

THE COST AND CYCLE TIME IMPLICATIONS OF SELECTED CONTRACTOR AND AIR FORCE SYSTEM PROGRAM OFFICE MANAGEMENT POLICIES DURING THE DEVELOPMENT PHASE OF MAJOR AIRCRAFT ACQUISITION PROGRAMS

by

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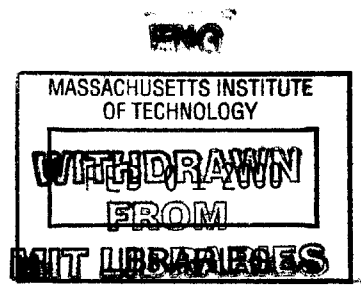
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ABSTRACT

The interactions between an Air Force System Program Office (SPO) and the prime contractor during the research and development phase of a major aircraft acquisition program are investigated using continuous-time simulation models. The cost and cycle time implications of select management policies are evaluated. The work confirms the high degree of interdependence inherent in the SPO-contractor relationship, indicating that a systems approach to managing this system is desirable. It also demonstrates that effective use of staffing policies and management reserves, as well as attention to process quality, can result in significant cost and schedule performance improvements.

Several basic project management insights are found to underlie many SPO-contractor system behaviors including that: quality drives the level of rework experienced by a program, workforce capability is a prime contributor to project quality, and proper management of the workforce is critical for optimal program cost and schedule performance. Explorations of SPO-contractor system behaviors imply a link between a focus on schedule adherence and increased program cost and schedule slip, and they advise that SPO productive capacity is critical for cost growth mitigation, as is control of contractor and workforce turnover, and that including realistic assessments of quality and productivity in early cost estimates are critical for their accuracy.

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## TABLE OF CONTENTS

<b>ABSTRACT</b> .....	<b>2</b>
<b>ACKNOWLEDGEMENTS</b> .....	<b>3</b>
<b>TABLE OF CONTENTS</b> .....	<b>4</b>
<b>LIST OF SYMBOLS</b> .....	<b>6</b>
<b>LIST OF TABLES</b> .....	<b>7</b>
<b>LIST OF FIGURES</b> .....	<b>7</b>
<b>1 INTRODUCTION</b> .....	<b>10</b>
1.1 BACKGROUND INFORMATION .....	10
1.1.1 <i>The External Environment</i> .....	11
1.1.2 <i>The Contractor and System Program Office</i> .....	12
1.2 RESEARCH AND STUDY METHODOLOGY .....	17
<b>2 THE BASIC PROJECT MODEL</b> .....	<b>19</b>
2.1 THE REWORK CYCLE.....	19
2.2 QUALITY.....	24
2.3 PRODUCTIVITY.....	28
2.4 WORKFORCE.....	30
2.5 SCHEDULE .....	37
<b>3 CONTRACTOR AND SYSTEM PROGRAM OFFICE MODEL</b> .....	<b>39</b>
3.1 MODELING THE CONTRACTOR.....	39
3.1.1 <i>Contractor’s Initial Estimates of Project Scope and Cost</i> .....	40
3.1.2 <i>Contractor Costs</i> .....	41
3.1.3 <i>Rework</i> .....	42
3.1.4 <i>Quality</i> .....	43
3.1.5 <i>Overtime and Fatigue</i> .....	44
3.1.6 <i>Productivity</i> .....	45
3.1.7 <i>Rework Discovery Time</i> .....	46
3.1.8 <i>Workforce</i> .....	47
3.1.9 <i>Schedule</i> .....	50
3.1.10 <i>Management Reserve</i> .....	51
3.2 MODELING THE SYSTEM PROGRAM OFFICE – KEY DIFFERENCES FROM THE CONTRACTOR .....	53
3.2.1 <i>Military Workforce</i> .....	53
3.2.2 <i>Determination of Manpower by Allocation Rather than by Scope</i> .....	54
3.3 VALIDATION OF THE SPO-CONTRACTOR MODEL .....	55
<b>4 ANALYSIS</b> .....	<b>57</b>
4.1 CONTRACTOR IN ISOLATION .....	57
4.1.1 <i>Half the Work in Half the Time Doesn’t Cost Half as Much</i> .....	57
4.1.2 <i>Schedule Compression</i> .....	62
4.1.3 <i>The Hidden Costs of Overtime</i> .....	68
4.1.4 <i>Workforce Management Revisited</i> .....	71
4.1.5 <i>Management Reserve</i> .....	74
4.2 CONTRACTOR AND PROGRAM OFFICE INTERACTION .....	78
4.2.1 <i>High officer turnover is expensive</i> .....	78
4.2.2 <i>Unrealistic initial estimates</i> .....	84

4.2.3	<i>SPO personnel allocation</i> .....	87
4.2.4	<i>The importance of a systems approach to managing the SPO-contractor system</i> .....	91
4.2.5	<i>Funding profiles</i> .....	94
<b>5</b>	<b>CONCLUSIONS AND RECOMMENDATIONS</b> .....	<b>101</b>
<b>6</b>	<b>FURTHER INVESTIGATIONS</b> .....	<b>110</b>
<b>7</b>	<b>REFERENCES</b> .....	<b>110</b>
<b>8</b>	<b>APPENDIX</b> .....	<b>114</b>
8.1	ACQUISITION COMMUNITY ORGANIZATION CHART .....	114
8.2	NEVISON OVERTIME EFFECTIVENESS CHART .....	116
8.3	SYSTEM DYNAMICS ESSENTIALS .....	117
8.3.1	<i>Causal loops</i> .....	117
8.3.2	<i>Stock and flow diagrams</i> .....	118
8.4	SIMPLE PROJECT MODEL DOCUMENTATION .....	120
8.4.1	<i>Simulation Control Parameters</i> .....	121
8.4.2	<i>Workforce Experience</i> .....	122
8.4.3	<i>Indicated Workforce</i> .....	124
8.4.4	<i>Productivity</i> .....	125
8.4.5	<i>Quality</i> .....	127
8.4.6	<i>Rework</i> .....	129
8.4.7	<i>Schedule</i> .....	131
8.4.8	<i>Workforce</i> .....	134
8.5	SPO-CONTRACTOR MODEL DOCUMENTATION .....	136
8.5.1	<i>Contractor Model Documentation</i> .....	137
8.5.2	<i>Program Office Model Documentation</i> .....	190
8.5.3	<i>Government Model Documentation</i> .....	261

## LIST OF SYMBOLS

Symbol	Definition
$C$ .....	Estimated program cost.
$C^*$ .....	Estimated program cost which includes the effects of quality and productivity.
$E_c$ .....	The cost estimation error resulting from not including quality and productivity effects, or the increment to cost from less than perfect quality and expected productivity.
$P$ .....	Expected average productivity of the workforce used to make initial cost estimations.
$P^*$ .....	Actual average gross productivity of workforce during program.
$q$ .....	Average project quality.
$S$ .....	Project scope. The total effort required to complete the project if quality was 100 percent.
$S^*$ .....	Total project scope; the total effort required to complete a project including rework.
$W$ .....	Average cost per worker.
$\rho$ .....	Ratio of actual gross productivity and expected productivity. ( $P^*/P$ )
$Pdy$ .....	Productivity
ACTIVE INITIAL(X,Y).....	ACTIVE INITIAL(active equation, initial equation) Returns the value of the active equation during simulation. However, for determining initial conditions the value of the initial equation is returned. Normally this function is used to break a loop of simultaneous initial value equations.
DELAY INFORMATION ...	DELAY INFORMATION (input, delay time, initial value) This function returns the value of the input delayed by the delay time – a material delay.
IF THEN ELSE .....	IF THEN ELSE(condition, true value, false value) This function returns first true value if the condition is true and false value if condition is false.
INTEG(X,Y).....	INTEG(rate, initial value) This function performs the integral of the given rate, starting from the initial value.
MAX(X,Y) .....	F Function which returns the greater of X or Y.
MIN(X,Y).....	Function which returns the lesser of X or Y.
SMOOTH(X,Y).....	SMOOTH(input, delay time) This function is equivalent to INTEG((input - SMOOTH)/delay time, input).
SMOOTH(X,Y,Z) .....	SMOOTH(input, delay time, initial value) Essentially the SMOOTH function with a designated initial value. It is equivalent to INTEG((input - SMOOTHI)/delay time, initial value)

## LIST OF TABLES

TABLE 1: COMPARISON OF PROGRAM COST AND SCHEDULE PERFORMANCE.....	94
TABLE 2: IMPORTANT SYSTEM VARIABLES AND THEIR IMPACT ON THE SPO-CONTRACTOR SYSTEM .....	106
TABLE 3: DEFINITIONS OF LINK POLARITY .....	117

## LIST OF FIGURES

FIGURE 1: STUDY BOUNDARIES AND EXTERNAL INFLUENCES .....	11
FIGURE 2: FUNDAMENTAL ELEMENTS OF THE REWORK CYCLE.....	20
FIGURE 3: A TYPICAL PATTERN OF PROJECT PROGRESS.....	21
FIGURE 4: A TYPICAL TIME TO DISCOVER REWORK TIME SERIES AS A FUNCTION OF PROJECT EXECUTION PERIOD .....	22
FIGURE 5: EFFECT OF TIME REQUIRED TO DISCOVER REWORK ON BUILDUP OF UNDISCOVERED REWORK ...	23
FIGURE 6: TYPICAL VALUES OF QUALITY IN DEVELOPMENT PROJECTS.....	24
FIGURE 7: FOUR DETERMINATES OF QUALITY OVER TIME .....	25
FIGURE 8: EXAMPLE OF PROJECT QUALITY OVER TIME.....	26
FIGURE 9: EXAMPLE FUNCTIONAL RELATIONSHIPS FOR THE EFFECT OF PAST WORK QUALITY ON PRESENT QUALITY.....	27
FIGURE 10: PROCESS QUALITY ISOLINES.....	27
FIGURE 11: DETERMINATES OF PRODUCTIVITY OVER TIME.....	28
FIGURE 12: COMPARISON OF PRODUCTIVITY VALUES .....	29
FIGURE 13: DETERMINATES OF WORKFORCE SIZE.....	30
FIGURE 14: BASIC WORKFORCE STRUCTURES.....	31
FIGURE 15: EXAMPLE WORKFORCE SIZE OVER A PROJECT'S LIFE .....	32
FIGURE 16: DILUTION OF WORKFORCE EXPERIENCE .....	32
FIGURE 17: GENERAL TRENDS IN PROCESS QUALITY ISOGRAMS FOR AFFECT OF NEW WORKER EXPERIENCE ON AVERAGE PROJECT QUALITY .....	33
FIGURE 18: EXAMPLE QUALITY LEARNING CURVE .....	33
FIGURE 19: TRENDS IN MAXIMUM WORKFORCE WITH STAFF-UP RATE.....	34
FIGURE 20: TRENDS IN QUALITY WITH STAFF-UP RATE.....	35
FIGURE 21: TRENDS IN SCHEDULE PRESSURE WITH STAFF-UP RATE .....	35
FIGURE 22: TRENDS IN LABOR COSTS WITH STAFF-UP RATE.....	36
FIGURE 23: PROJECT SCHEDULE DYNAMIC ELEMENTS .....	37
FIGURE 24: POTENTIAL WORKFORCE BENEFITS OF REALISTIC SCHEDULES .....	38
FIGURE 25: POTENTIAL QUALITY IMPLICATIONS OF REALISTIC SCHEDULES .....	38
FIGURE 26: CONTRACTOR'S INITIAL PROJECT SCOPE AND COST ESTIMATE STRUCTURE.....	40
FIGURE 27: CONTRACTOR'S COST CALCULATION STRUCTURE.....	41
FIGURE 28: CONTRACTOR'S REWORK CYCLE STRUCTURE.....	42
FIGURE 29: CONTRACTOR'S QUALITY STRUCTURE .....	43
FIGURE 30: OVERTIME AND FATIGUE STRUCTURE.....	44
FIGURE 31: PRODUCTIVITY STRUCTURE.....	45
FIGURE 32: DETERMINATES OF CONTRACTOR'S TIME TO DETECT REWORK .....	46
FIGURE 33: CONTRACTOR'S WORKFORCE STRUCTURE .....	47
FIGURE 34: WORKFORCE EXPERIENCE STRUCTURE .....	48
FIGURE 35: WORKFORCE SIZING STRUCTURE.....	48
FIGURE 36: WORKFORCE SIZE CONTROL STRUCTURE.....	49
FIGURE 37: DISTRIBUTION OF EFFECTIVE WORKFORCE STRUCTURE .....	49
FIGURE 38: PROJECT SCHEDULE STRUCTURE.....	50
FIGURE 39: MANAGEMENT RESERVE STRUCTURE.....	51

FIGURE 40: DECISION RULE FOR MANAGEMENT RESERVE RELEASE.....	52
FIGURE 41: SPO MILITARY WORKFORCE STRUCTURE.....	53
FIGURE 42: SPO CIVILIAN WORKFORCE SIZING INCLUDING CIVILIAN AUTHORIZATION.....	54
FIGURE 43: COMPARISON OF REAL AND SIMULATED DATA.....	56
FIGURE 44: NON-LINEAR EFFECTS OF PROPORTIONAL VARIATIONS IN SCOPE AND DESIRED COMPLETION INTERVAL FOR DIFFERENT WORKFORCE LEARNING CURVES, NORMALIZED ACROSS SERIES ...	58
FIGURE 45: NON-LINEAR EFFECTS OF PROPORTIONAL VARIATIONS IN SCOPE AND DESIRED COMPLETION INTERVAL FOR DIFFERENT WORKFORCE LEARNING CURVES, NORMALIZED WITHIN SERIES....	58
FIGURE 46: CROSS SECTIONAL EFFECTS OF LEARNING CURVE VARIATIONS, TIME SERIES COMPARISON .....	59
FIGURE 47: WITHIN SERIES EFFECTS OF SCOPE VARIATIONS, TIME SERIES COMPARISON.....	60
FIGURE 48: EFFECTS OF SCHEDULE COMPRESSION ON COST AND SCHEDULE SLIP TRENDS .....	63
FIGURE 49: TIME SERIES COMPARISON OF SCHEDULE COMPRESSION EFFECTS FOR BASELINE CONFIGURATION.....	64
FIGURE 50: TIME SERIES COMPARISON OF SCHEDULE COMPRESSION EFFECTS WITH FASTER LEARNING CURVE TRAVERSAL.....	65
FIGURE 51: TIME SERIES COMPARISON OF SCHEDULE COMPRESSION EFFECTS WITH HIRING OF MORE EXPERIENCED WORKERS.....	66
FIGURE 52: CROSS SECTIONAL COMPARISON OF LEARNING CURVE AND NEW WORKER EXPERIENCE EFFECTS .....	67
FIGURE 53: EFFECTS OF FATIGUE AND OVERTIME ON PROJECT PERFORMANCE .....	69
FIGURE 54: EFFECTS OF FATIGUE AND OVERTIME ON WORKFORCE NUMBERS .....	70
FIGURE 55: EFFECTS OF PUNCTUATED HIGH WORKFORCE TURNOVER ON QUALITY AND PRODUCTIVITY ...	72
FIGURE 56: EFFECTS OF PUNCTUATED HIGH WORKFORCE TURNOVER ON CONTRACTOR SCHEDULE, COST, AND WORKFORCE SIZE.....	73
FIGURE 57: MANAGEMENT RESERVE EFFECTS ON COST AND SCHEDULE SLIP TRENDS .....	74
FIGURE 58: TIME SERIES COMPARISON FOR MIDDLE SCENARIO, MANAGEMENT RESERVE RELEASED ONLY AFTER 50 PERCENT COMPLETION .....	76
FIGURE 59: TIME SERIES COMPARISON FOR LATE SCENARIO, MANAGEMENT RESERVE RELEASED ONLY AFTER 75 PERCENT COMPLETION.....	77
FIGURE 60: EFFECTS OF AVERAGE OFFICER TENURE ON COST AND SCHEDULE SLIP TRENDS.....	79
FIGURE 61: TIME SERIES COMPARISON OF AVERAGE OFFICER TENURE EFFECTS FOR BASELINE CONFIGURATION.....	80
FIGURE 62: CROSS SECTIONAL COMPARISON OF LEARNING CURVE AND INTERCONNECTIVITY EFFECTS ON SPO.....	81
FIGURE 63: CROSS SECTIONAL COMPARISON OF LEARNING CURVE AND INTERCONNECTIVITY EFFECTS ON CONTRACTOR .....	82
FIGURE 64: EFFECTS OF QUALITY AND GROSS PRODUCTIVITY ASSUMPTIONS ON COST ESTIMATE PRECISION .....	84
FIGURE 65: COST AND SCHEDULE SLIP TRENDS WITH SPO SIZE AND LEVEL OF EFFECTIVITY ON CONTRACTOR LATE PROGRAM PRODUCTIVITY .....	88
FIGURE 66: MODE TRANSFORMATION OF SPO QUALITY WITH INCREASING SPO PERSONNEL ALLOCATION .....	89
FIGURE 67: EFFECTS ON CONTRACTOR EFFECTIVE PRODUCTIVITY OF INCREASING LEVELS OF CONTRACTOR DEPENDENCE ON SPO INPUTS NEAR PROJECT COMPLETION .....	89
FIGURE 68: EFFECT OF SPO PERSONNEL ALLOCATION ON ONSET OF HOLD-UP .....	90
FIGURE 69: FUNCTIONAL RELATIONSHIPS BETWEEN PROGRESS AND THE PROGRESS REQUIRED TO SUPPORT THAT LEVEL OF PROGRESS.....	91
FIGURE 70: EFFECTIVE PRODUCTIVITY RAMIFICATIONS OF DIFFERENT SPO REQUIRED PROGRESS FUNCTIONS .....	92
FIGURE 71: SPO PERSONNEL PROFILES.....	95
FIGURE 72: PROFILES OF FUNDING MADE AVAILABLE TO THE CONTRACTOR.....	95
FIGURE 73: CONTRACTOR WORKFORCE TIME SERIES WITH CONSTANT SPO PERSONNEL AUTHORIZATION	96



FIGURE 74: CONTRACTOR WORKFORCE TIME SERIES WITH DECLINING SPO PERSONNEL	
AUTHORIZATION.....	96
FIGURE 75: PROGRAM EFFECTS OF VARIATIONS IN AVAILABLE FUNDING PROFILE LEVELS .....	98
FIGURE 76: CONTRACTOR QUALITY AND EFFECTIVE PRODUCTIVITY .....	99
FIGURE 77: ACQUISITION COMMUNITY ORGANIZATION CHART.....	115
FIGURE 78: JOHN NEVISON OVERTIME EFFECTIVENESS DATA COMPILATION.....	116
FIGURE 79: CAUSAL LOOP DIAGRAM OF REWORK CYCLE .....	117
FIGURE 80: STOCK AND FLOW DIAGRAM OF THE REWORK CYCLE .....	118
FIGURE 81: STOCK AND FLOW DIAGRAM NOTATION WITH EXAMPLE.....	118

# 1 INTRODUCTION

In a period of declining budgets, reductions in cost are seen as the means to maintain or even increase capability and profits, while in periods of rapid technological change, reductions in cycle time are viewed as the means to reduce long term planning risk – predominately technological and ideological obsolescence. Because both budgetary limitations and rapid advances in technology are relevant concerns for advanced military aircraft development, this study looks at the interactions between an Air Force System Program Office (SPO) and the prime contractor<sup>1</sup> for a major aircraft acquisition program.<sup>2</sup> In particular, it investigates the effects of management decisions on cost and cycle time. Its purpose is to develop an improved understanding of the interactions between program coordination, human resource management, and initial estimates of project cost and size, and discusses the resultant effects on program performance. In particular, the effects of staffing policies, process quality, and management reserves are examined.

