	40000	0.826	0.954	0.775	0.962	1.477
6.020	6.000	Block 1 Functional Check Flight	1	2	15	1	2	248	0	24800	24800	0.853	0.923	0.920	0.863	1.477
6.030	6.000	Block 1 Envelope Expansion	1	3	40	2	4	832	0	83200	83200	0.826	0.963	0.784	0.965	1.477
6.040	6.000	Configuration Change	1	4	40	3	4	832	0	83200	83200	0.855	0.770	0.894	0.907	1.477
6.050	6.000	Block 2 Tech Brief & Crew Brief	1	5	40	4	2	416	0	41600	41600	0.935	0.934	0.924	0.911	1.477
6.060	6.000	Block 2 Functional Check Flight	1	6	50	5	2	228	0	22800	22800	0.751	0.959	0.789	0.792	1.477
6.070	6.000	Block 2 Envelope Expansion	1	7	15	6	8	248	0	24800	24800	0.860	0.943	0.954	0.951	1.477
6.080	6.000	Operational Test Flights	1	8	40	7	4	832	0	83200	83200	0.993	0.789	0.767	0.910	1.477
6.090	6.000	Research Test Flights	1	9	10	7	4	240	0	24000	24000	0.866	0.848	0.757	0.898	1.477
6.100	6.000	Project Management 7	1	10	5	0	23	920	0	184000	184000	0.843	0.885	0.787	0.817	1.000
6.110	6.000	Closeout & Final Report	0	11	257	8	4	472	0	47200	47200	0.766	0.978	0.826	0.795	1.847
							35	5668								
						QTR =	3	4								

Figure 8-5 Reference WBS Level 2 Elements for Category I Projects (Part 1 of 2)