## 1.1 Background Information

The SPO and prime contractor operate beneath an organizational structure of over 50 government offices and agencies<sup>3</sup> – each with input to the acquisition process. Figure 77 in the Appendix presents an organizational chart showing positions of the SPO and contractor relative to other acquisition system participants.

To understand clearly the factors affecting program performance it is important to distinguish between internal and external forces. Because the area of interest is the SPO-Contractor system, all influences external to that system<sup>4</sup> are treated as exogenous.<sup>5</sup> However, a brief review of some of the major external influences is necessary to provide an adequate context for the study. This is graphically depicted in Figure 1.

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<sup>1</sup> Throughout this work, I use the terms “prime contractor” and “contractor” interchangeably. The terms are intended to indicate an entity directly contracted by the SPO to perform a major function related to the completion of an acquisition program. This could include a major sub-system supplier.

<sup>2</sup> An example would be the F-22 acquisition program.

<sup>3</sup> Based upon the author’s survey of U.S. Government World Wide Web sites that reported participation in the acquisition process.

<sup>4</sup> The current trend under IWSIM SPO is to move the support community into the SPO. However complete integration has yet to be realized as of this writing.

<sup>5</sup> Forrester, Jay W., *Principles of Systems*, Productivity Press, Portland OR, 1971, Pages 4-1,2.

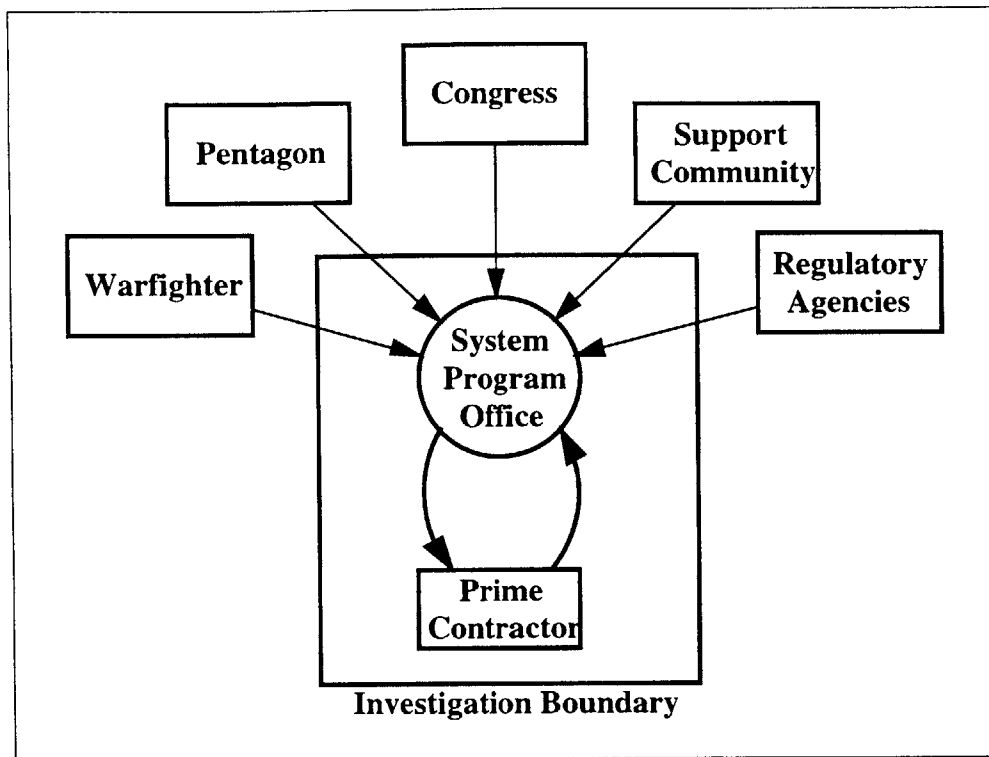


Figure 1: Study Boundaries and External Influences

### 1.1.1 The External Environment

The SPO and contractor are affected by the aggregate external influences of the United States Congress, the Pentagon, various government regulatory agencies,<sup>6</sup> the warfighter,<sup>7</sup> and support community.<sup>8</sup>

Congress controls the timing, number and procurement rate of new aircraft through the appropriation and budgeting process. Congressional support is determined by local politics, national politics, and budget considerations. The congressman asks: "Is it good for my constituents? Is it good for the country? Can we afford the program?" They also influence the performance requirements of the aircraft. Congress is never satisfied with parity, consistently demanding that U.S. weapons must be significantly better than the competition. Insufficient performance margin is grounds for cancellation or modification of an aircraft development program. [Franken]

Department of Defense (DOD) exercises control over programs through the budgeting process, where by program guidance and budgets are submitted to Congress, and through oversight and regulation of the services. Each service must defend the funds allocated to it; otherwise, the money goes into the DOD pool. [Shields, McNutt] At the highest levels of the DOD, need and viability determine the value of a program. Is there a demonstrable need for the system given the prevailing national military strategy, is it technically feasible, and is it affordable? Of course, a program may have political and personal value as well – for example, the continuation of a program for an additional year to secure funds for a different project, or having one's name attached to the successful completion of a previously broken program. [Deutch] To

<sup>6</sup> The General Accounting Office and General Services Administration are examples.

<sup>7</sup> Unified Combatant Commands and Major Commands, the ultimate user of the aircraft.

<sup>8</sup> Logistics and Systems (grouped together under Air Force Material Command) are responsible for maintenance and support of all Air Force systems.

focus on such behavior is to ignore the truth that the real tension between perceived need and available funding creates fertile ground for differences of opinion between well-intentioned individuals. Obviously, the DOD's push to shorten program cycle times and reduce acquisition costs has its source in this tension, with shorter cycle times seen a mechanism that will allow program completion before obsolescence. [McGrath]

An additional important source of funding variability is the levying of "taxes" by the Pentagon to pay for specific military operations.<sup>9</sup> Such taxes result in a reduction in program funding for the given fiscal year within which they are levied and have a direct impact on available contractor funding and SPO operation and maintenance budgets. [Ruffkin, Watern, Rutley]

Unified Combatant Commands and Major Commands, the ultimate users of the aircraft, want the equipment to perform the given mission. Their influence is most important very early in the acquisition process during the initial requirements definition. However, during the design build and use phases, they represent a source of modification and upgrade requests.

Because they are responsible for upgrades, the support community's influence is greatest after the system has become operational. However, as the significant operational cost advantage of designing for sustainment has been recognized, such issues are being addressed in the earlier program phases, increasing the importance of the support community's input to the early design process.<sup>10</sup>

Obviously, the various regulating agencies define the rules and regulations followed by the SPO and contractor, as well as providing independent program auditing.

One interesting and curious result of the acquisition regulations relates to program budget preparation. Because no money may be spent until a program is official; money to support the preparation of a project's budget must be pulled from the SPO's overhead funds pool. This can result in program budgets that are put together very quickly, sometimes the night before they are due. [Ruffkin, Watern]

To summarize, the aggregate influences, from these external agents, are potential changes in:  
*defined program scope* – revisions to program requirements having the net effect of increasing or decreasing the program's official work definition.<sup>11</sup>  
*program funding period* – the time period over which funds are made available for the program.  
*funding profile* – the amount and rate at which funds are disbursed to both contractor and SPO

### 1.1.2 The Contractor and System Program Office

The main functions of the SPO are contractor oversight and program coordination and integration.<sup>12</sup> The oversight role is clear in principle – ensure contractor contract compliance. However, project scope, duration, and constituencies conspire, making the oversight process anything if not contentious. As discussed in the previous section, each constituent has a different set of priorities and different means to influence the process. In addition, the SPO's actual authority is limited to contract enforcement and day to

---

<sup>9</sup> U.S. operations in Bosnia resulted in acquisition programs being charged a "Bosnia Tax."

<sup>10</sup> The Lean Sustainment Research Project, a joint research project between Headquarters Air Force Material Command (HQ AFMC/LG), Air Force ManTech, and MIT created in 1997, is indicative of the importance of this issue to the Air Force.

<sup>11</sup> This is in contrast to the actual effort that must be expended to complete the project. This will be address in more detail in Section 3.1.3.

<sup>12</sup> Contractor oversight, perhaps the most visible SPO function, becomes important only after the program is initiated (Milestone 1) while coordination activities are required throughout the life of the SPO.

day operational decisions – they have almost no authority.<sup>13</sup> This suggests that the most important function of the SPO is program coordination. In its role as coordinator, the SPO acts as the communications interface between the disparate project constituencies and facilitates the integration process.

The SPO's functions demand a product focus – its ultimate purpose is building the aircraft the warfighter needs at a fair price. Thus while at higher levels of the acquisition system, a program's value is determined by the capability it provides and the perceived need it fills, at the SPO level, value is determined by product delivery, value to the taxpayer, and of course, value to the warfighter. [Rutley]

Several unique features of a SPO, which provide an important context for understanding its function and behavior must be mentioned. First, its maximum staff level is set every year by the Acquisition or Logistics Center responsible for the SPO.<sup>14</sup> [Rutley] There is no formulaic way to size a SPO though, there have been past efforts to do so. [Sutton] It has a dual workforce, military and civilian, with different program tenures and career tracks. Finally, three distinct categories of funding for specific functions flow through the SPO: civilian workforce, operations and maintenance, and SPO administered. These result in important structural differences between the SPO and contractor.

Providing design, manufacturing, and integration services to the SPO, resulting in delivery of the desired aircraft, is the contractor's purpose. These contractors are typically large, widely held public corporations, with the ultimate requirement of providing shareholder value. This value is generated by only undertaking positive net present value projects.<sup>15</sup> If the company fails to follow this maxim, the investors will withdraw their funds and the company will soon collapse. Obviously then the terms of any acquisition program must provide the contractor the potential of positive net present value. However, because aircraft design and manufacture requires large quantities of very specialized assets, both physical and human, diversification is not prevalent. This results in fierce competition between companies and as demand has dwindled, has led to industry consolidation.<sup>16</sup> In a further effort to maintain shareholder value, the industry has begun to embrace lean production techniques, pioneered by Toyota<sup>17</sup> and later adopted by the United States auto industry, as a mechanism to reduce costs while at the same time to improve productivity and quality. This has brought a new understanding of the values of process consistency and innovation.<sup>18</sup>

In its most basic form, the acquisition process, as directly related to the contractor and SPO, begins with presentation of the initial desired requirements for the aircraft to the contractor – the request for proposal (RFP).<sup>19</sup> The requirements are then refined through discussions between the contractor and the SPO. With agreement reached on the requirements, contracts are written, entered, and money for design begins to flow. As the program progresses there are continued interactions between the contractor and SPO. For example, requirement changes are negotiated, oversight materials are prepared and transmitted, and various tests are

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<sup>13</sup> This depends to some extent on the rank of the SPO director. If the individual is of General officer rank, their decision authority increases. However, for things such as source selection and milestone approval, decisions are made at the Pentagon level. [Rutley]

<sup>14</sup> Air Logistics Center (ALC) or the Product Center [Rutley]

<sup>15</sup> The sum of the project cash flows, discounted by the opportunity cost of capital, should be greater than zero. See Brealey, Richard. A. and Myers, Stewart. C., *Principles of Corporate Finance*, McGraw-Hill, 1996, Page 989

<sup>16</sup> The number of major airframe manufacturers has been reduced from at least nine in the late 1970's to two in 1998. See: Distillation of the Defense Industry, *Air Force Magazine*, July 1998, Pages 54-59.

<sup>17</sup> See: Ohno, Taiichi, *Toyota Production System: Beyond Large-Scale Production*, Productivity Press, Portland OR, 1988

<sup>18</sup> See: Kandebo, Stanley W. and Scott, William C., *Lean Aerospace Manufacturing*, *Aviation Week & Space Technology*, McGraw-Hill, July 28, 1997, Pages 56-66

<sup>19</sup> Of course, this is ignoring the contractor's efforts to direct the acquisition planning process before the RFP is issued.

coordinated and conducted. Work continues until the program is either completed or cancelled. With cost,<sup>20</sup> schedule,<sup>21</sup> and aircraft performance used as the metrics of program success.

Interactions between the contractor and SPO fall into two broad transactional categories: material and information exchanges, the salient characteristics of which are the transaction's opportuneness<sup>22</sup> and quality – providing the required product on time. Consider the history of the C-17 program which demonstrates the complexity of the SPO-contractor relationship, as well as how deficiencies in these characteristics can reverberate through the SPO-contractor system and the resulting implications for cost and schedule.

On October 1, 1992, a C-17 static test article "flying" at 32,100 feet and weighing 585,000 pounds was hit with a simulated strong wind gust. As the wings bent to handle the stress, a symmetrical crack occurred on the upper wing skin between fuel access doors on both wings. Later calculations determined the wing had failed in conditions representing only 128 percent of the load requirement. The contract requires the plane's wings to be able to withstand 150 percent of the load requirement.

Specialists from McDonnell Douglas and the Air Force pored over test data and the static article itself to determine what had gone wrong. They concluded the root causes were a computational error by the McDonnell Douglas engineers who designed the wing, optimistic design assumptions, and a high and uneven distribution of the test pads on the wing.

Program officials tended to downplay the gravity of the wing failure and contended that it would require only \$ 50 million to fix the static article and incorporate a fix on the production line aircraft. Congressional officials, skeptical of that estimate, expect the total cost ultimately will be higher.

McDonnell Douglas test official Ned Newman said the company is almost finished with repairs on the static article. The solution appears to be a fairly modest technical chore of bolstering isolated areas of the wing with "stiffeners." This change, like many others, will add weight -- another 744 pounds. GAO claims the effect of the computational error is being seen in other areas of the wing and fuselage.<sup>23</sup>

Here an error made during the initial aircraft design remained undetected for over 10 years<sup>24</sup>. Furthermore, while the design error remained undiscovered, it generated additional errors in work that relied on the original design. The C-17 demonstrates two important characteristics of complex system design: mistakes can remain undiscovered for significant periods and a single error can propagate throughout the system.

The first order effect of the C-17 wing design error was the wing structure had to be redesigned. However, the "fix" increased the weight of the already over-weight aircraft, requiring structural modifications in other parts of the aircraft and spurred additional effort to reduce the aircraft's total weight. This increased the

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<sup>20</sup> Cost non-performance is called an overrun, defined as the incremental increase in real cost over the official cost estimates.

<sup>21</sup> Schedule non-performance is referred to as schedule slip, the incremental increase in time required to achieve any particular program milestone.

<sup>22</sup> In this context, opportuneness is progress relative to required progress. For example, near the end of a program, the contractor may require SPO certification of a particular modification. If the SPO has not completed the work required to make a determination about the modification within the expected time interval, it has not made sufficient progress relative to that required.

<sup>23</sup> Lynch, David J., *Despite The Problems, The Air Force Still Believes This Is The Airlifter Of The Future*, *Air Force Magazine*, July, 1993 Page 34-37.

<sup>24</sup> Preliminary design for the C-17 began in 1981.

effort required to complete the project – beyond the initial estimates. As a result, the contractor's costs were increased through additional wages and fixed costs because the increased level of effort required increasing the effective workforce<sup>25</sup> and slipping the schedule. Moreover, because the contractor is barred from including the correction of unanticipated errors in the initial scope definition, these costs augmented the aircraft's budget over-run.

Unanticipated errors by the contractor can affect the SPO as well. The flight test plan for the aircraft is a prime example.

The first few C-17s arrived at Edwards requiring additional work before they were ready for full-scale operations. Then, persistent fuel leaks slowed progress. Finally, McDonnell Douglas found itself well behind schedule -- the result, perhaps, of what Air Force officials now call an overly ambitious test plan.

The original schedule, drafted by McDonnell Douglas and approved by the Air Force, called for a ninety-one percent efficiency rate in the testing, with an average of thirty-three flight hours per aircraft per month. The General Accounting Office maintains that the actual figures have been forty-seven percent efficiency and twenty-nine hours per aircraft per month.

McDonnell Douglas was to finish C-17 testing by January 1994. The GAO, which recently conducted a critical review of the program, claims that the program is likely to be nineteen months late. The Air Force projects a fifteen-month slip.

Since delivery to the test site, the C-17s have spent more than one-third of their time in "work programs to perform maintenance, complete deferred work, fix problems such as fuel leaks, and correct other aircraft design and system problems," according to GAO.<sup>26</sup>

Here, the contractor did not expect the aircraft to spend one-third of the test program under repair and thus underestimated the time required for the flight test program. The SPO working from the contractor's inputs evaluated and approved the program. However, the test program could not be executed according to plan because the amount of rework had been underestimated, causing the development program to slip. This underscores another important characteristic of complex development programs – partner interdependency amplifies the effects of error propagation. The C-17 shows that undiscovered contractor errors can induce errors by the SPO. Of course, the reverse is also true, and both have cost and schedule implications, directly increasing cost and schedule slip through rework of the errors.

One last example illustrates the complexity of aircraft development programs and hints at the intimate relationship between workforce management and program performance.

McDonnell Douglas officials vigorously dispute the GAO testimony, insisting they have made the necessary investments [needed to improve production and the aircraft's design]. Likewise, the company disputes the office's figures showing that the amount of work being redone because of failure to do it right the first time has been holding steady at close to forty percent. McDonnell Douglas figures show such so-called rework declining on each new plane.

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<sup>25</sup> This is accomplished by adding more workers, working existing employees overtime, or both.

<sup>26</sup> Ibid Footnote 23.

GAO disputes this. It claims that, if one uses another measure of production efficiency, McDonnell Douglas had its worst month to date in January -- completing just twenty-six cents of planned work for each dollar spent. McDonnell Douglas says the GAO numbers are based on outdated contract work plans.

Both sides agree on one thing: The C-17 program has been hurt by constant and increasing labor turnover. Because the aircraft program shares McDonnell Douglas's Long Beach facility with the company's commercial jet assembly lines, workers laid off from the MD-11 and MD-80 passenger jet programs can exercise union seniority rights to claim jobs on the C-17 line. This has led to constant churning. Up to one-third of the company's 10,000 C-17 workers came into the program last year. Up to one-half of the work force will be replaced this year.<sup>27</sup>

This illustrates the connection between high levels of rework and high workforce turnover. When a worker from the passenger jet program claimed a job on the C-17 line, he or she displaced a skilled worker already familiar with its procedures and idiosyncrasies. This reduced the productivity and quality of the workforce. For the new worker to attain the same level of skill and productivity as the displaced worker required training and experience. Naturally, the new workers were trained by the remaining experience workers, causing a further reduction in productivity. Finally, until the new workers had traversed the learning curve, their error rates were higher than normal, increasing the amount of rework. In essence, the workforce never moves up the learning curve.

Aside from presenting the connection between workforce turnover and rework, it is a prime example of how a distant, seemingly unrelated management decisions can create problems -- the poor performance of a McDonnell Douglas's commercial business helped degrade its military contract performance because of a labor contract.

While the forgoing examples were specific to the C-17 program, the problems they portray are characteristic of aircraft development programs in general and serve to illustrate the complexity of the SPO-contractor relationship. Rare is the program that delivers the desired aircraft on time and on budget. It is for just this reason that the study of the SPO-contractor system is important.

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<sup>27</sup> Ibid Footnote 23.



## 1.2 Research And Study Methodology

Undoubtedly, the causes of aircraft development program cost, and schedule under-performance are varied, complex, and interrelated. Consequently, this study employs a methodology that facilitates the investigation of such complex phenomenon. System dynamics or industrial dynamics are terms frequently applied to the quantitative analysis of organizations using continuous time series simulation.

Industrial dynamics models are built on the same information and evidence used for the manager's usual mental model of the management process. The power of industrial dynamics models does not come from access to better information than the manager has. Their power lies in their ability to use more of the same information and to portray more usefully its implications.<sup>28</sup>

A concise understanding of the implications of a management decision, allows the development of global solutions, mitigating the tendency of local optimizations to provide less than optimum system performance – unintended consequences.

In its most analytic form, the system dynamics methodology provides a convenient tool for manipulating large numbers of integral equations – the explicit rendering of a system's structure and management's decision making processes in mathematical terms. The methodology is especially useful when the equations constitute a high-order system of interconnected multiple feedback-loop structures with nonlinear relationships. The number of integral equations required to describe a system determines the order of that system. Feedback loops are cause and effect relationships which are recursive in nature and can be either goal-divergent or goal-seeking. Although some feedback relationships are proportional, many are nonlinear. The combination of these characteristics defines a complex system,<sup>29</sup> and their interplay causes dynamically complex behavior.

Using system dynamics as a tool to analyze research and development project performance is rooted in the works of Roberts,<sup>30</sup> Cooper,<sup>31</sup> and Lyneis.<sup>32</sup> This study, as an extension of their work applied to the SPO-contractor system during a new aircraft development program, affords a novel perspective on the aircraft acquisition program performance.

The classic project model structure was adapted to reflect the unique structures of the SPO-contractor system through extensive discussions with system experts and participants.<sup>33</sup> Following the work of Lyneis<sup>34</sup> and Sterman<sup>35</sup> on the interaction between development system partners, SPO-contractor quality and productivity interactions were modeled.

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<sup>28</sup> Forrester, Jay W. *Industrial Dynamics*. Portland OR, Productivity Press, 1961, Page 117.

<sup>29</sup> Forrester, J. W. (1969), *Urban Dynamics*, pp. 107-114.

<sup>30</sup> Roberts, Edward, B., *The Dynamics of Research and Development*, Harper & Row, New York, 1964

<sup>31</sup> Cooper, Kenneth G., *Naval Ship Production: A Claim Settled And a Framework Built*, *Interfaces*, Vol. 10, No. 6, December 1980, Pages 20-36.

Cooper, Kenneth G., *THE \$2,000 HOUR: How Managers Influence Project Performance Through the Rework Cycle*, *Project Management Journal*, Vol. XXV, No.1, March 1994

<sup>32</sup> Lyneis, James M. *Corporate Planning and Policy Design*. Portland OR: Productivity Press, 1980

<sup>33</sup> A listing of all individuals consulted in this capacity is found in the Reference Section.

<sup>34</sup> Lyneis, James M. *Course Lecture Notes*, 15.976: Project Management, MIT, Fall 1997.

<sup>35</sup> Sterman, John D., et al, *Unanticipated Side Effects Of Successful Quality Programs: Exploring a Paradox of Organizational Improvement*, MIT Sloan School of Management, Cambridge MA 02142, March 1994, Revised August 1994, D-4390-1.

Although cost and cycle time are inextricably linked and thus can not be studied in isolation, previous studies have not looked at the SPO–contractor system in such terms, but rather have tended to focus on cost or cycle time, separately. By utilizing a system dynamics approach, their intimate relationship can be captured and analyzed. By making explicit the system’s causal structure and simulating its behavior under the governing decision rules, greater insight into the causes of aircraft development program performance is obtainable than through the use of more traditional modeling techniques.<sup>36</sup>

In the next section, the basics of the classical project model are introduced. Armed with the insights it provides, the contractor and SPO models are then presented in Section 3. Analysis and conclusions naturally follow.

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<sup>36</sup> Regression models or financial models are examples.

## 2 THE BASIC PROJECT MODEL

This section introduces the basic project model structure<sup>37, 38</sup> and discusses the essential, project management insights applicable to aerospace development projects derived therefrom.<sup>39</sup> It also serves as an introduction to both contractor and SPO models, providing a core from which to understand their structure and behavior.

### 2.1 The Rework Cycle

The central element of a project model is the rework cycle. It captures the truths that some portion of the effort expended on any project is spent redoing work previously thought to be complete and that this “rework” may lay undiscovered for a significant fraction of the project’s duration. Figure 2 is a representation of the rework cycle. The five factors that govern the cycle’s behavior are: the initial amount of work,<sup>40</sup> workforce productivity, average work quality, and the time required to discover rework. It is important to recognize that not all parts of the rework cycle are easily visible to project managers: *Work to be Done*, *Perceived progress*, *Productivity* and *Apparent progress rate* are the most accessible. Of course, the other parameters can be estimated, but to do so requires effort and an intimate understanding of the flow of work around the cycle.

An analogy can be drawn between the rework cycle and a hydraulic system. In Figure 2 the rectangular boxes can be thought of as reservoirs interconnected by pipes with valves or pumps in various locations – represented by the hourglass shaped symbols. To start, all the reservoirs are empty except *Work to be Done*, which is full. In this analog, the goal of a project is pumping the tasks from the *Work to be Done* reservoir to the *Real Progress* reservoir. Workforce *Productivity* is the pump, which pushes the tasks through the system. *Quality* controls two valves, diverting the task flow partly to the desired destination, *Real Progress*, but also to the *Undiscovered Rework* reservoir. The level in the *Undiscovered Rework* reservoir builds, increasing pressure on the *Discovering Rework* valve. The flow through this valve is determined by reservoir level and rework detection time, with its outflow rate increasing with increased *Undiscovered Rework* level and reduced *Time to detect rework*. Once through the valve, the rework flows back into the *Work to be Done* reservoir – to be pumped around again and again, until the *Work to be Done* reservoir is empty. How the rework cycle functions in the context of a development project is described next.

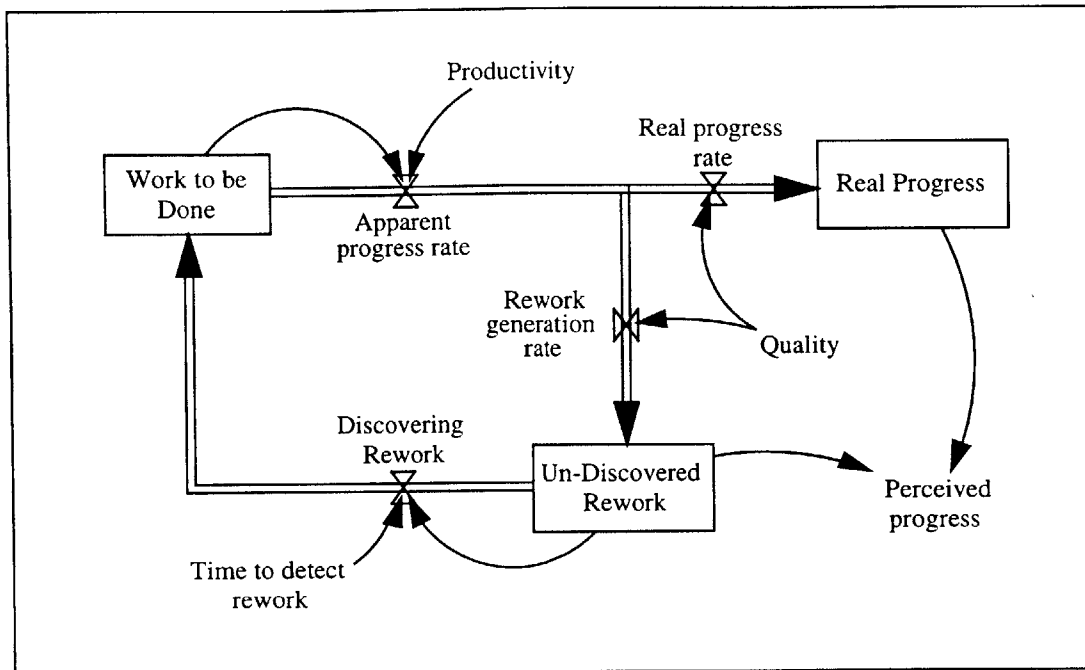
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<sup>37</sup> Section 8.3 in the Appendix provides the essential elements required to read the stock and flow diagrams used to describe the structures presented in this and following sections.

<sup>38</sup> This basic project model borrows heavily from one developed by James M. Lyneis as part of System and Project Management, 15.962, a class he co-taught in the Fall of 1997 at the Massachusetts Institute of Technology. A complete listing of the equations for this model may be found in the Appendix, Section 8.4.

<sup>39</sup> Many of these insights are presented in Cooper’s compelling analysis of project mismanagement: Cooper, Kenneth G., *The \$2,000 Hour: How Managers Influence Project Performance Through the Rework Cycle*, Project Management Journal, vol. XXV, No.1, March 1994

<sup>40</sup> For simplicity, in this example the project’s size is assumed to be known from its initiation and constant for its duration. However, relaxation of this assumption does not alter the important dynamics.



**Figure 2: Fundamental Elements of the Rework Cycle**

Starting with the known set of tasks required to complete the project, work begins. As the workforce completes tasks, some of their work will contribute to the finished product – *real progress* – but some tasks will need to be repeated because the work contains undiscovered errors.<sup>41</sup> This collection of tasks, with yet to be detected defects, is *undiscovered rework*. However, because it can not be distinguished from real progress, both contribute to the project’s *perceived progress*.

As shown in Figure 2 the factor that directs the flow of completed tasks is quality. Essentially, it is the fraction of tasks, at any given time, which are completed with no defects. Determined by the aggregate product of workforce skill, process influences, and other factors, the notion of quality is central to the project model and will be discussed in detail in Section 2.2. Of course, managers have long known that quality was important, what then distinguishes the rework cycle from other project models?

The crucial insight of the rework cycle is that rework is not discovered immediately, but remains hidden for some period – often a significant fraction of the time allotted for the project – and requires additional work to reveal its existence.<sup>42</sup> Once discovered, the rework flows back to the list of tasks that must be completed,

<sup>41</sup> A deliberately iterative design process can be thought of as a series of small projects, one for each iteration. The sum of *real progress* and *undiscovered rework* of the first project would determine the *work to be done* of the second and so on. Work would not begin on the second until sufficient *perceived progress* had been made on the first. Obviously, errors that remain undetected in the first iteration would create errors in the second. This perspective provides two insights. First, defining a process as iterative is an official recognition of rework. In essence there is admission that a task or set of tasks will need to be repeated several times to “get it right.” Second, rework can become institutionalized, a crutch to support poor design practice. The distinction between the two is a focus on continuous process improvement.

<sup>42</sup> An example would be the discovery of cracks in the C-17’s wing during loads testing, which required the wing to be redesigned. In this case design was begun in 1981 and the rework was not discovered until the Fall of 1992.

increasing the total effort which must be expended to bring the project to completion. Of course, any rework that remaining undiscovered before the project is delivered would be defects in the finished product.

It is the delay between rework creation and discovery, which creates the familiar pattern of project progress: initially progress appears satisfactory, but then begins to slow or even go backward during the latter stages. [Milauskas] Figure 3 demonstrates how undiscovered rework, invisible to the project manager, builds. It also shows that the perceived slow down in progress is just that, perceived. Real progress has been increasing steadily and does so until near the end of the project, when the remaining work to do is predominately newly discovered rework. What has happened is that the rework discovery rate becomes a significant fraction of the apparent progress rate – rework is being discovered almost as fast as the workforce can produce. To the casual observer it appears that huge amounts of effort, and therefor money, are being spent and yet little progress is being made.<sup>43</sup>

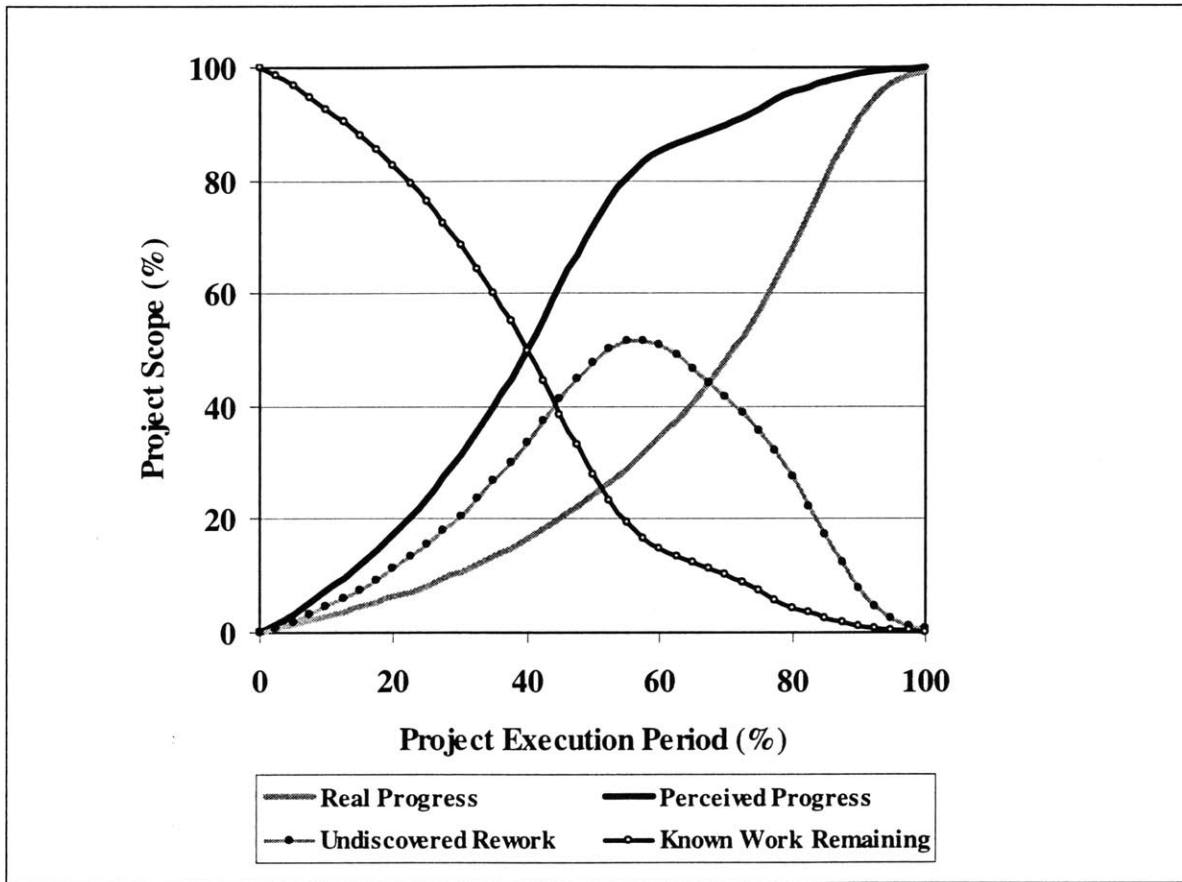
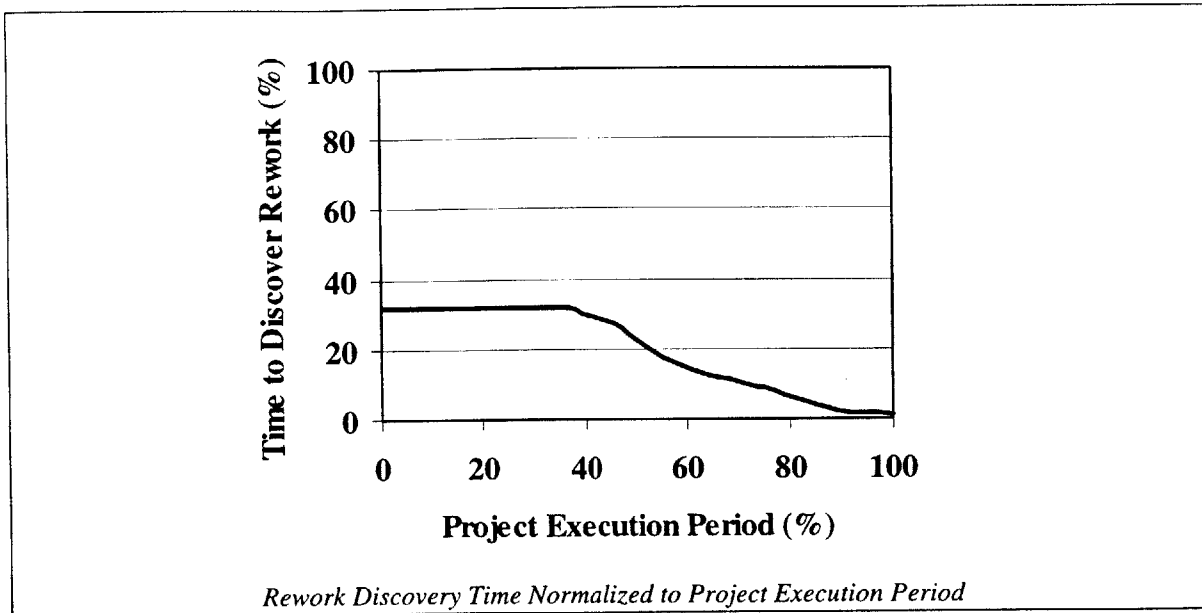


Figure 3: A Typical Pattern of Project Progress

Figure 4 is a typical time series for the time required to discover rework. Initially, the period is high and relatively constant because so little is known about the design that rework discovery is practically impossible. However, as the project begins to coalesce, and real progress is made, rework discovery time begins to decline. Toward the end of a project, the nature of the tasks changes to work for which mistakes are easier to find, for example from structural design and analysis to writing certification documentation.