Project: X-43A			Staff Requirements									
WBS	Phase	Description	RA	RC	RF	RI	RP	RS	OE	FR/FE	S	P
1.010	1.000	Mission Requirements	96	96	96	96	96	96	80	64	80	128
1.020	1.000	System Architecture	10	20	20	8	10	20	8	0	0	10
1.030	1.000	Systems Engineering Reqt	10	20	20	10	20	20	20	0	20	0
1.040	1.000	Software Requirements	0	40	80	10	10	5	0	0	16	0
1.050	1.000	T&V Plan	10	20	40	25	20	20	20	0	16	0
1.060	1.000	Conceptual Design	20	5	10	5	10	20	16	0	8	8
1.070	1.000	System Safety Plan	8	8	16	8	8	16	16	0	40	16
1.080	1.000	Configuration Control Plan	2	4	8	4	4	4	16	0	0	16
1.090	1.000	Acquisition Plan	1	16	16	16	4	4	8	0	8	24
1.100	1.000	Project Plan	4	8	8	4	8	2	8	0	4	80
1.110	1.000	Project Management 1	0	0	0	0	0	0	0	0	0	540
1.120	1.000	Systems Requirement Review	160	160	160	160	160	160	40	40	80	80
		Sub-Total_1	321	397	474	346	350	367	232	104	272	902
			0.5	0.7	0.8	0.6	0.6	0.6	0.4	0.2	0.5	1.5
2.010	2.000	Kickoff & Orientation	20	20	20	20	20	20	20	20	20	32
2.020	2.000	Airframe Layouts	320	128	128	16	256	384	64	16	64	16
2.030	2.000	Prelim Aero Model	240	16	4	4	8	8	48	0	24	0
2.040	2.000	Prelim GN&C Design	8	640	120	0	80	80	40	0	20	0
2.050	2.000	Prelim Propulsion Design	8	16	16	8	40	7	32	0	16	0
2.060	2.000	Prelim Avionics Design	0	64	192	8	0	0	32	0	16	0
2.070	2.000	Software Alpha Version	0	240	768	40	40	16	48	0	24	0
2.080	2.000	Prelim Sim Models	24	40	40	8	40	40	32	256	16	0
2.090	2.000	Interface Control Dwgs	32	64	128	96	64	160	32	0	16	0
2.100	2.000	Update Requirements & Plans	16	40	20	16	16	16	12	8	6	0
2.110	2.000	Project Management 2	0	0	0	0	0	0	0	0	0	1,480
2.120	2.000	PDR	160	160	160	160	160	160	40	40	80	80
		Sub-Total_2	828	1,428	1,596	376	724	891	400	340	302	1,608
			0.7	1.1	1.3	0.3	0.6	0.7	0.3	0.3	0.2	1.3
3.010	3.000	Detailed Design Planning	20	20	20	20	20	20	20	20	20	32
3.020	3.000	Structural Drawings	0	0	0	0	0	40	24	0	0	0
3.030	3.000	CFD Model	52	16	0	0	16	0	0	0	0	0
3.040	3.000	GN&C Design	40	3,744	936	0	40	40	0	0	0	0
3.050	3.000	Propulsion Design	16	16	24	24	120	0	0	0	0	0
3.060	3.000	Avionics Design	16	40	192	16	0	0	0	0	0	0
3.070	3.000	Software Beta Version	0	600	5,760	40	40	0	0	0	120	0
3.080	3.000	Real Time Sim/Bench Design	80	160	160	0	80	40	0	960	0	0
3.090	3.000	Instrumentation	40	16	24	512	16	24	0	0	0	0
3.100	3.000	Mechanisms Designs	0	8	16	0	24	40	0	0	40	0
3.110	3.000	Procurement release	0	24	16	24	0	0	0	24	0	0
3.120	3.000	Project Management 3	0	0	0	0	0	0	0	0	0	2,680
3.130	3.000	CDR	320	320	320	320	320	320	80	80	160	160
		Sub-Total_3	584	4,964	7,468	956	676	524	124	1,084	340	2,872
			0.3	2.3	3.5	0.4	0.3	0.2	0.1	0.5	0.2	1.3
4.010	4.000	Build Plan	40	40	40	64	40	80	80	40	40	64
4.020	4.000	Airframe fab	960	0	0	0	0	960	240	0	0	0
4.030	4.000	Support Structure fab	0	0	24	24	0	480	240	0	0	0
4.040	4.000	Avionics Fab/Procure	0	0	2,080	1,040	416	0	260	0	16	0
4.050	4.000	Propulsion Fab/Procure	0	0	0	0	1,040	0	520	0	0	0
4.060	4.000	Flight Software V&V	0	520	3,328	0	52	0	52	0	0	0
4.070	4.000	HIL Development	0	960	960	0	192	0	0	3,072	0	0
4.080	4.000	Electrical Fabrication	0	0	260	832	52	0	0	0	0	0
4.090	4.000	Mechanical fab/procure	0	24	24	240	312	0	0	0	16	0
4.100	4.000	Subsystems Integration	0	40	320	1,024	320	384	384	0	40	0
4.110	4.000	GSE/FSE Fab	0	52	208	520	26	0	624	260	40	0
4.120	4.000	Project Management 4	0	0	0	0	0	0	0	0	0	2,800
4.130	4.000	Test Readiness Review	80	160	160	160	160	160	160	80	80	80
			1,080	1,796	7,404	3,904	2,610	2,064	2,560	3,452	232	2,944
			0.5	0.8	3.4	1.8	1.2	1.0	1.2	1.6	0.1	1.4
5.010	5.000	Test Readiness Review	80	80	80	80	80	80	80	80	80	80
5.020	5.000	Vehicle Delivery/Release	0	0	4	0	0	0	8	0	0	0
5.030	5.000	Software Installation	0	24	40	24	0	0	0	0	16	0
5.040	5.000	Instrumentation calibration	24	0	24	120	8	40	40	24	0	0
5.050	5.000	Ground Vibration Test	0	16	16	40	0	384	192	0	24	0
5.060	5.000	Combined Radiation Test	8	24	40	40	8	8	16	40	0	0
5.070	5.000	Combined Systems Test	8	40	40	40	8	8	16	40	8	0
5.080	5.000	Control Room Simulations	24	24	24	24	24	24	24	24	24	0
5.090	5.000	Engine Runup Tests	4	4	8	16	24	4	24	0	4	0
5.100	5.000	Taxi Tests	0	16	24	16	24	0	40	0	8	0
5.110	5.000	Project Management 6	0	0	0	0	0	0	0	0	0	1,120
5.120	5.000	Flight Readiness Review	40	120	120	40	40	120	80	40	40	0
			188	348	420	440	216	668	520	248	204	1,200
			0.2	0.4	0.4	0.5	0.2	0.7	0.5	0.3	0.2	1.3
6.010	6.000	Tech Brief & Crew Brief	40	40	40	40	40	40	40	40	40	40
6.020	6.000	Block 1 Functional Check Flight	24	40	24	40	24	24	24	40	8	0
6.030	6.000	Block 1 Envelope Expansion	64	96	96	128	64	96	128	128	32	0
6.040	6.000	Configuration Change	64	96	96	128	64	96	128	128	32	0
6.050	6.000	Block 2 Tech Brief & Crew Brief	32	48	48	64	32	48	64	64	16	0
6.060	6.000	Block 2 Functional Check Flight	4	40	40	40	4	4	64	24	8	0
6.070	6.000	Block 2 Envelope Expansion	24	40	24	40	24	24	24	40	8	0
6.080	6.000	Operational Test Flights	64	96	96	128	64	96	128	128	32	0
6.090	6.000	Research Test Flights	32	32	32	24	32	32	24	16	16	0
6.100	6.000	Project Management 7	0	0	0	0	0	0	0	0	0	920
6.110	6.000	Closeout & Final Report	80	120	80	24	40	80	24	16	8	0
			428	648	576	656	388	540	648	624	200	960
			0.4	0.6	0.5	0.6	0.4	0.5	0.6	0.6	0.2	0.9

Figure 8-6 Reference WBS Level 2 Elements for Category I Projects (Part 2 of 2)