<sup>43</sup> The typical response is to increase the effective size of the workforce by hiring or increasing overtime. This will be examined in more detail in Section 3.1.5.



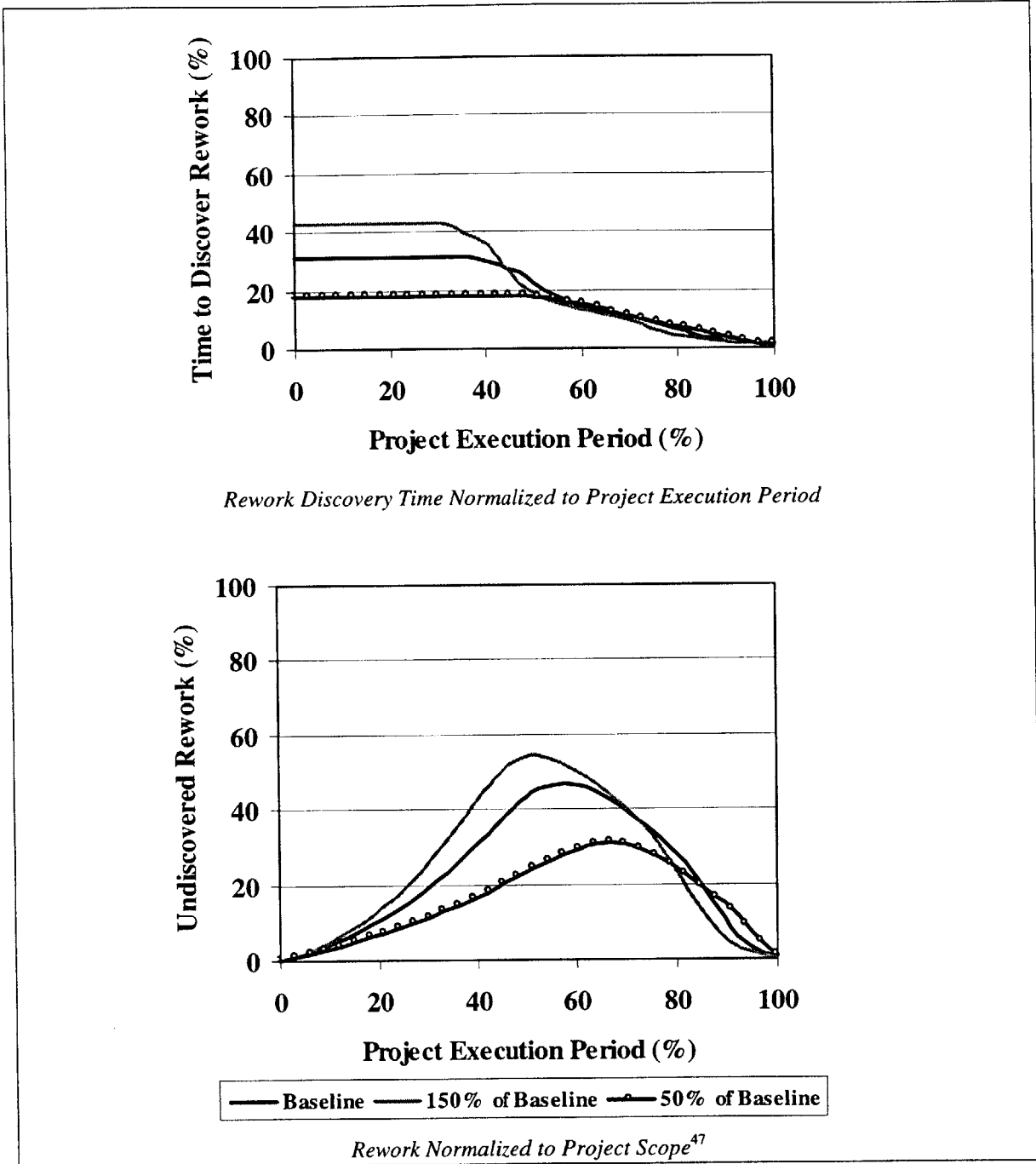
**Figure 4: A Typical Time to Discover Rework Time Series as a Function of Project Execution Period**

The effects on the growth of undiscovered rework resulting from increasing or decreasing the time required to discover rework are compared in Figure 5. It indicates that decreasing the time to discover rework, reduces the buildup of undiscovered rework. This also tends to reduce schedule slip because the slower than expected progress rate is detected earlier causing a slight increase in the initial workforce buildup. However, care must be taken in jumping to the conclusion that shorter is always better. In the early stages of a program, when the design is in flux, obsolescence can flush rework from the system. Effort is saved by not fixing errors in designs that will be abandoned. However, because early errors in the final design have tremendous cost, quality, and schedule leverage over the rest of the program, it is important to discover these errors early.<sup>44,45</sup> This is but one of the seeming contradictions which make program management so complex.<sup>46</sup>

<sup>44</sup> Roskam, Jan, *Airplane Design: Part VIII: Airplane Cost Estimation: Design, Development, Manufacturing And Operation*, Roskam Aviation and Engineering Corp., Ottawa, KS 1990, Page 10

<sup>45</sup> McMasters, John H., *Commercial Aircraft Design And Systems Engineering*, Engineering Division Summer Internship Training Program Manual, Boeing Commercial Aircraft Group, Aerodynamics Engineering, August 1994

<sup>46</sup> A partial solution to this contradiction is better human resource management, which will be discussed in Section 4.1.



<sup>47</sup> For the run, *150% of Baseline*, the *time to detect rework* calculated by the model was multiplied by 1.5. Similarly, for the *50% of Baseline* run, a multiple of 0.5 was used. Differences in program execution period are responsible for the seeming contradiction in the top graph where the ratio of *150% of Baseline* to *Baseline* is only 1.36. The *Baseline* program execution period was 38 months, while the *150%* and *50%* runs had execution periods of 42 and 33 months respectively.

## 2.2 Quality

Quality in the context of the rework cycle is the fraction of any completed task, which will *never* need to be reworked.<sup>48</sup> Shown in Figure 2, quality is one of the prime determinates of program performance. If quality and scope are assumed constant over the course of the project, the total effort required to complete the project can be shown to be the quotient of scope and quality.<sup>49</sup> Conversely, if the total project effort is known relative to the actual project scope, the project's average quality may be estimated. Figure 6 aggregates data on average project quality derived by Pugh-Roberts Associates/PA Consulting Group for development projects ranging from aerospace to large construction. Note that one rework cycle is equal to the project's scope. Thus for example, if quality equals 0.5, the total effort is two hundred percent of the expected value and number of rework cycles is one.

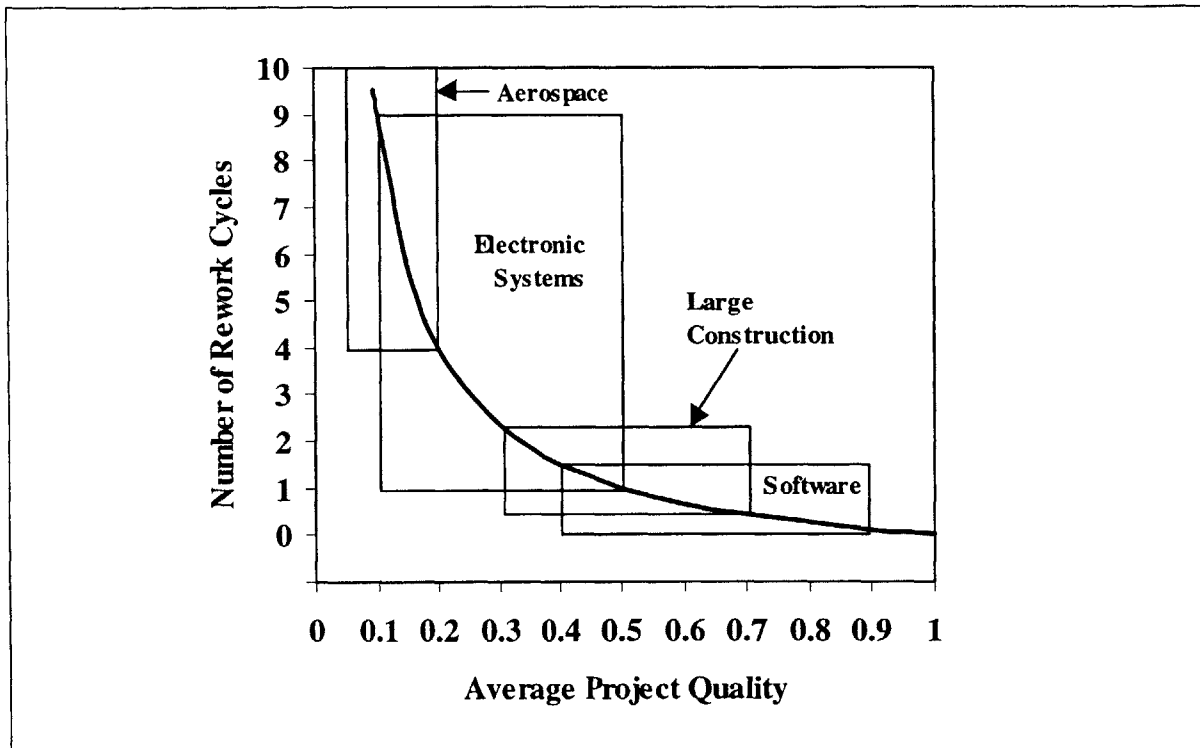


Figure 6: Typical Values Of Quality In Development Projects<sup>50</sup>

While the average project quality is a good indication of aggregate performance, it is important to recognize that quality is not constant over the life of a project. The utilized processes, workforce skill, and other factors, in particular the quality of previous work determine, its value. Of course, the extent to which past quality affects the present quality is a function of the complexity of the system being developed.

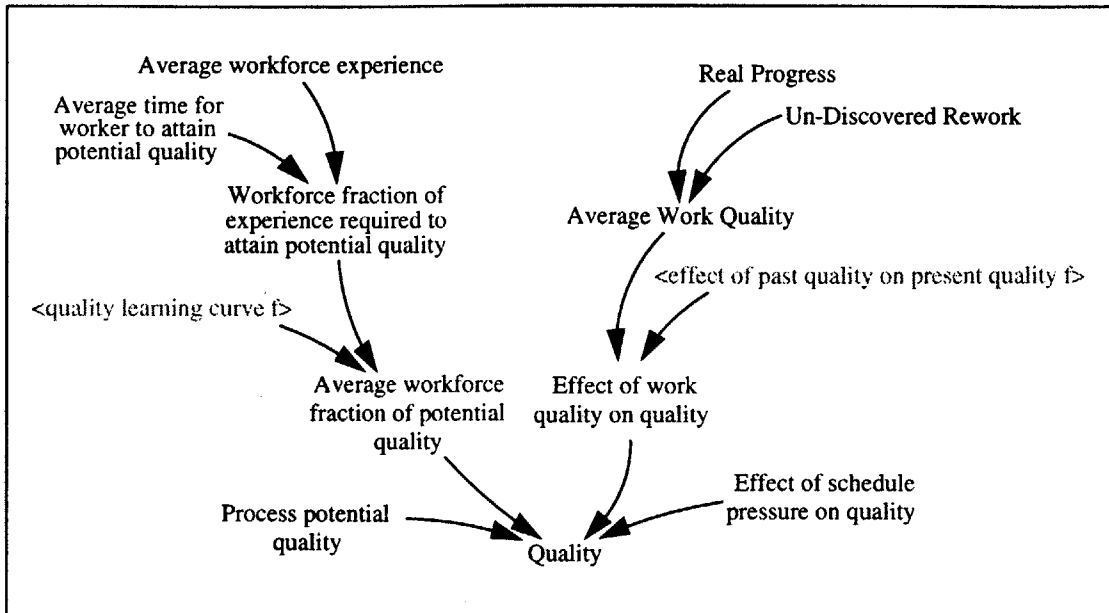
<sup>48</sup> Cooper, Kenneth G., *The Rework Cycle: Benchmarks For The Project Manager*, Project Management Journal, Number 1, Volume XXIV, March 1993, Project Management Institute, Drexel Hill, PA

<sup>49</sup> Total Effort = Scope  $(1 + (1-q) + (1-q)^2 + (1-q)^3 + \dots + (1-q)^n)$  where  $q$  = Quality  
 Multiplying through by  $(1-q)$  and subtracting from the first equation, for  $0 \leq q \leq 1$  and  $n \rightarrow \infty$ , gives:  
 $q(\text{Total Effort}) = \text{Scope}$  or: Total Effort = Scope/ $q$

<sup>50</sup> This graph is copied from the reference in Footnote 48.



Figure 7 shows four of the more important factors that affect quality.<sup>51</sup> Process potential quality is determined by the existing processes – the optimal quality that can be achieved with a skilled workforce using the given tools and methods. The goal of quality improvement techniques, such as the Toyota Production System, is to increase this variable's value. Because the minimum possible project effort is determined by the maximum process quality, the desirability of implementing Lean practices is underscored.<sup>52</sup> In practice, intervening factors prevent the achievement of any process's full potential.

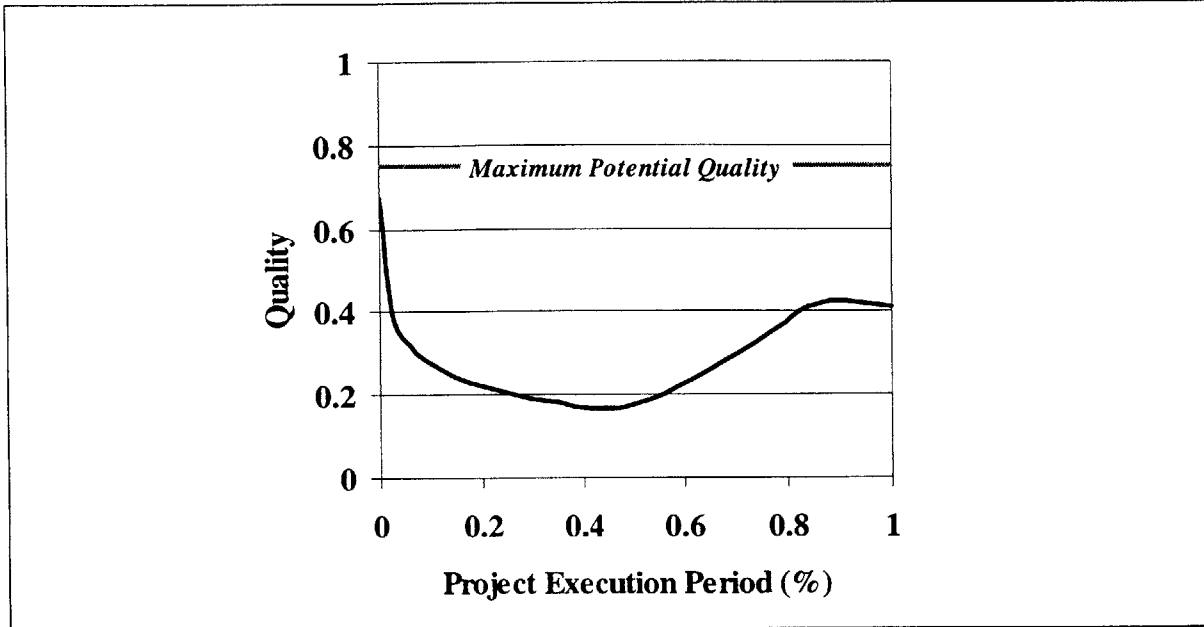


**Figure 7: Four Determinates Of Quality Over Time**

One reason why full process quality is seldom obtained is an under-skilled workforce, which degrades the basic process performance to something often far less than its potential. Because it takes training and experience to become proficient, the shape and duration of the learning curve are paramount in determining the level of quality over the course of the project. For example, during the initial staff-up the influx of novice workers drags down quality as they learn the processes used on the project. A typical response of quality to workforce changes can be seen in Figure 8. The initial precipitous drop in quality is the direct result of introducing inexperienced workers onto the project, both directly through average workforce experience and indirectly through the feedback effect of past work quality on present quality.

<sup>51</sup> Quality is modeled as the product of the input variables. See Equation 47 in the Appendix, Section 8.4.5.

<sup>52</sup> For example, if process quality is 0.75 the minimum effort required to complete the project will be 130% of what it would have been if the process were perfect.