8.2 Appendix 2: Default WBS Level 2 Activity Networks for DFRC Projects

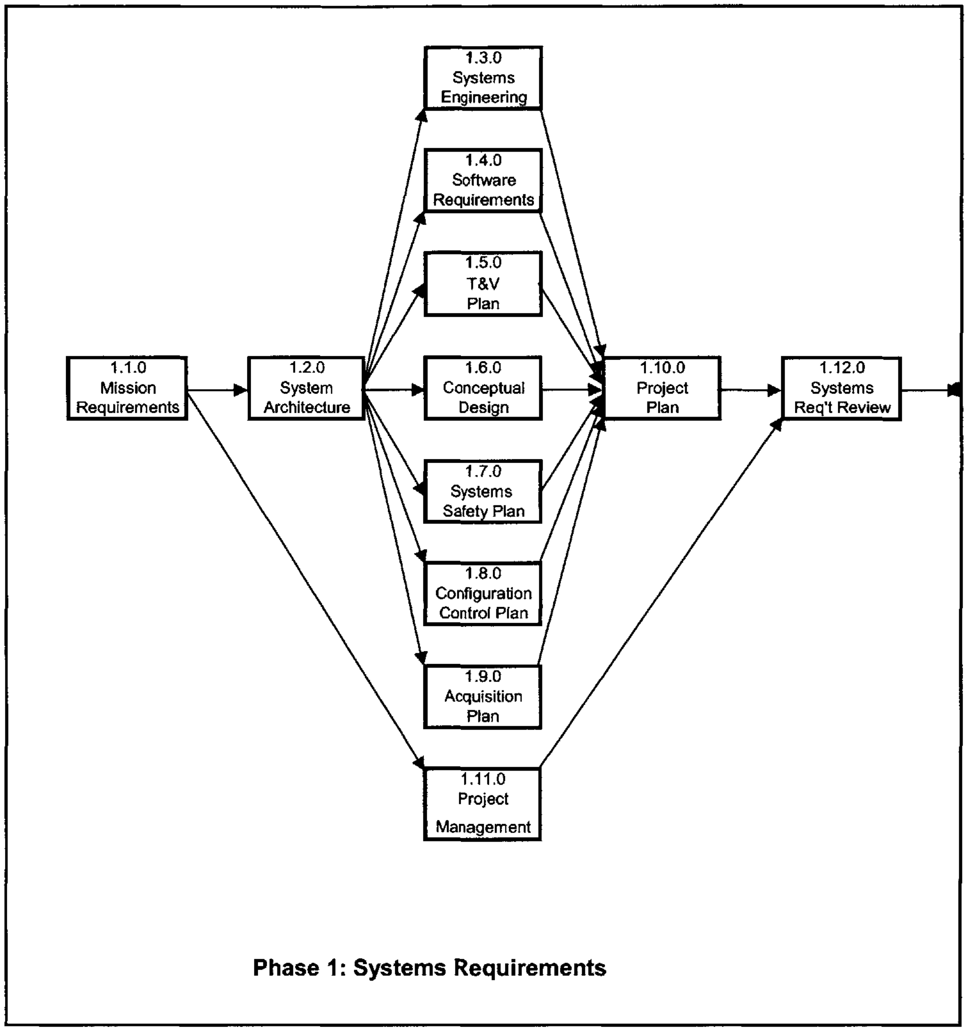

Figure 8-7 Generic Phase 1 WBS Level 2 Activity Network

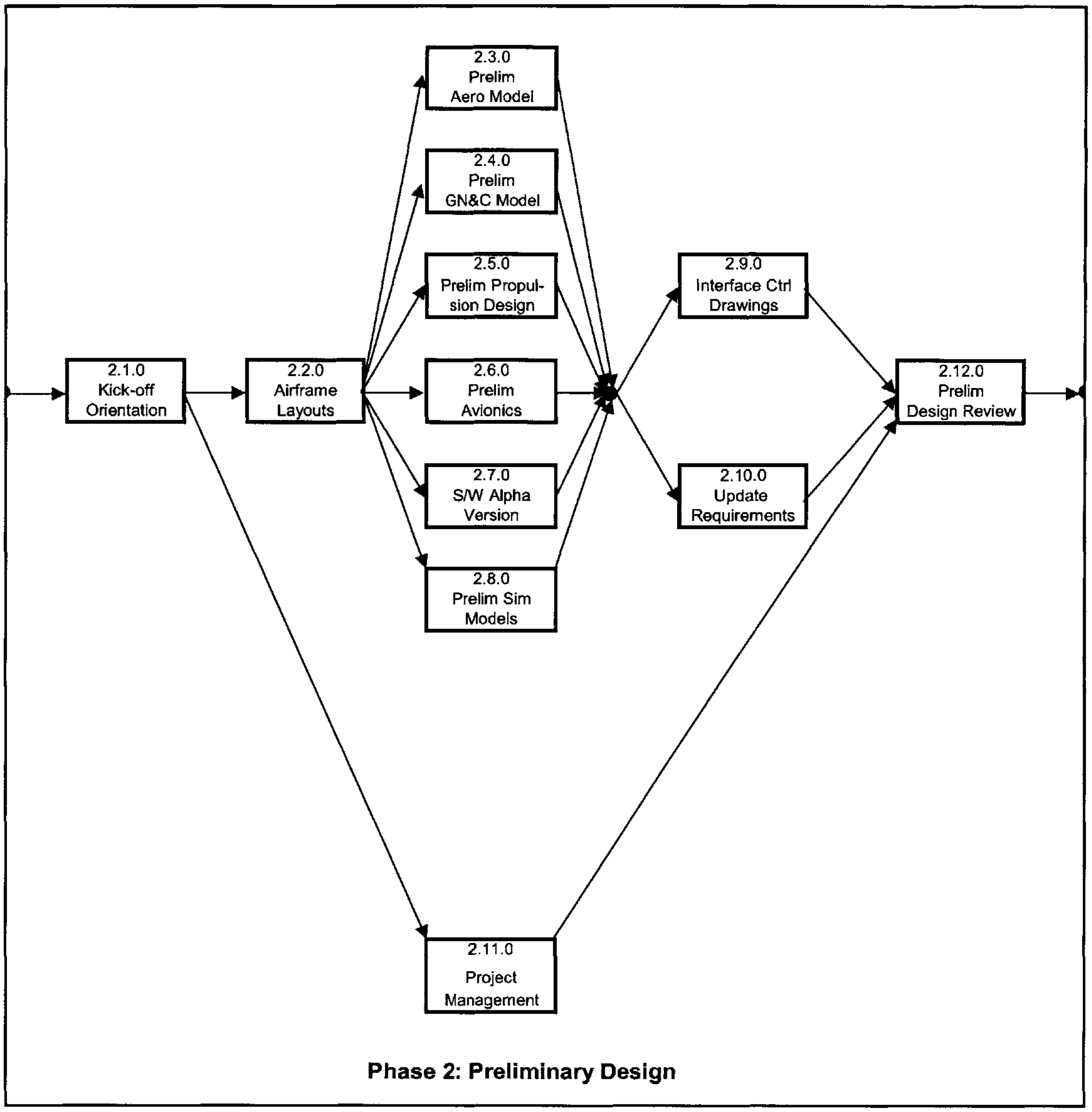

Figure 8-8 Generic Phase 2 WBS Level 2 Activity Network

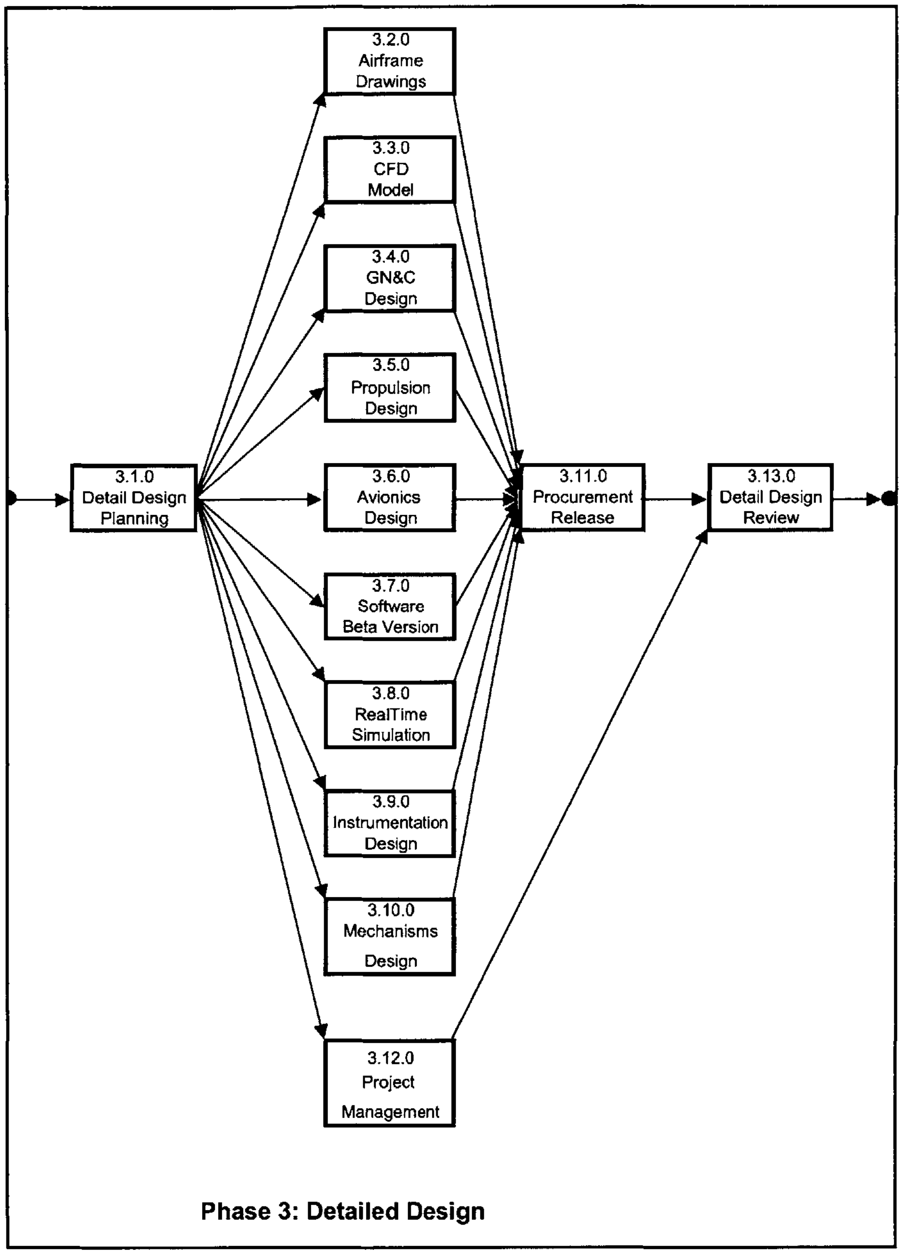

Figure 8-9 Generic Phase 3 WBS Level 2 Activity Network

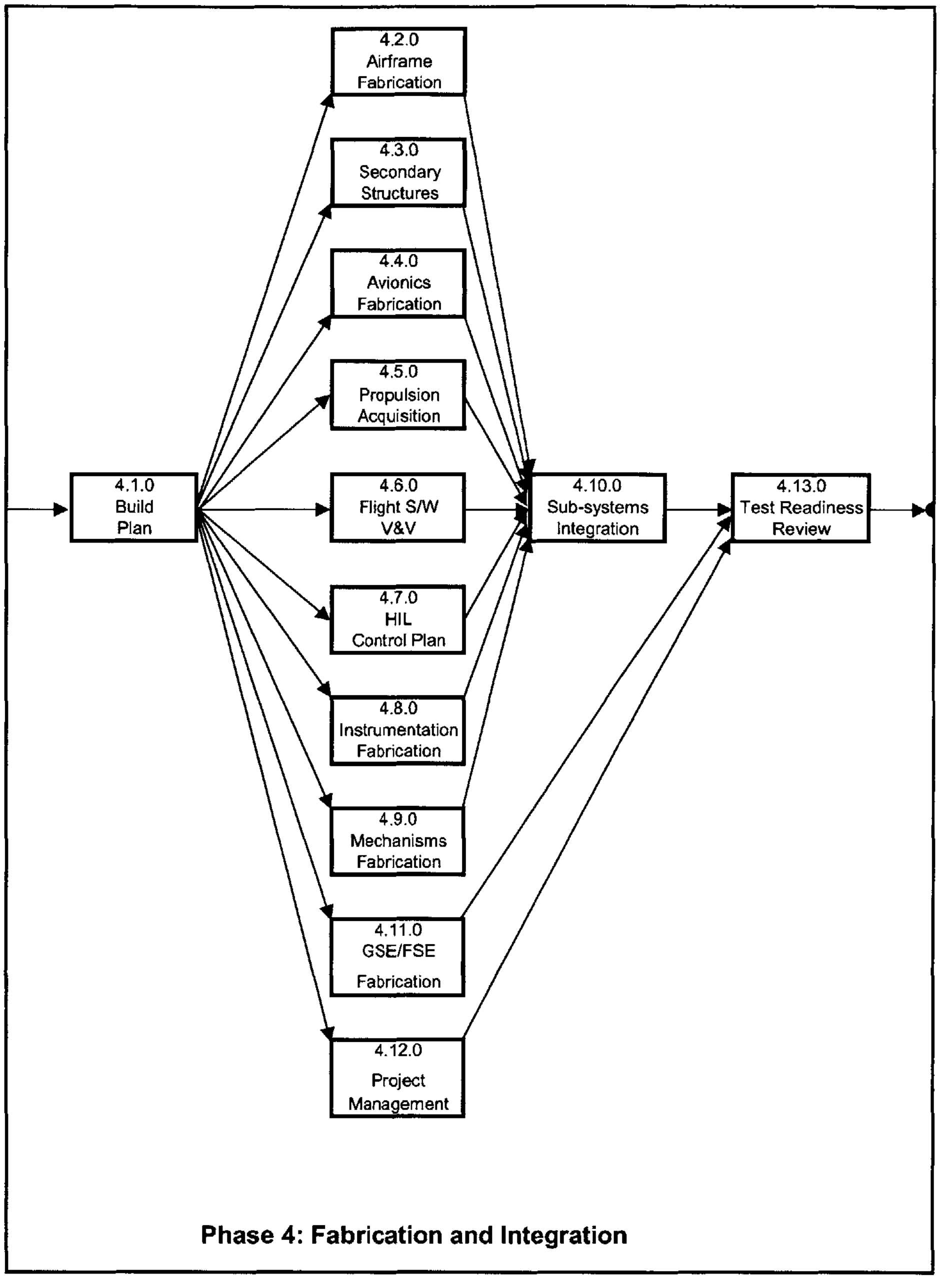

Figure 8-10 Generic Phase 4 WBS Level 2 Activity Network

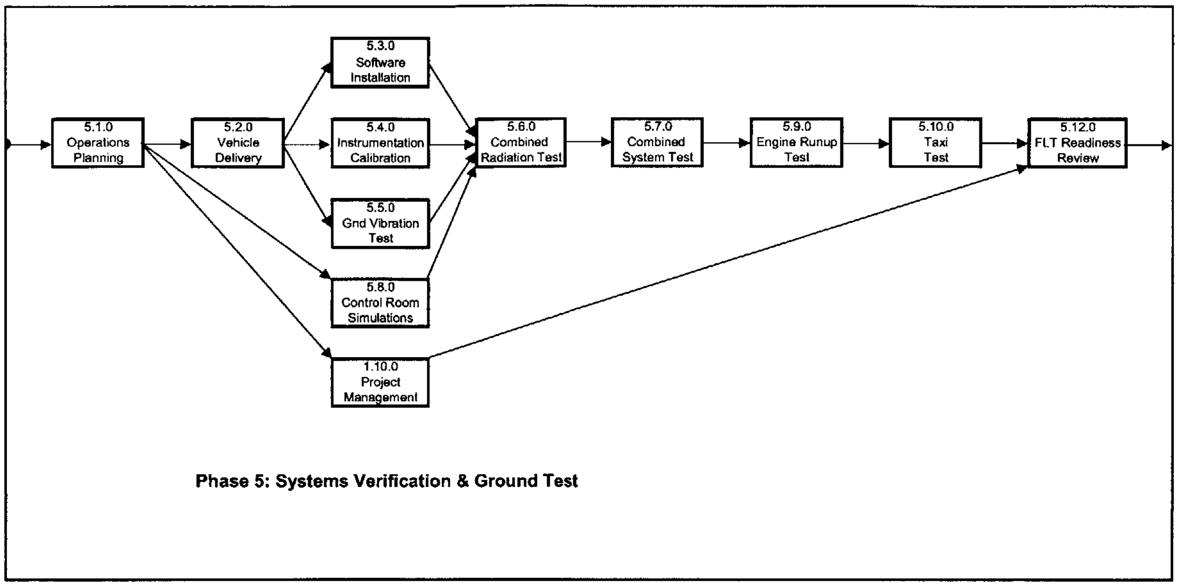

Figure 8-11 Generic Phase 5 WBS Level 2 Activity Network

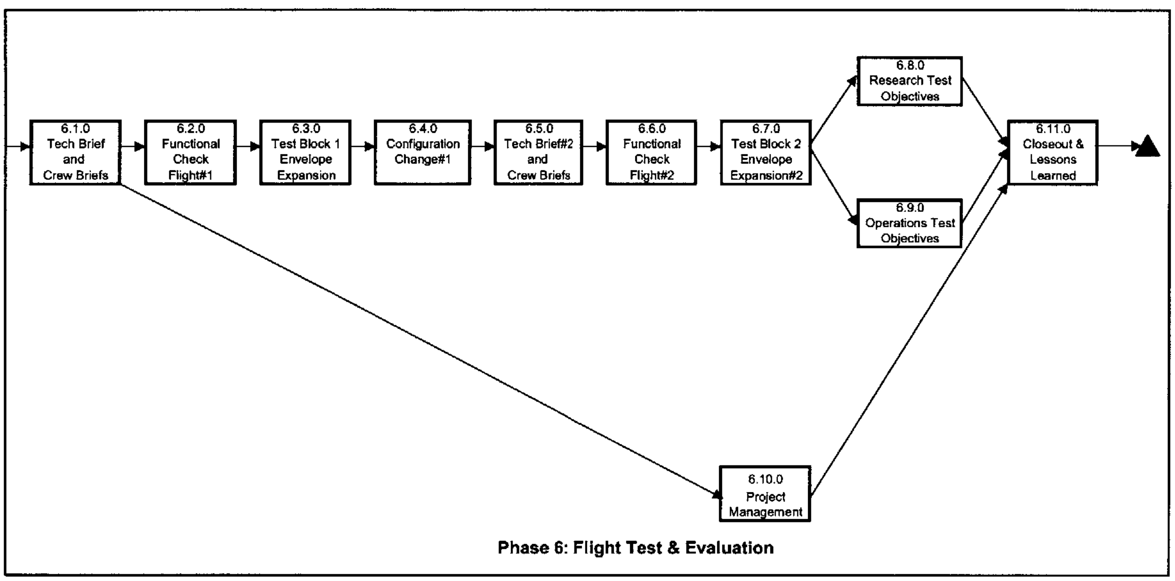

Figure 8-12 Generic Phase 6 WBS Level 2 Activity Network

8.3 Appendix 3: Definition of NASA Technology Readiness Level

Office of Aerospace Technology

Technology Readiness Levels

Basic Research		**Level 1**	Basic principles observed & reported
		Level 2	Technology concept/application formulated
Applied Research		**Level 3**	Analytical & experimental (laboratory or flight) critical function and/or characteristic proof-of-concept
Focused Technology Development		**Level 4**	Component and/or test article validation in laboratory environment (ground or flight)
		Level 5	Component and/or test article validation in relevant environment (ground or flight)
Technology Validation	**NASA** ↑	**Level 6**	System/subsystem demonstration in a relevant environment (ground or flight)
Technology Application (Prototypes)	↓ **Industry**	**Level 7**	System prototype demonstration in a flight environment
		Level 8	Actual system completed and "flight qualified" through test and demonstration (ground or flight)
Product Design, Development & Production		**Level 9**	Actual system "flight proven" through successful mission operations