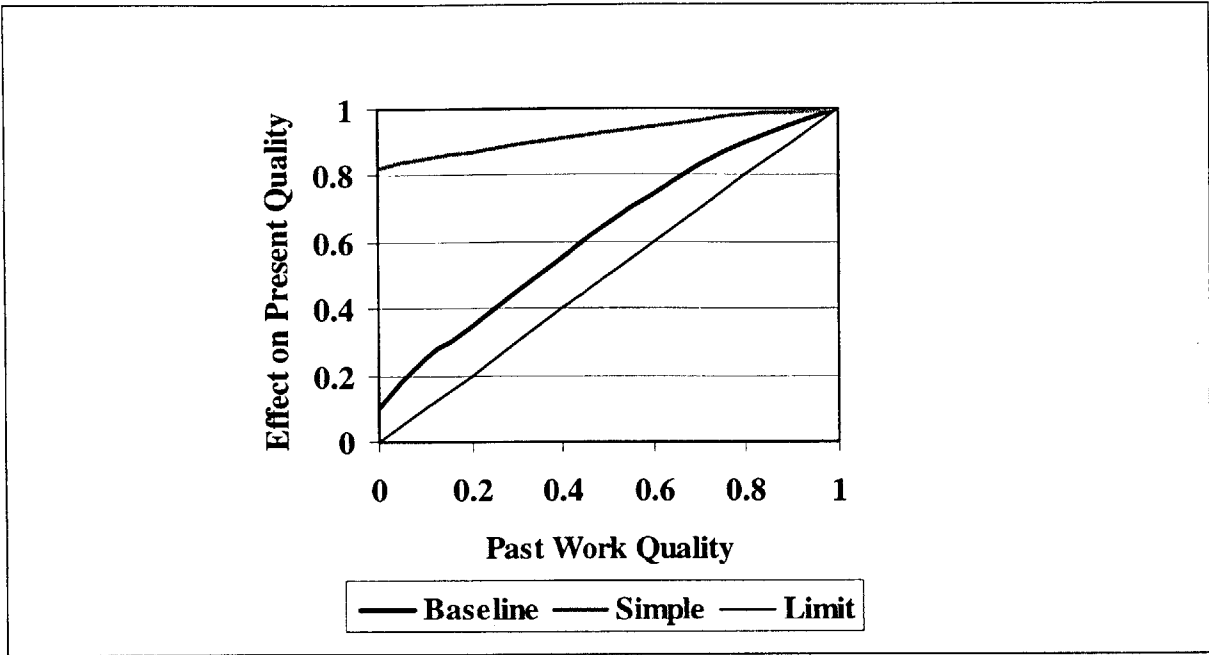
**Figure 8: Example Of Project Quality Over Time**

Crucial to the understanding of project quality, the effect of past quality on present quality captures error propagation through the project and is reflective of system complexity. It also suggests that a system design that carefully manages component interfaces would have tremendous cost leverage by containing error propagation.<sup>53,54</sup> Figure 9 depicts several possible functional relationships reflecting different levels of system complexity. For example, using the “Limit” curve, if past work quality is 80% then current quality is reduced by 20% – quality that would have been 0.75 is instead 0.60. If a function were to lie below the “Limit” curve the project would never be completed as the value of quality would converge to zero. For the system in this section, the “Baseline” curve was used. The quality on quality effect exacerbates the initial drop in the quality triggered by unskilled new hires.

In Figure 8, approximately half way through the project, the tide of new workers begins to ebb and quality begins to improve. However, rushing to meet schedule thwarts the gains in quality that result from increasing experience. Under pressure to meet a deadline, even a highly skilled worker’s error rate will go up. This is the effect of schedule pressure on quality. It is particularly acute at the very end of the project and responsible for quality’s final down turn.

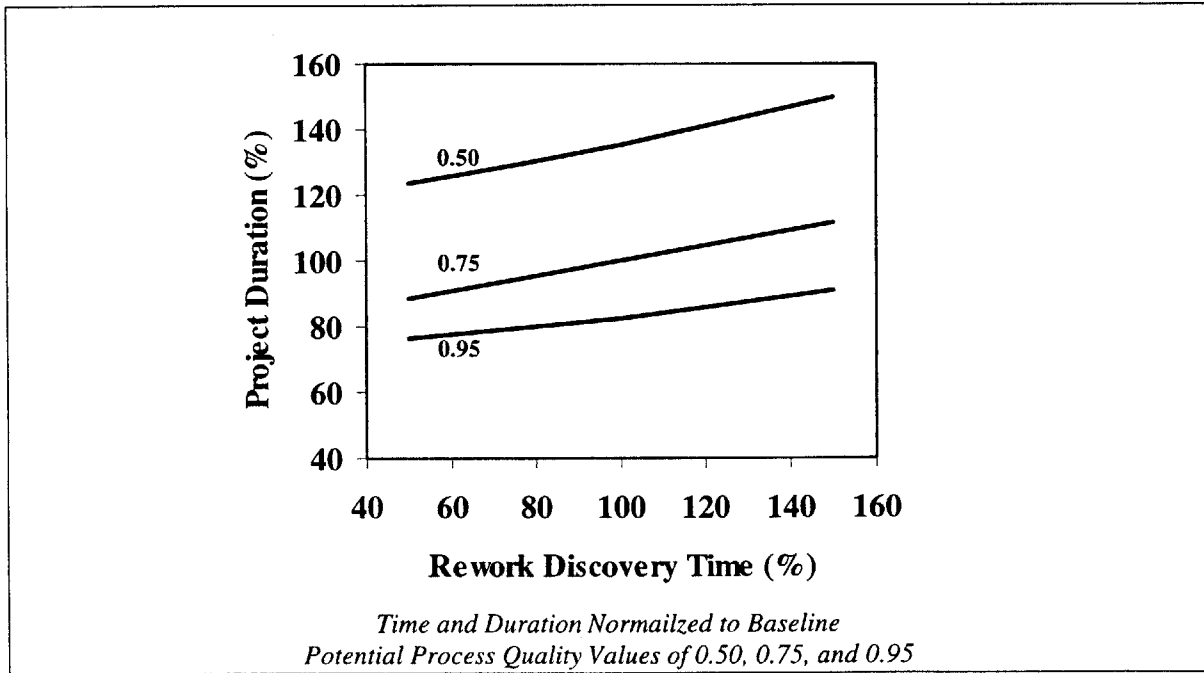
<sup>53</sup> Suh, Nam P. *Principles of Design*, Oxford University Press, New York, 1990

<sup>54</sup> Ulrich, Karl T., Eppinger, Steven D., *Product Design and Development*, McGraw-Hill, New York, 1995



**Figure 9: Example Functional Relationships For The Effect Of Past Work Quality On Present Quality**

To complete this section on quality, Figure 10 presents project duration trends for constant values of potential process quality and varying rework discovery times. It serves to reinforce the benefits of intrinsically high quality, transparent processes that allows the production of a minimum number of mistakes, and the early discovery of those that slip through.



**Figure 10: Process Quality Isolines**

## 2.3 Productivity

Productivity is the turbine of the rework cycle. One important lesson from the productivity structure, shown in Figure 11, is the difference between gross and real productivity. Gross productivity, the average worker's productivity<sup>55</sup> adjusted to reflect schedule pressure, directly determines the rate at which work is completed. Assuming the workforce is not resource constrained, it is the rate of productivity that would be measured on the shop floor or in the office – rework and all. Real productivity is the gross productivity rate corrected for quality – the rework free, unconstrained productivity. Both real and gross rates indirectly influence the time required to complete the project through management's perception of productivity, which is used to determine the number of employees required to complete on schedule. Figure 12 compares the three and illustrates the lag between real productivity and perceived productivity as well as how quality reduces gross productivity.

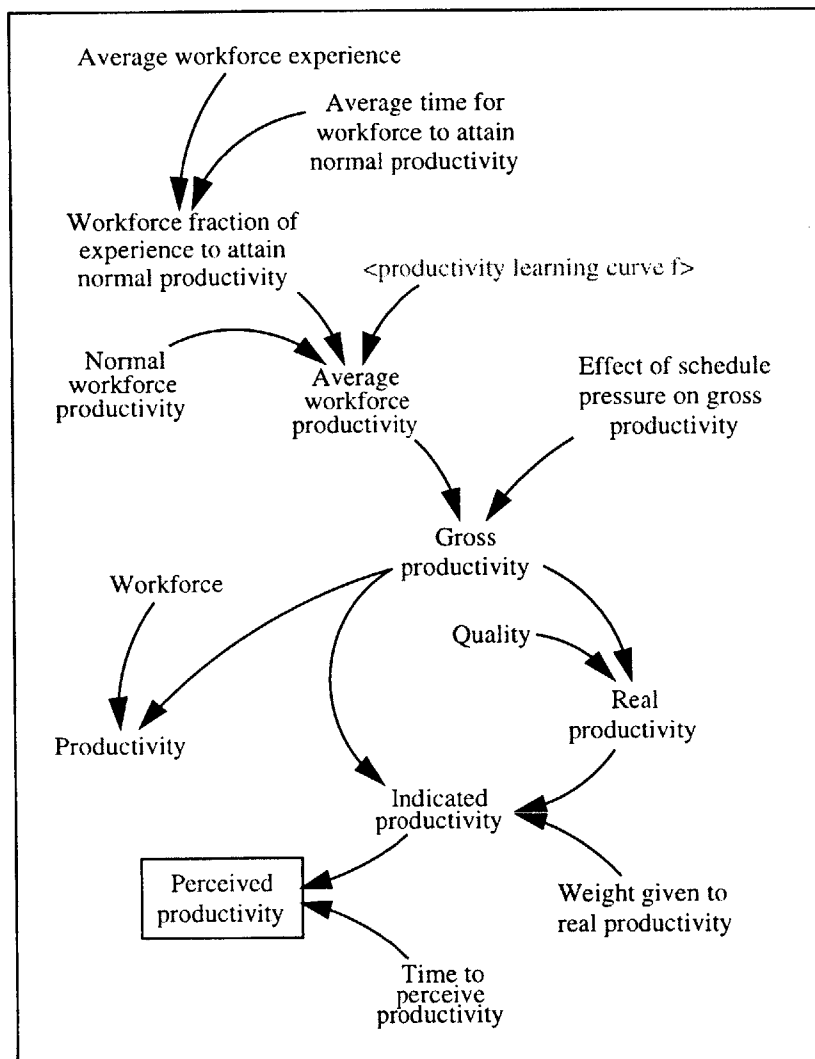
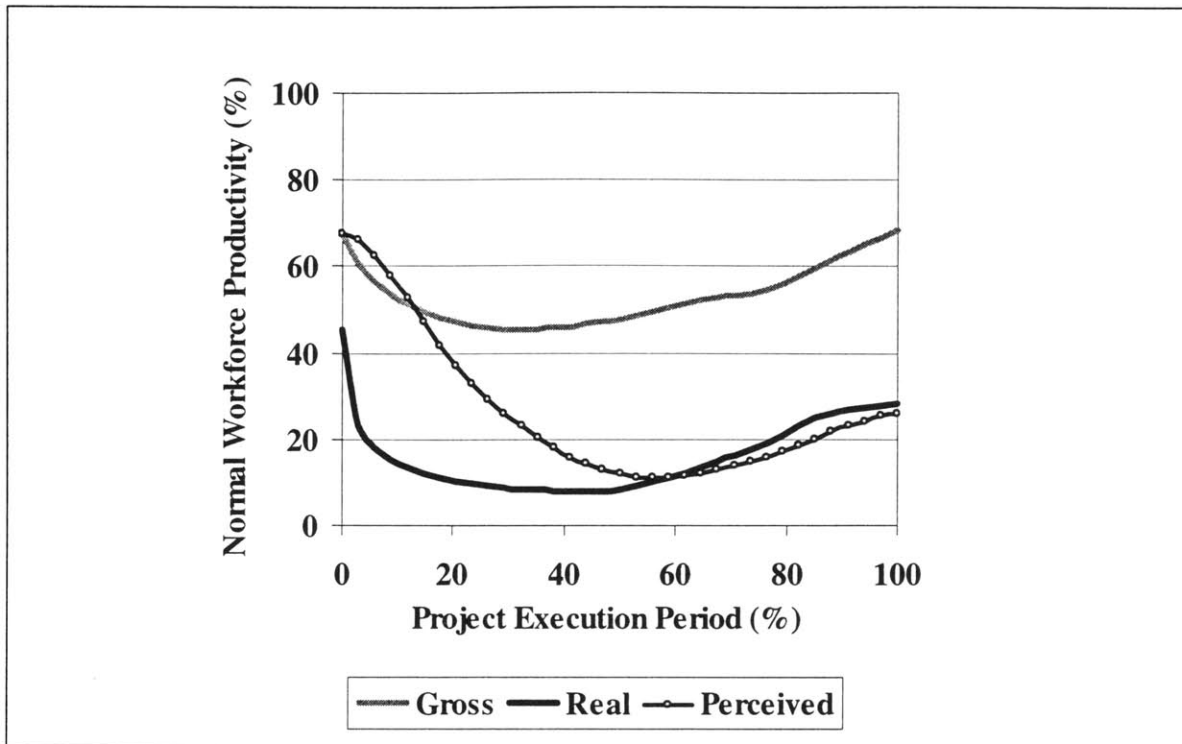


Figure 11: Determinates Of Productivity Over Time

<sup>55</sup> Typical units would be: tasks/(man·month).

Quality and gross productivity have similar dynamics because both are process limited and affected by workforce experience and schedule pressure. As with quality, the ultimate process capability or potential is important, however in this case it is the desirability of increasing the average output per worker that is highlighted. Given that project scope and quality determine total effort, the minimum time required to finish the project will be resolved by the maximum productivity of the process.<sup>56</sup> Of course, other factors will intervene, increasing the required development time beyond the minimum.



**Figure 12: Comparison of Productivity Values**

Gross productivity drops initially, just as with quality, due to the influx of new workers – building proficiency at a new process requires experience. Captured in the productivity learning curve, this effect again suggests that policies serving to hasten the employee’s transition through the learning curve represent a potential cost and schedule benefit.

As workforce proficiency begins to build, real productivity, under quality’s influence, recovers more slowly than gross productivity in spite of the boost from schedule pressure as the project nears completion. Here is another important lesson – schedule pressure’s contradictory influence. Schedule pressure increases productivity, increasing the rate at which work is completed, but decreases quality, which increases the amount of work that must be done. The net effect on the project tends to be negative because the first order consequence of a change in productivity is linear, while that of quality is exponential. The increase in the amount of work overwhelms the increase in the rate of doing work.

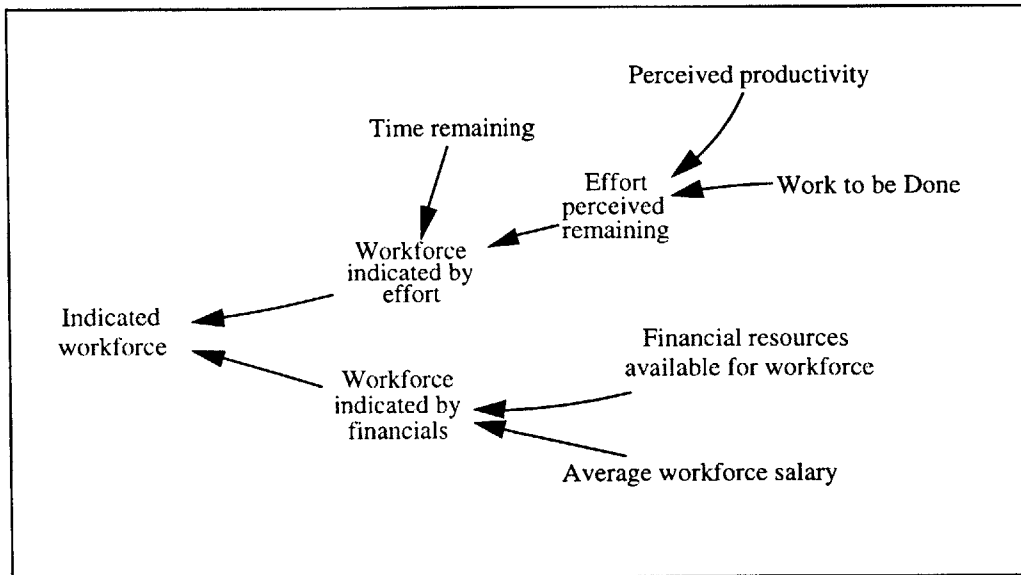
The complexity of this seemingly simple system becomes apparent in this example of unintended consequences. The manager thinks he is keeping the project on track by pushing his workers, while actually his actions will cause the project to take longer and cost more.<sup>57</sup>

<sup>56</sup> Workforce availability and level of concurrent engineering are also limiting factors.

<sup>57</sup> Ibid. Footnote 39

## 2.4 Workforce

Workforce management is a powerful tool for controlling a development project. Workforce experience is a major component of quality. Likewise, workforce size and experience determine productivity. Figure 13, the decision rule for determining the workforce size, shows the connections between workforce size, the remaining work to do and productivity as perceived by management. Thus the causal connections between the project work remaining, workforce management, quality and productivity become clear. Financial resources appear here as a limiting factor in the decision rule, capping the potential workforce size.



**Figure 13: Determinates of Workforce Size**

In previous sections, the power of inexperienced workers to degrade the project's performance was illustrated. Figure 15 is a typical profile of workforce size over the life of a project, while Figure 16 demonstrates the effects of changes in that profile on average workforce experience. Containing three important control mechanisms of the workforce's influence: the experience of new workers, and the times required to add and remove workers from the project, Figure 14 suggests one solution – build and maintain a pool of experienced workers. By doing so, the project manager is able to staff a program with individuals who have already traversed the learning curves. This keeps skill and quality high which reduces the total amount of rework on the project. Less rework means fewer workers are needed to complete the project so the project costs less and experiences less schedule slip. Of course, this is possible only if processes are consistent from project to project, or if when new processes are introduced, training is provided between projects.<sup>58</sup> Figure 17 indicates the potential benefits of increased initial new worker experience with the influence of the learning curve, shown in Figure 18, clearly visible in the mode shape. Viewed from this perspective, the periodic, massive layoffs at large aerospace companies are probably counterproductive – indicative of lost opportunities to improved long-term financial performance.

<sup>58</sup> The reference below gives a case history of manufacturing firm that has successfully integrated such a process into its management policies.