Figure 8-13 Definition of NASA Technology Readiness Levels

8.4 Appendix 4: SEMPRO Internal Data Structures

```
Type Project_WBS
   Project_Name As String
   WBSN(N_phase, Max_Task) As Double
   Phase(N_phase, Max_Task) As Integer
   Description(N_phase, Max_Task) As String
   Task_OPR(N_phase, Max_Task)  As String
   Task_id(N_phase, Max_Task) As Integer
   Subtasks(N_phase, Max_Task) As Integer
   Precedants(N_phase, Max_Task) As Integer
   Duration(N_phase, Max_Task) As Integer
   Effort(N_phase, Max_Task) As Single
   M_cost(N_phase, Max_Task) As Currency
   L_Cost(N_phase, Max_Task) As Currency
   T_cost(N_phase, Max_Task) As Currency
   Uncertainty(N_phase, Max_Task) As Single
   Risk(N_phase, Max_Task, 3) As Single
   Complexity(N_phase, Max_Task) As Single
   F_factor(N_phase, Max_Task) As Single
   Task_Staff(N_phase, Max_Task, M_dept) As Single
   N_tasks(N_phase) As Integer
   Phase_Duration(N_phase) As Integer
   Phase_Staff(N_phase, M_dept) As Integer
   Phase_FTE(N_phase, M_dept) As Single
   Phase_Start(N_phase) As Integer        ' QTR (from Load_PCP_Results)
   Phase_Finish(N_phase) As Integer       ' QTR (from Load_PCP_Results)
   WBS_status(N_phase, Max_Task, 2) As Variant
```

Figure 8-14 Internal Database for Project WBS

```
Type P_Update
   N_Active As Integer
   N_Full_Reg As Integer
   N_Full_OT As Integer
   N_Partial As Integer
   N_Complete As Integer
   N_Wait As Integer
   N_starved As Integer
   N_Failed As Integer
   Active_Tasks(Max_Task) As Integer
   Complete_Tasks(Max_Task) As Integer
   Wait_Tasks(Max_Task) As Integer
   Starved_Tasks(Max_Task) As Integer
   Failed_Tasks(Max_Task) As Integer
   Partial_Tasks(Max_Task) As Integer
   Minimum_WF As Single   ' percent
   BCWP As Currency
   ACWP As Currency
   SPI As Double                 ' scalar ~ 1.0 from Project_Performance()
   CPI As Double                 ' scalar ~ 1.0 from Project_Performance()
   Remaining_Budget As Currency
   Estimate_To_Complete As Currency
   Plan_Start(N_phase) As Integer    ' Days: From Load_PCP_Results (in QTR's)
   Plan_Finish(N_phase) As Integer   ' Days: From Load_PCP_Results(in QTR's)
   Plan_Duration(N_phase) As Integer  ' Days: = Plan_Finish(i) - Plan_Start(i)
   Plan_Slip(N_phase) As Integer     ' Days: From Project_Perf: = Plan_Start(i) -
Actual Finish(i)
   ESD(N_phase) As Integer         ' Days: = Plan_start(i) + Plan_Slip(i-1)
   ECD(N_phase) As Integer         ' Days: = ESD(i) + Plan_Duration(i)
   Actual_Start(N_phase) As Integer   ' Days: from Phase_Management
   Actual_Finish(N_phase) As Integer  ' Days: from Phase_Management
   Quality_metric As Double
   Productivity_metric As Double
   WF_Efficiency As Double
   Plan_effort As Double
   Actual_effort As Double
   Earned_value As Currency
   Percent_complete(N_phase) As Double
   Plan_Demand(M_dept, Tmax_qtr) As Single
   Update_Demand(M_dept, Tmax_qtr) As Single
```

Figure 8-15 Internal Database for Each Project Update

```
Type P_status
   State As Variant
   Current_Phase As Integer
   Phase_Status(N_phase) As String
   Review_Status(N_phase) As String
   Priority As String
   Visibility As String
   Schedule_Pressure As Single
   Budget_Pressure As Single
   Quality As Double
   Productivity As Double
   Cost_status As String
   Schedule_status As String
   Staffing_status As String
   Project_Morale As Single
   Project_Momentum As Double
   New_Phase_Event As Boolean
   New_Task_Event As Boolean
   Branch_OT(M_dept) As Boolean
End Type
Dim Project_Status(N_Projects) As P_status
```