Fast, Norman, *The Lincoln Electric Company*, HBS Case Service, Harvard Business School, Boston, MA, 1975, Case Number 376-028

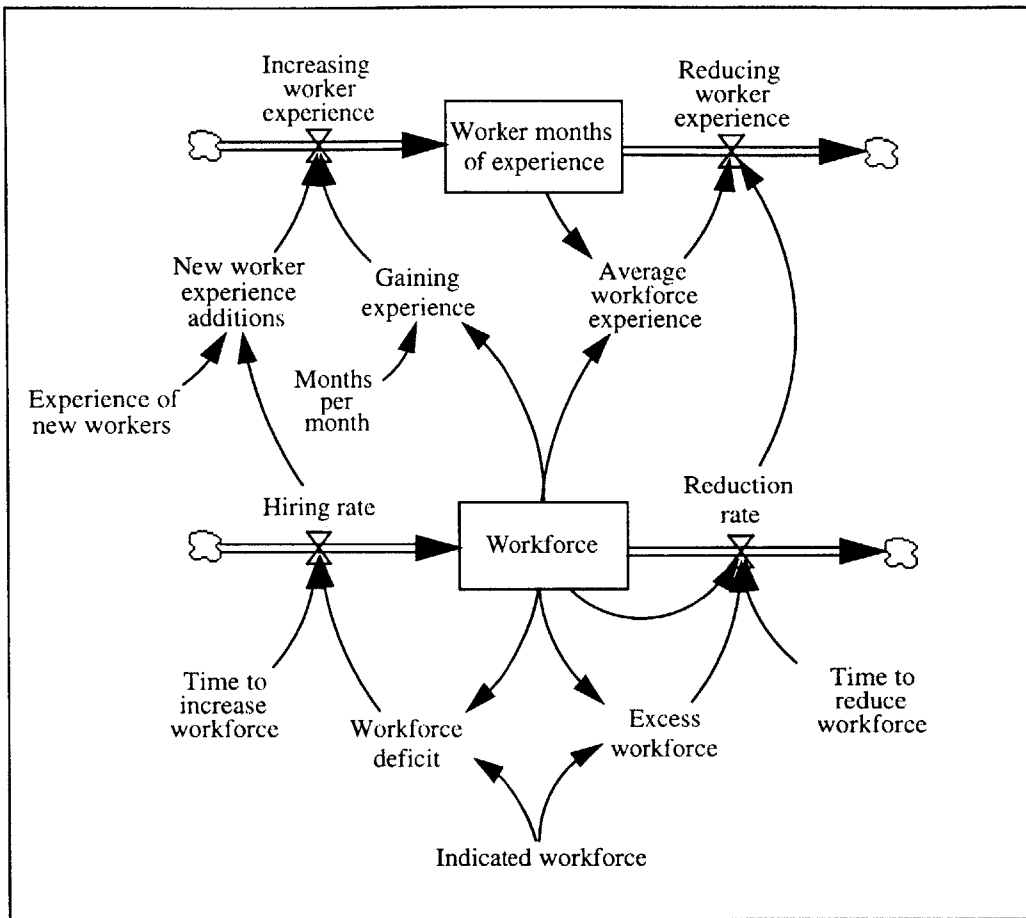


Figure 14: Basic Workforce Structures

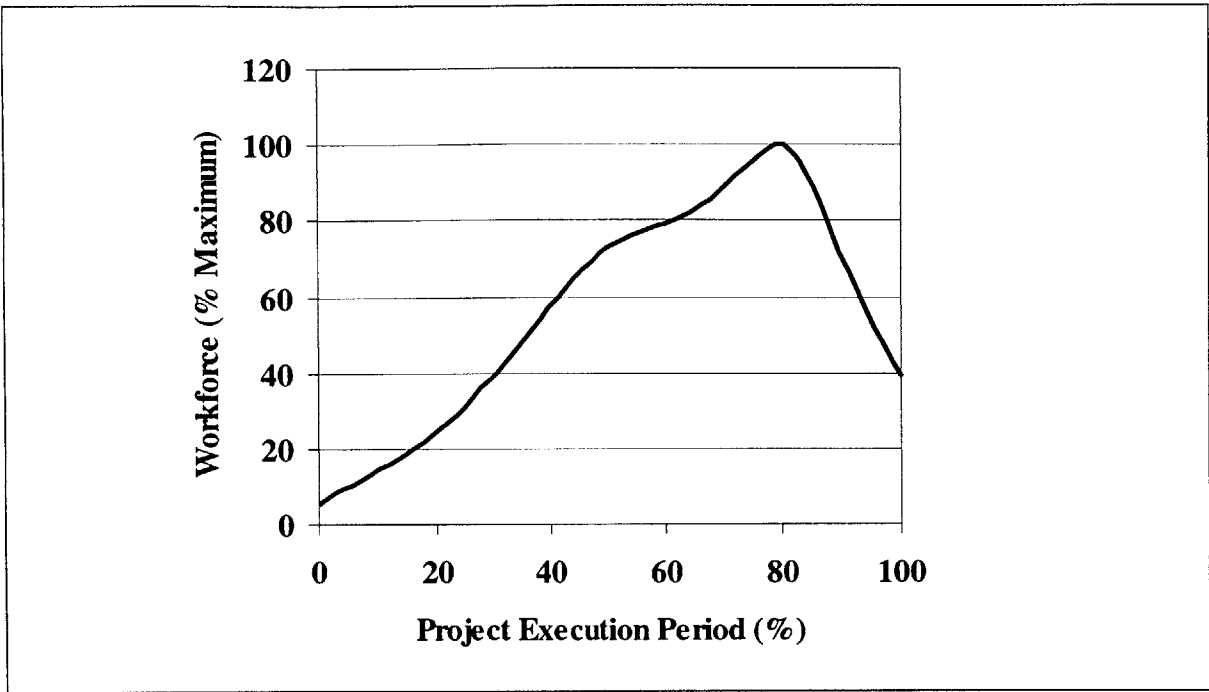


Figure 15: Example Workforce Size Over A Project's Life

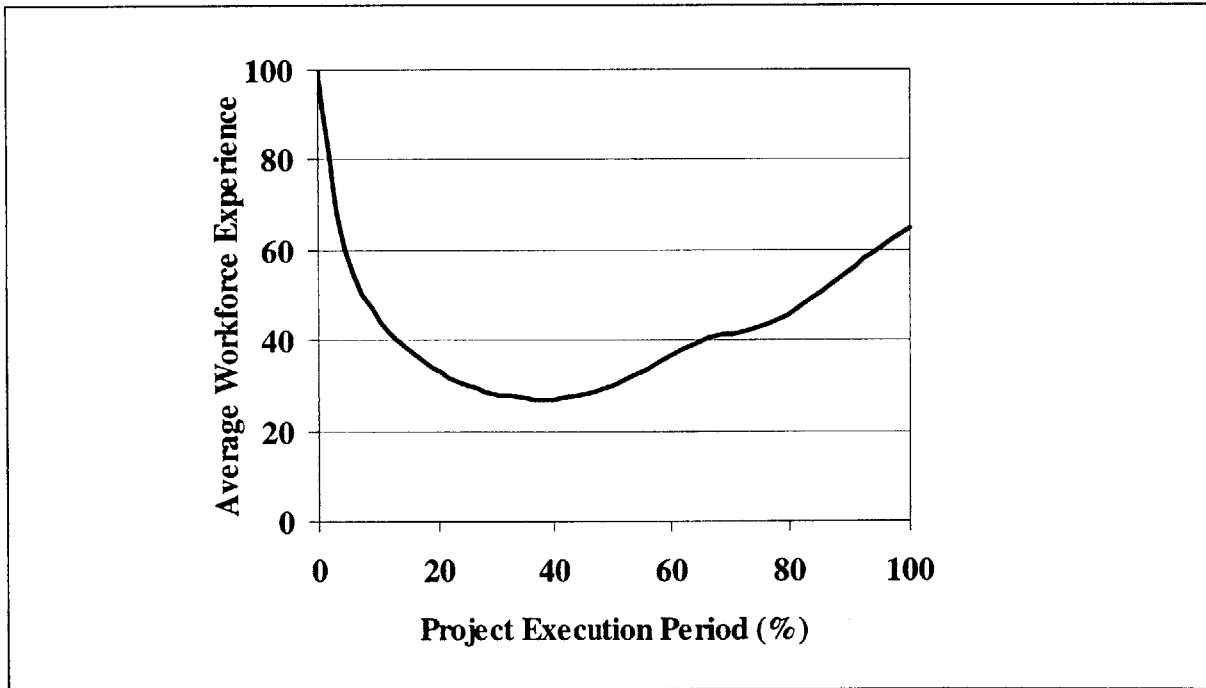


Figure 16: Dilution of Workforce Experience



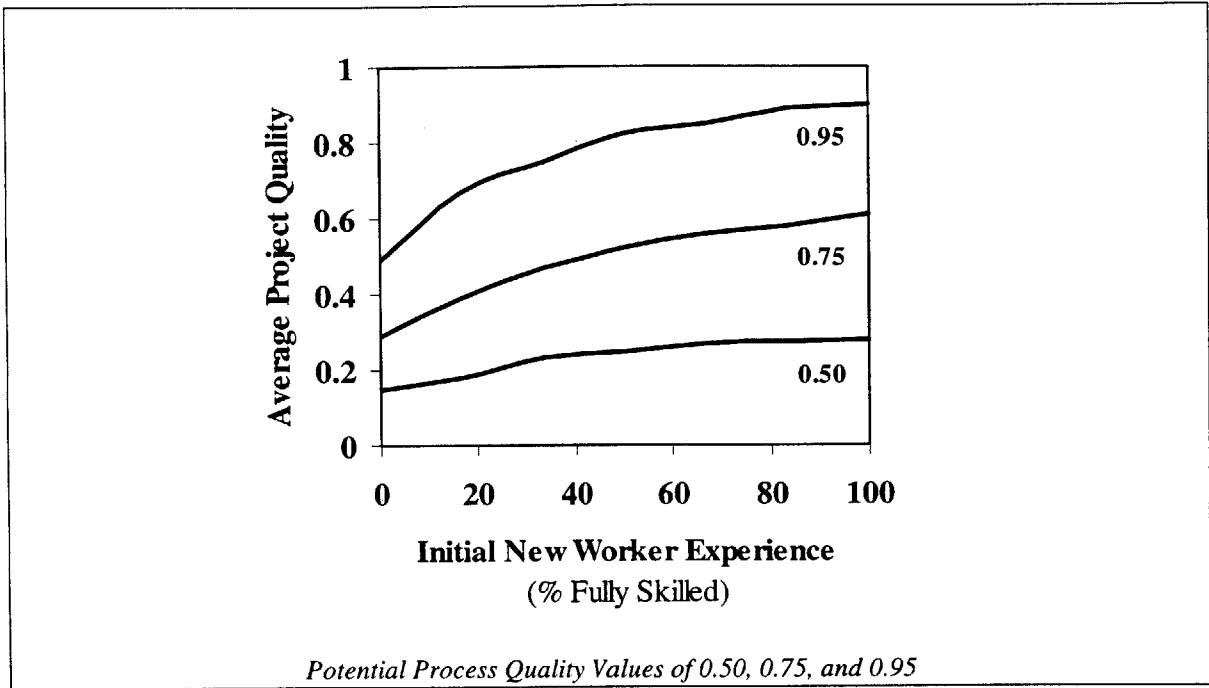


Figure 17: General Trends In Process Quality Isoforms For Affect Of New Worker Experience On Average Project Quality

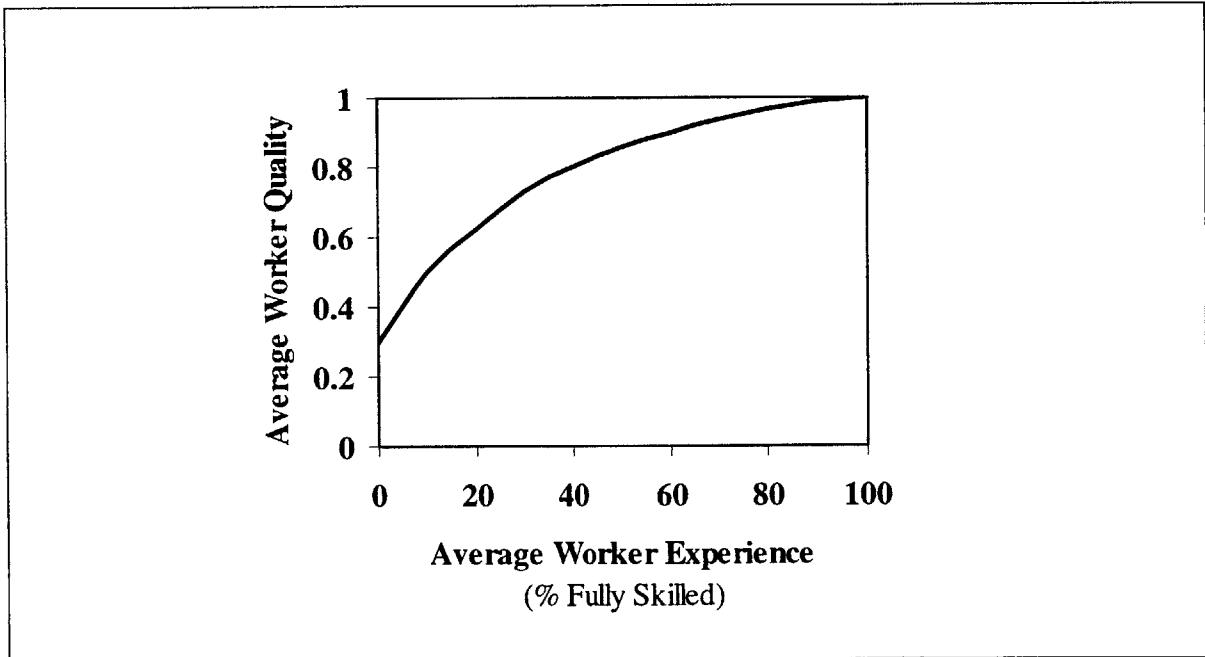
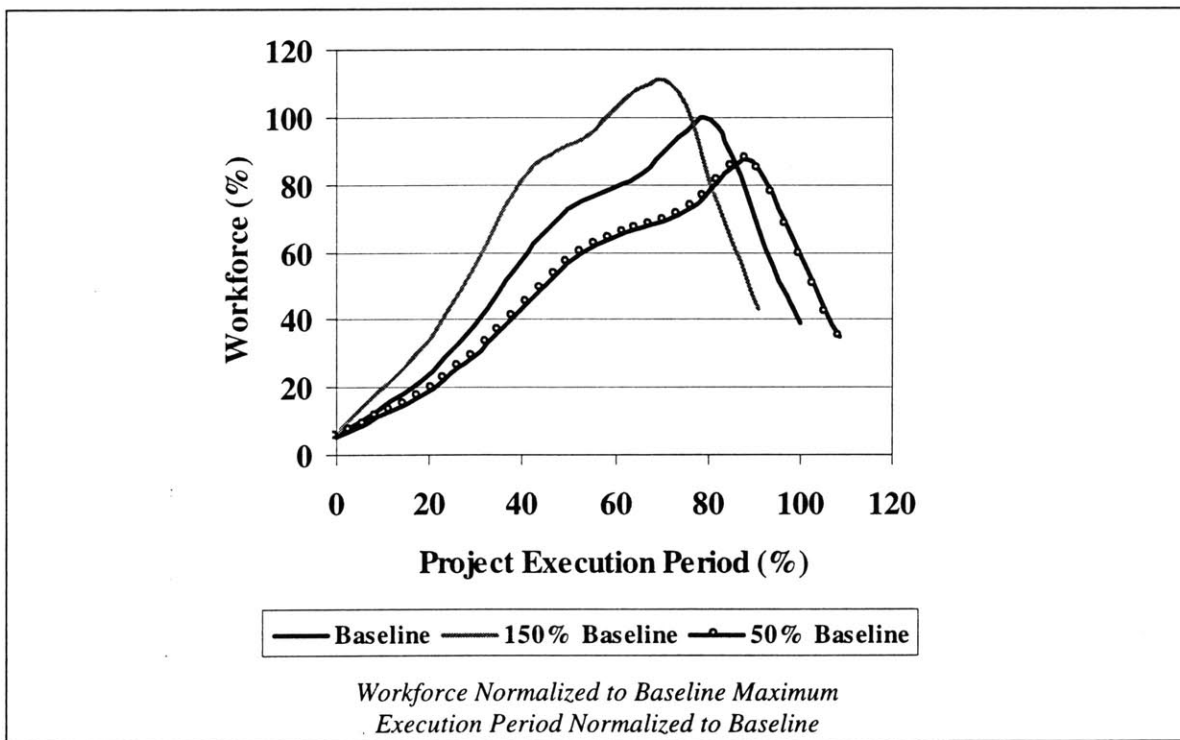


Figure 18: Example Quality Learning Curve

Before leaving this discussion of workforce, an instructive reminder about the complex behavior of this simple model is had by examining the phenomena of rapid staff-up. The net result of which is a higher maximum number of worker's and thus higher labor costs, slightly less schedule slip, but lower average project quality. Figure 19 through Figure 22 chronicle the phenomena for several staff-up rates.

An influx of new workers, because they represent a large fraction of the existing workforce, drives the average workforce experience down. This has the predictable effect of reducing quality, exacerbated by the effect of past quality on present quality. Productivity is also depressed, resulting in more workers being required to complete the project on schedule. Lower quality has increased the amount of rework which, when discovered pushes the demand for workers even higher. The project does finish sooner given the large workforce when experience does begin to climb. But of course carrying the extra workforce on the payroll results in increased total labor costs.

If workers are added more slowly, the effects are reversed to some extent, but less than expected. The surprise is from increased schedule pressure. Slower staffing causes the schedule to slip more earlier in the project's life. This increases the effects from schedule pressure, increasing gross productivity, but decreases quality, which negates some of the benefits of slower staff-up. Of course, one solution is to just accept the schedule slip and keep schedule pressure to a minimum.



**Figure 19: Trends In Maximum Workforce With Staff-up Rate**

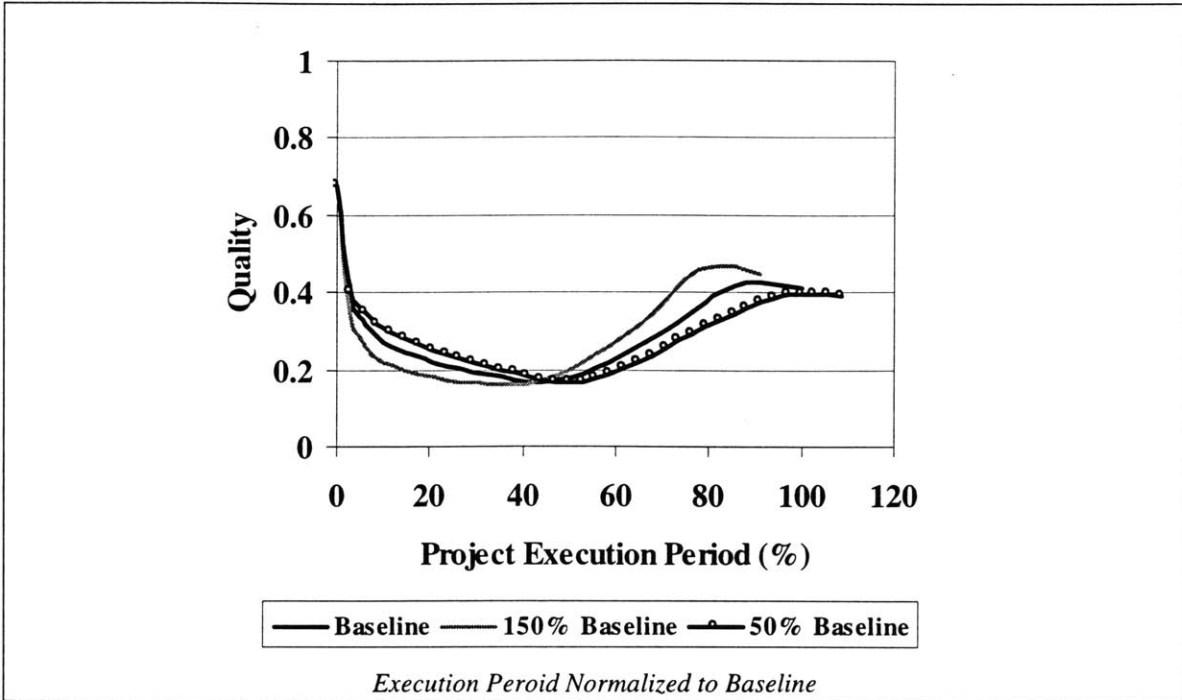


Figure 20: Trends In Quality With Staff-up Rate

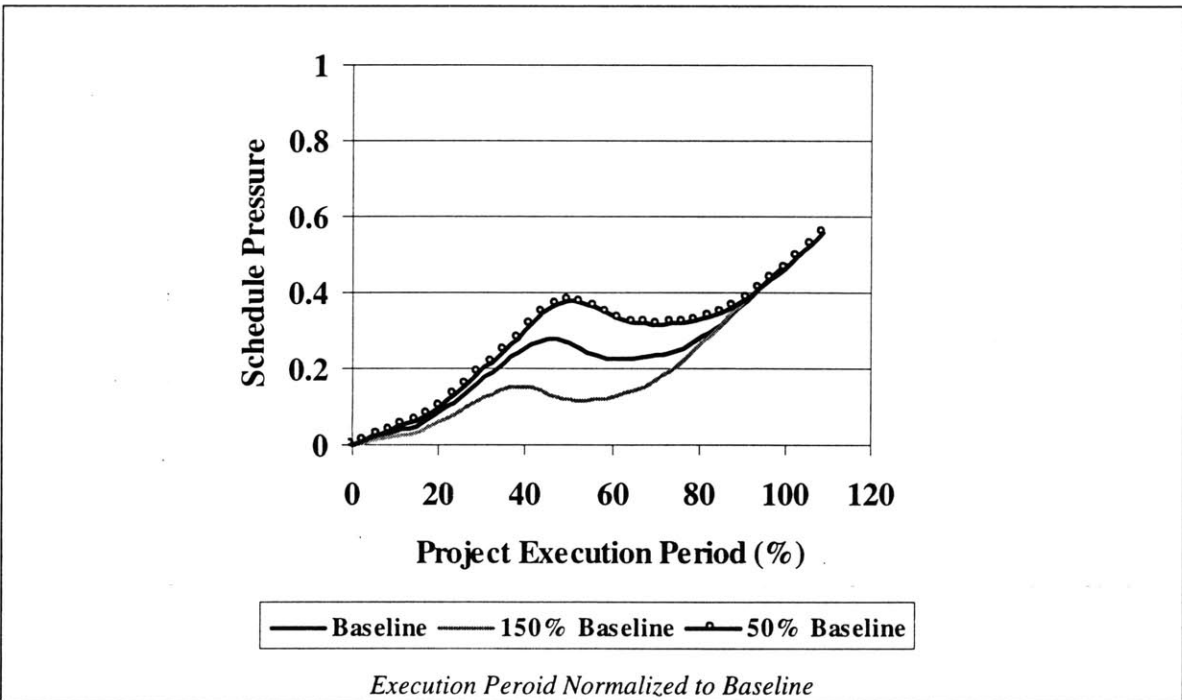
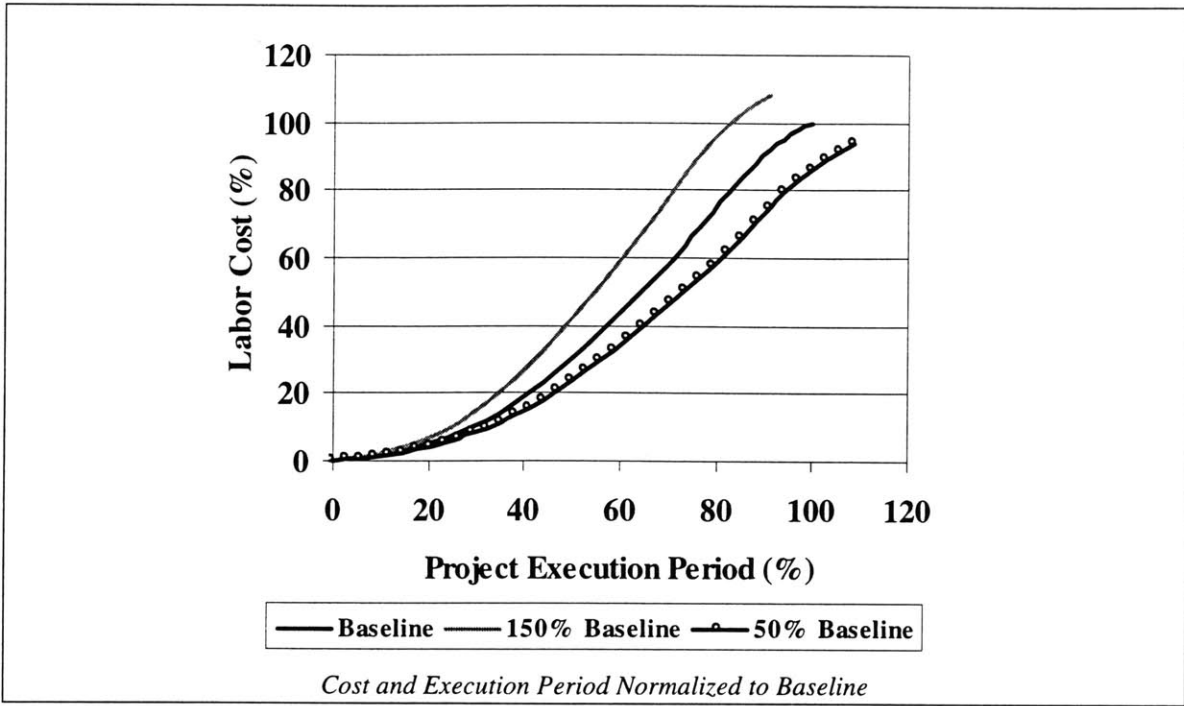


Figure 21: Trends In Schedule Pressure With Staff-up Rate

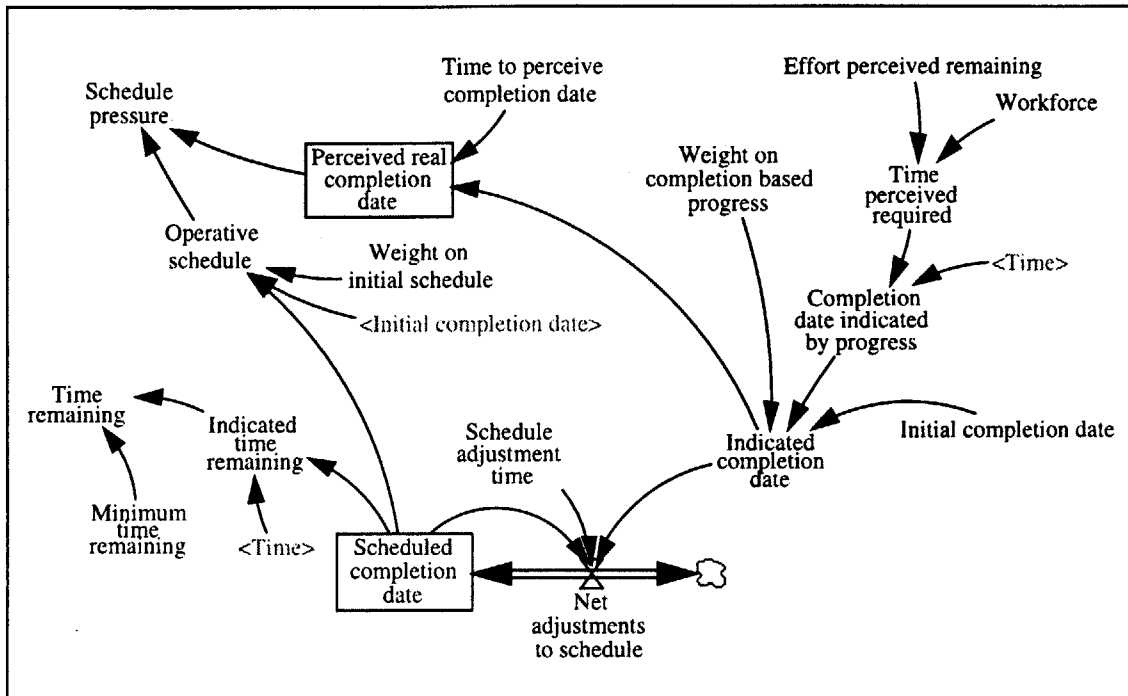


*Cost and Execution Period Normalized to Baseline*

**Figure 22: Trends In Labor Costs With Staff-up Rate**

## 2.5 Schedule

Schedule or more precisely the period allotted for the performance of the project is an essential component of the project model. Given the work remaining and the perceived productivity, the workforce required is determined by the time remaining for completion. Quality and productivity as well are influenced by pressure created by the impending arrival of the completion date. Figure 23 shows the structure for scheduled completion date and schedule pressure.



**Figure 23: Project Schedule Dynamic Elements**

Scheduled completion date is the official completion date. It tends to lag the indicated completion date because much time and energy is invested in changing the official date. Managerial control is modeled by the weight functions, *Weight on initial schedule* and *Weight on completion based progress*. As the project is staffing up the manager ignores what little progress has been made and the initial completion date is the scheduled completion date. However, after sufficient progress and hiring, the date indicated by progress begins to be accepted and used to make program decisions.

Schedule pressure represents the tension between the operative schedule, the date management is holding the workforce to, and the perceived real completion date, derived from the existing workforce and effort perceived remaining. The more importance the manager places on the initial completion date, rather than scheduled completion date, the more pressure there will be when the two diverge, with all the deleterious effects discussed in the previous sections. Figure 24 and Figure 25 hint at the potential benefits of working to realistic deadlines. There, by allowing the schedule to slip easily, the project takes no longer than the baseline but has much lower labor costs.

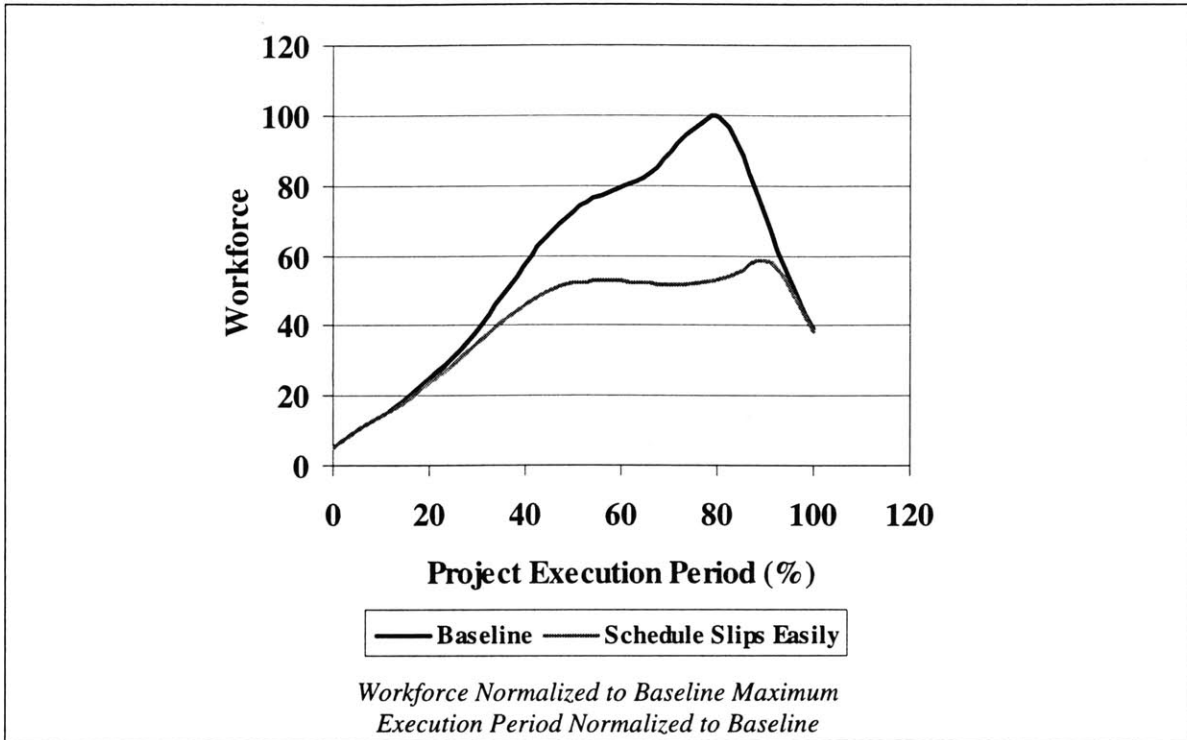


Figure 24: Potential Workforce Benefits Of Realistic Schedules

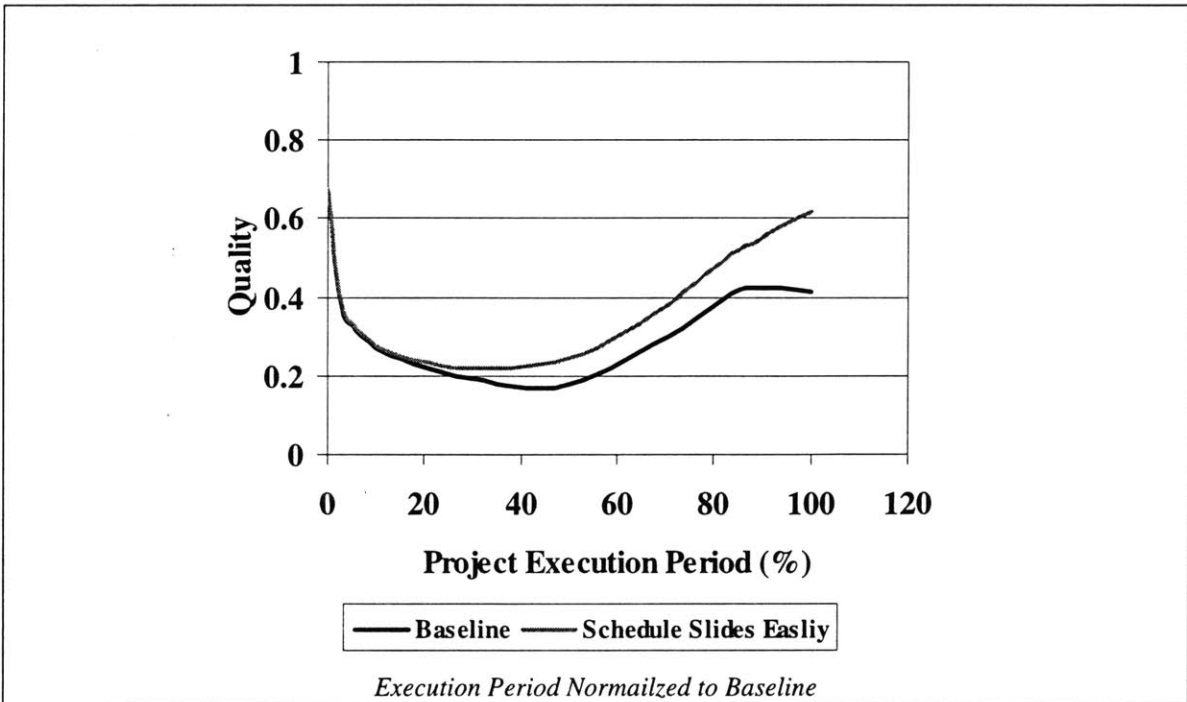


Figure 25: Potential Quality Implications Of Realistic Schedules

### **3 CONTRACTOR AND SYSTEM PROGRAM OFFICE MODEL**

This study seeks to explain some of the cost and schedule dynamics observed in Air Force acquisition programs, and while the basic project model provides powerful insights applicable to both SPO and prime contractor, there are features unique to the combined SPO-contractor system that must be captured to obtain a deeper understanding of those dynamics. In this section, the important modifications to the basic model, which characterize the contractor and SPO structures are presented and contrasted.<sup>59</sup> Techniques used to validate the model are also discussed. Then, in Section 4, the behavior of the system and the management insights derived therefrom will be investigated.

#### **3.1 Modeling The Contractor**

An extension of the basic project model, the contractor portion of the model incorporates additional features important to SPO-contractor interactions. These include: the initial estimates of project scope and cost, the use of overtime to increase productivity, the use of management reserves, and the effects of SPO performance upon the contractor's performance.

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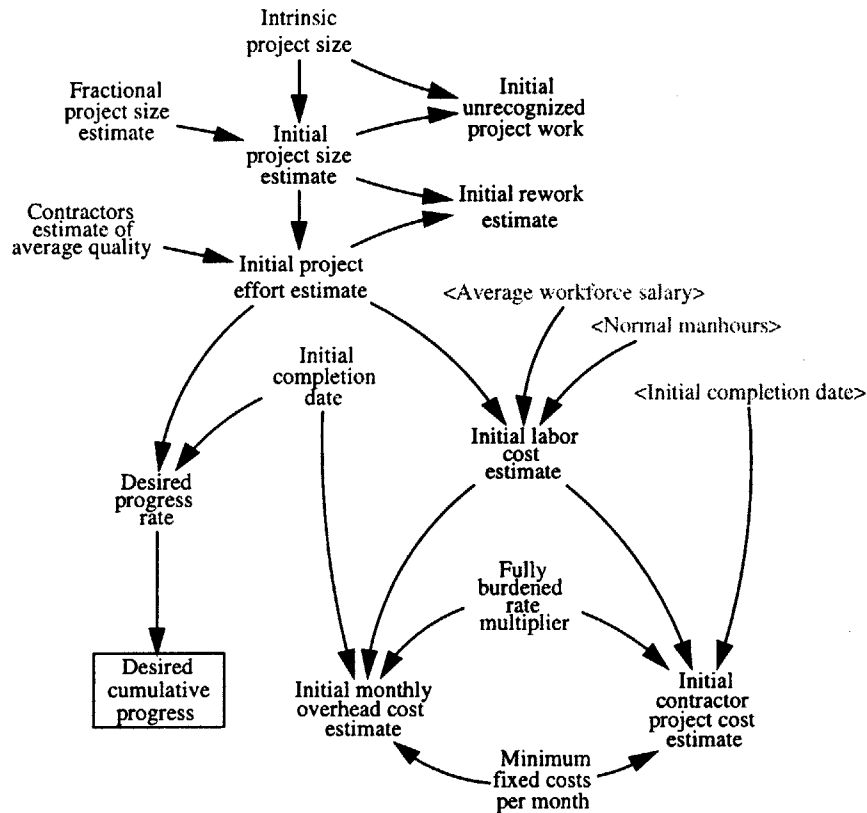
<sup>59</sup> The complete model structure and equation listing is given in the Appendix, Section 8.5. Section 8.3 provides a basic introduction to the stock and flow diagrams used to present the model structure.