Figure 8-16 Internal Database for Individual Project Status

```
Type Task_Queue
   Phase As Integer
   Task_id(Max_Task) As Integer
   State(Max_Task) As Integer
   N_subtasks(Max_Task) As Integer
   U_ramp(Max_Task) As Single
   T_duration(Max_Task) As Integer
   T_effort(Max_Task) As Integer
   T_start(Max_Task) As Integer
   T_stop(Max_Task) As Integer
   T_run(Max_Task) As Integer
   T_residual(Max_Task) As Double
   T_uncertainty(Max_Task) As Single
   T_risk(Max_Task) As Single
   T_complexity(Max_Task) As Single
   T_Factor(Max_Task) As Single
   T_WF_Required(Max_Task, M_dept) As Single
   T_WF_Assigned(Max_Task, M_dept) As Single
   T_WF_Productivity(Max_Task, M_dept) As Single
   T_Eff_Productivity(Max_Task) As Single
   Q_result(Max_Task) As String
   Effort(Max_Task) As Double
   Cost(Max_Task) As Currency
   N_queue As Integer
   Task_Completion_Event(Max_Task) As Boolean
   T_Ap(Max_Task, Nxp, Nxp) As Double
   T_Bp(Max_Task, Nxp) As Double
   T_Cp(Max_Task, Nyp, Nxp) As Double
   T_Xp(Max_Task, Nxp) As Double
   T_Xp1(Max_Task, Nxp) As Double
   T_Yp(Max_Task, Nyp) As Double      ' T_Yp = task ouputs: 1 = Effort; 2 = Output; 3 = Product
   T_Uc(Max_Task) As Double           ' T_Uc = task command generator: Ramp-up to N_subtasks
   T_Kr(Max_Task) As Double           ' Kr = productivity gain (should equal Kw and kp) <= 1
   T_Kq(Max_Task) As Double           ' Kq = quality gain <= 1
   T_Kp As Double                     ' Kp = Management proportional gain
   T_Ki As Double                     ' Ki = Management integral gain
   T_Kw(Max_Task) As Double           ' Effective productivity
   T_W1(Max_Task) As Double           ' Task Lag time constant = 2*pi*Tduration (rad/sec)
```

Figure 8-17 Internal Database for Each Project Phase Task Queue

```
Type Branch_status                         ' For each Branch: per employee
   Rindex As Integer                        ' Row index for worksheet "Branch"
   Number_EP As Integer                     ' Current number of Branch Employees
   Utilization As Single                    ' percent (project demand/capacity)
   State As String                          ' Empty/Nominal/Saturated
   Available As Single                      ' Unused capacity (manhours/qtr)
   Morale As String                         'Low/Normal/High
   Annual_Leave(Max_EP) As Integer          ' hrs/FTE/YR
   Annual_Admin(Max_EP) As Integer          ' hrs/FTE/YR
   Annual_Training(Max_EP) As Integer       ' hrs/FTE/YR
   Staff_Grade(Max_EP) As Integer           ' GS Level
   Time_In_Grade(Max_EP) As Integer         ' years
   FullCost_hr(Max_EP) As Currency          ' $/hr
   QTR_Leave(Max_EP) As Integer             ' hrs/FTE/QTR
   QTR_Admin(Max_EP) As Integer             ' hrs/FTE/QTR
   QTR_Training(Max_EP) As Integer          ' hrs/FTE/QTR
   QTR_Available(Max_EP) As Integer         ' hrs/FTE/QTR
   Project_Exp(Max_EP, Max_Projects + 1) As Single                       ' hrs/FTE/qtr
   Project_Proficiency(Max_EP, Max_Projects + 1) As Single               ' percent
   Project_Assignments(Max_EP, Max_Projects) As Single                   ' hrs/FTE/QTR
   Project_workload(Max_EP) As Single                                    ' hrs/FTE/QTR
   Net_productivity(Max_EP) As Single                                    ' output hrs/QTR
   Unused_Capacity(Max_EP) As Single                                     ' output hrs/QTR
   Project_Daily(Max_EP + 1, Max_Projects + 1) As Single                 ' percent
   Project_Daily_OT(Max_EP + 1, Max_Projects + 1) As Single              ' percent
   Project_QTR_OT(Max_EP + 1, Max_Projects + 1) As Single                ' percent
   Project_QTR_Total(Max_EP + 1, Max_Projects + 1) As Single             ' percent
   Project_Task_Daily_Assign(Max_EP, Max_Projects, Max_Task) As Single   ' hrs/day
   Branch_Capacity As Single                                             ' Billable manhours/qtr
   Effective_total(Max_Projects) As Single                               ' hrs/qtr
   Branch_Productivity As Single                                         ' Effective output hrs/qtr
   Branch_Availability As Single                                         ' Unused workhours/qtr
   Project_Demand(Max_Projects) As Single                                ' hrs/qtr
   Branch_Demand As Single                                               ' Total Project Hrs/QTR
   Branch_Utilization As Single                      ' Percent: Branch_Demand/Branch_Capacity
   Project_total(Max_Projects) As Single             ' hrs/qtr
   Effective_productivity(Max_Projects) As Single    ' hrs/qtr
   Effective_cost(Max_Projects) As Currency          ' $/Branch-hour
   N_unassigned As Integer
   Unassigned(Max_EP) As Integer
```

Figure 8-18 Internal Database for Individual Branch Status