### 3.1.1 Contractor's Initial Estimates of Project Scope and Cost

Every project has an intrinsic scope. Of course, it is often not known with certainty at project inception and therefore the amount by which initial estimates deviate from this intrinsic scope constitutes the initially unrecognized project work. The mechanism, by which it will be discovered over the course of the project, is discussed in Section 3.1.3.

With the initial scope estimate in hand, the contractor determines the effort that should be required.<sup>60</sup> Then using the initial completion date, average salary, and normal productivity, the program labor costs are estimated. Total costs are then calculated as the sum of labor and overhead costs. In this case, overhead is estimated to be a fraction of labor costs.<sup>61</sup> Program cost overrun is then calculated, using this total cost estimate as the basis for its determination.

Finally, a fact that has important implications for development projects is that currently contractors are not allowed to account for the presence of rework in their initial estimates of effort. [Milauskas, Almojuela] The result being that cost is determined by effectively assuming *perfect* average quality – that no errors will be made.<sup>62</sup>



**Figure 26: Contractor's Initial Project Scope and Cost Estimate Structure**

<sup>60</sup> In this case:  $initial\ project\ effort\ estimate = initial\ project\ size\ estimate / contractor\ estimate\ of\ average\ quality$ . This follows from the derivation in Footnote 49

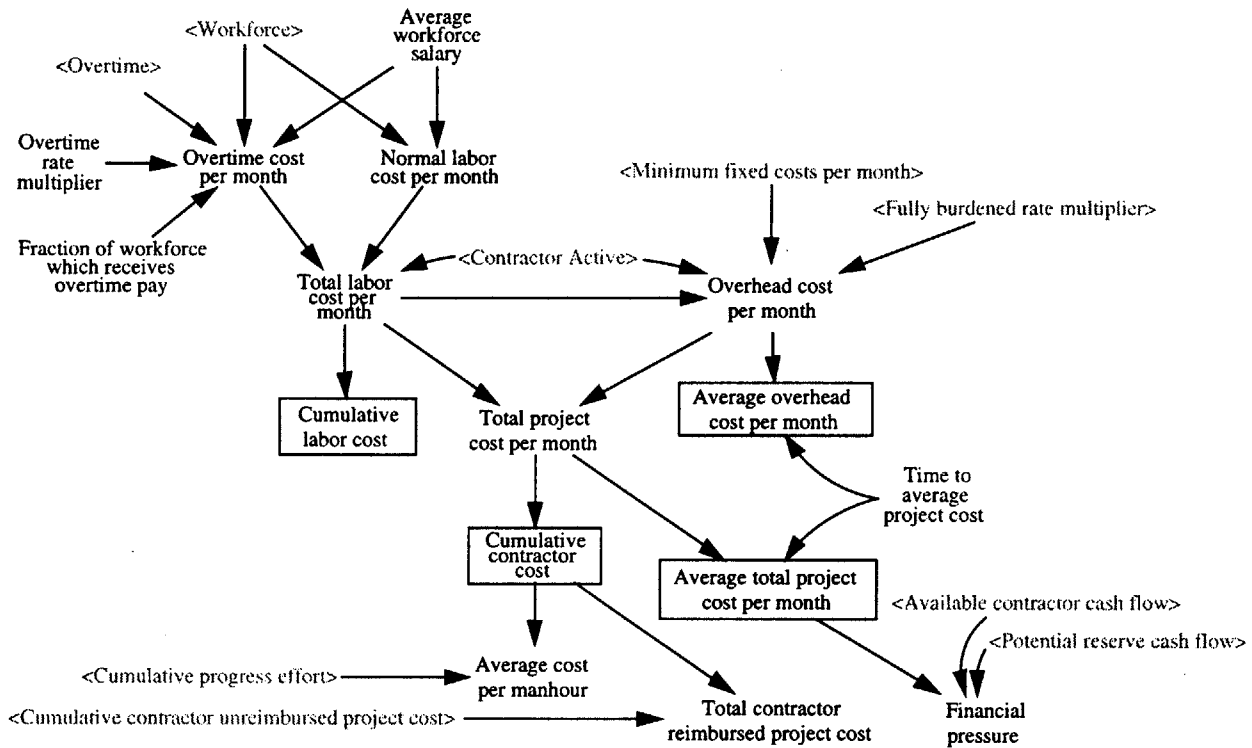
<sup>61</sup> A widely used practice in the aerospace industry is to estimate the total cost by multiplying the average salary cost by a “fully burdened” multiplier. Values vary widely from company to company, even from department to department, with a typical range of 1.9 to 3.0. [Almojuela] Thus, the fraction for overhead cost alone would be calculated by subtracting one from the fully burdened multiplier.

<sup>62</sup> The desirability of using these initial cost estimates as a metric of program performance is clearly questionable.



### 3.1.2 Contractor Costs

Actual contractor costs are calculated from the sum of normal labor, overtime, and overhead costs per month. Overtime is not paid to all members of the workforce and is assumed to be reimbursed at a fraction of the normal salary. Monthly costs are aggregated to give the cumulative contractor's cost. Because the contractor is not compensated for all cost, unreimbursed costs<sup>63</sup> are subtracted to give the total contractor project cost. This is the government's cost for the contractor's work. Profit has not been explicitly modeled and is assumed to be included in cost.



**Figure 27: Contractor's Cost Calculation Structure**

<sup>63</sup> Unreimbursed costs are those, incurred by the contractor in the execution of the contract, for which the government is not obligated to reimburse, under the terms of the contract.

### 3.1.3 Rework

Two modifications were made to the basic rework cycle. First, to incorporate project definition growth, it was expanded to include the discovery of undiscovered work. Defined in section 3.1.1 as the difference between the intrinsic project scope and the contractor's initial estimate, this difference can be thought to include growth due to both requirements changes and that intrinsic to the development process. In the design and construction of any complex system, detailed work is required to reveal completely the true project scope, especially where new technology or processes are involved. Thus, the discovery rate of the new work is a function of project progress. Finally, the pool of known work has been disaggregated to make explicit the known rework existing at any time.

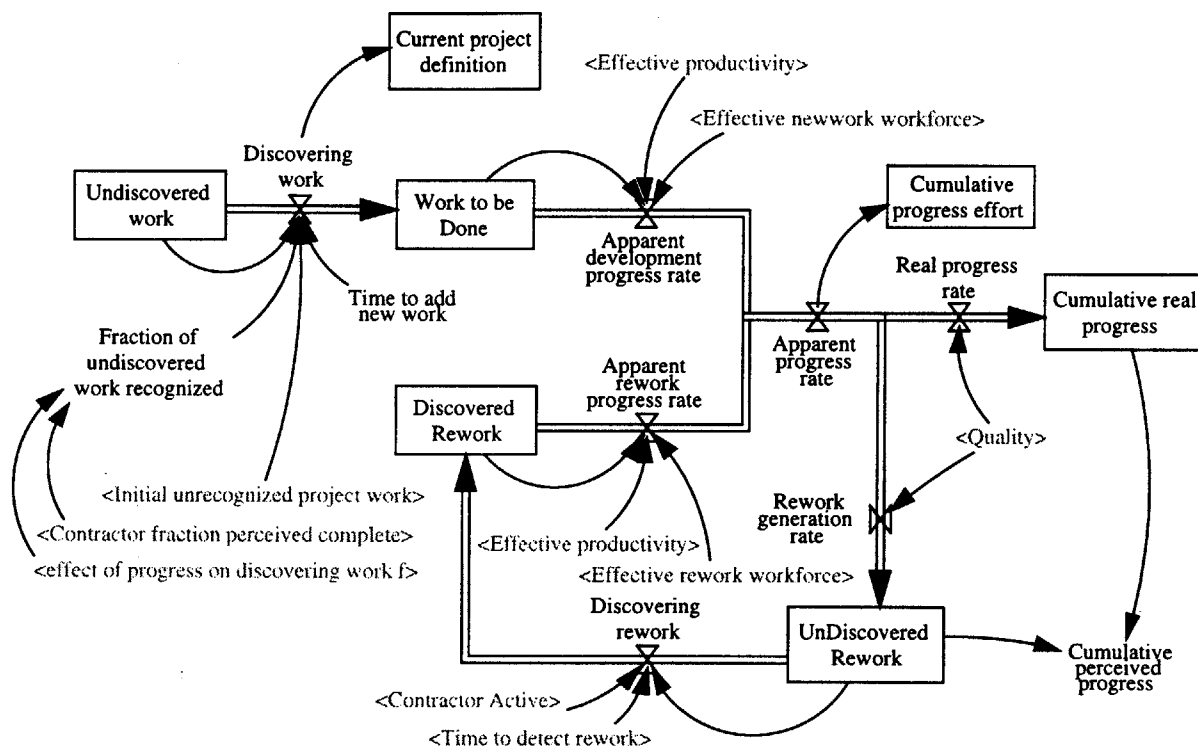
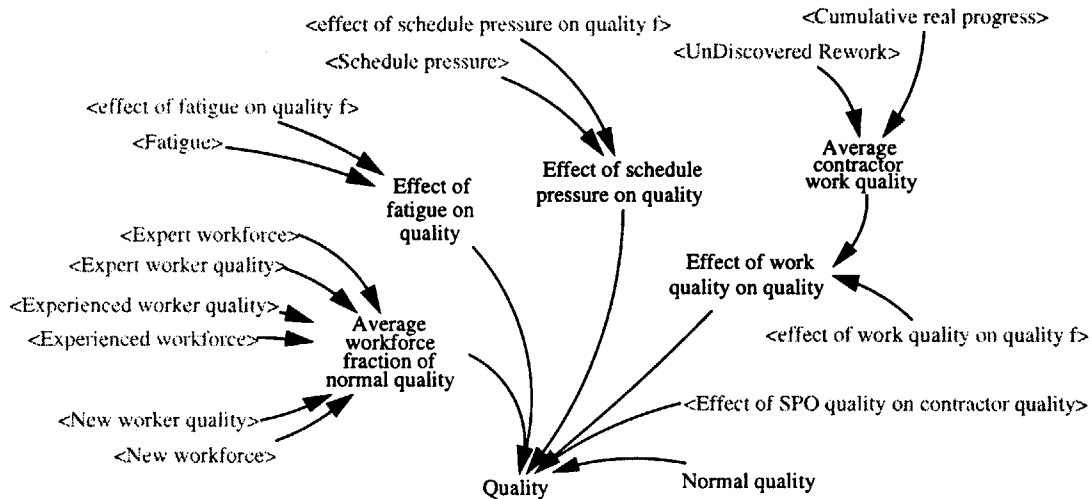


Figure 28: Contractor's Rework Cycle Structure

### 3.1.4 Quality

Two additional influences on quality have been added to the basic structure. Most important is the effect of SPO quality. To the extent that the contractor relies on inputs from the SPO, undiscovered errors in those inputs will reduce the contractor's quality. For example, the aircraft is designed for a maximum cruise Mach number as specified by the warfighter. If a mistake was made by the SPO in generating the trade space used to select that Mach number, the contractor generates significant rework by designing to an erroneous specification.

Another important influence is workforce fatigue, because as workforce fatigue increases, error rates tend to increase, depressing quality. Fatigue's deprecatory effect on quality must be included also because of its link to workforce management policies through the use of overtime, discussed in the next section.



**Figure 29: Contractor's Quality Structure**



### 3.1.6 Productivity

In the previous section the effect of fatigue on productivity was eluded to. It is another example of unintended consequence – as overtime continues, fatigue builds and begins to degrade gross productivity, the very opposite of the intended effect. However, the lag between the initiation of overtime and the reduction in productivity hides the cause and effect relationship. A natural reaction is to increase overtime even more when the progress rate has not increased – the only way to break the cycle is to give the workforce a rest.

A direct link between the SPO and contractor also appears in the productivity structure. If the contractor is forced to wait for inputs from the SPO, the effective productivity of the contractor is reduced. An example would be waiting for certification of a program modification near the delivery date, with most of the work completed there is little to do but wait. The result could be literally a day for day schedule slip. [Weiss] Of course, accrual of the additional days' fixed and labor costs incrementally increases total project cost.

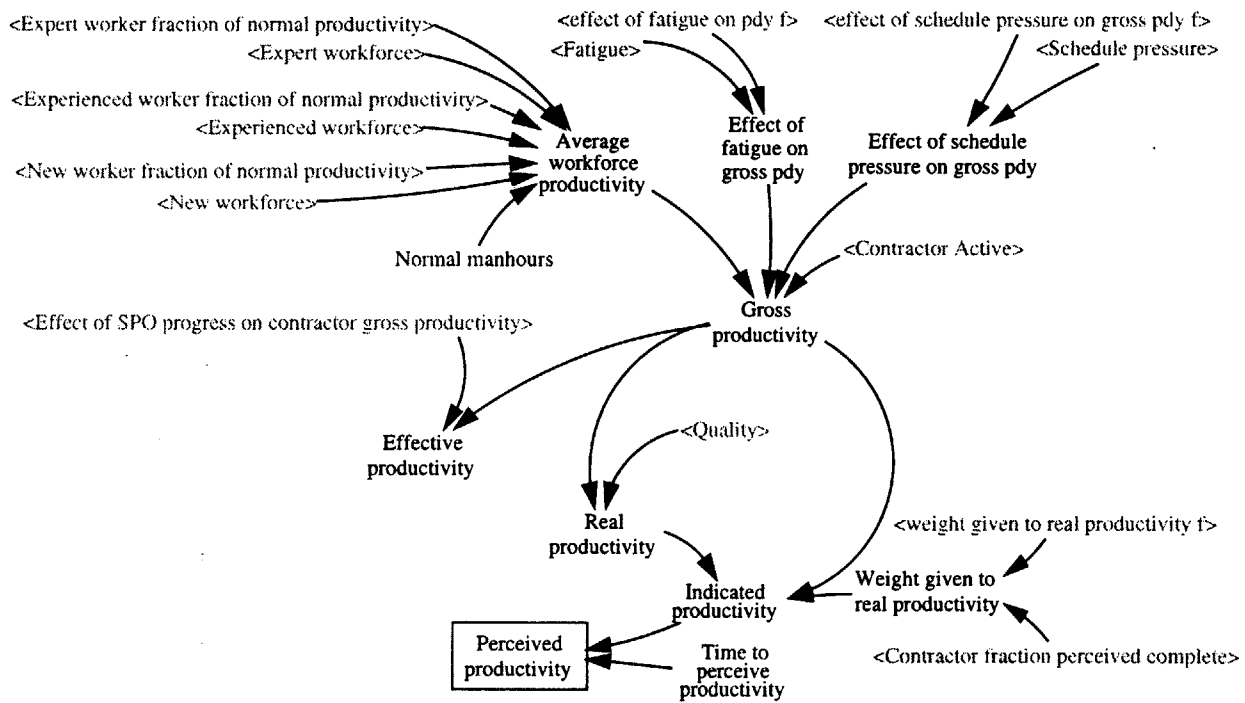


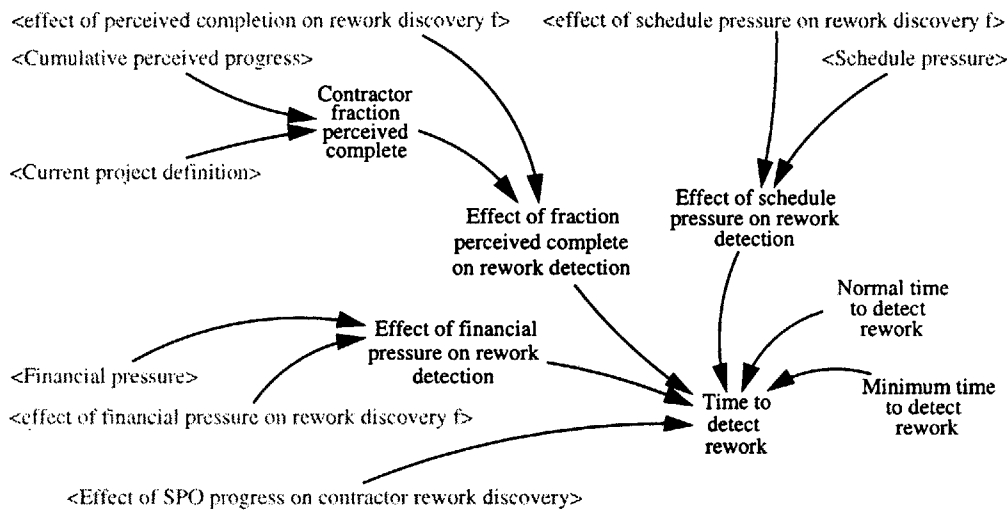
Figure 31: Productivity Structure<sup>66</sup>

<sup>66</sup> In the figure, pdy is an abbreviation for the word productivity.

### 3.1.7 Rework Discovery Time

One area where SPO-contractor interaction provides positive benefits is reducing the time to discover rework. Through its coordination and review efforts, SPO activities naturally lead to the discovery of miscommunications and mistakes by the contractor. Of course, the contractor performs the same service for the SPO. In addition, given an acquisition program's diverse customers, the SPO serves to reduce the contractor's rework discovery time through increasing communication network efficiency.<sup>67</sup>

Financial pressure's effect on rework discovery time has also been included. When financial resources are found to be in short supply, the natural tendency will be to focus on the completion of the known work rather than searching for errors. Financial pressure then has the tendency to increase the contractor's rework discovery time.



**Figure 32: Determinates of Contractor's Time to Detect Rework**

<sup>67</sup> The SPO is the broker at the center of an information network. With the SPO, the number of direct communication links required for all  $N$  constituencies (not counting the SPO) to exchange information is:  $N$ . Without such an information broker, the number of links required goes up to:  $N(N-1)/2$ . The potential communication efficiency provided by the SPO is clear.

### 3.1.8 Workforce

Because much of the contractor's cost is related to personnel, the workforce structure of the basic project model has been disaggregated to provide a more accurate representation of the workforce's distribution and dynamics.<sup>68</sup> The workforce was separated into new, experienced and expert workers, facilitating the modeling of experience building within the workforce. Figure 34 is the expanded workforce experience structure corresponding to the segregated workforce structure, Figure 33. In addition, because of its dynamic implications, the effect of fatigue on new hire attrition has been included.<sup>69</sup>

Figure 35 depicts the workforce sizing structure, determination of which is complicated by the more explicit modeling of financial resources, including overhead and cash flow from management reserves. Added flexibility in the exploration of workforce management is provided by the willingness to change workforce structure. Driven by perceived completion, it allows simulation of management disregarding the indicated workforce and tending to keep the workforce size constant. Finally, Figure 36 and Figure 37 are the expanded structures required for workforce management.

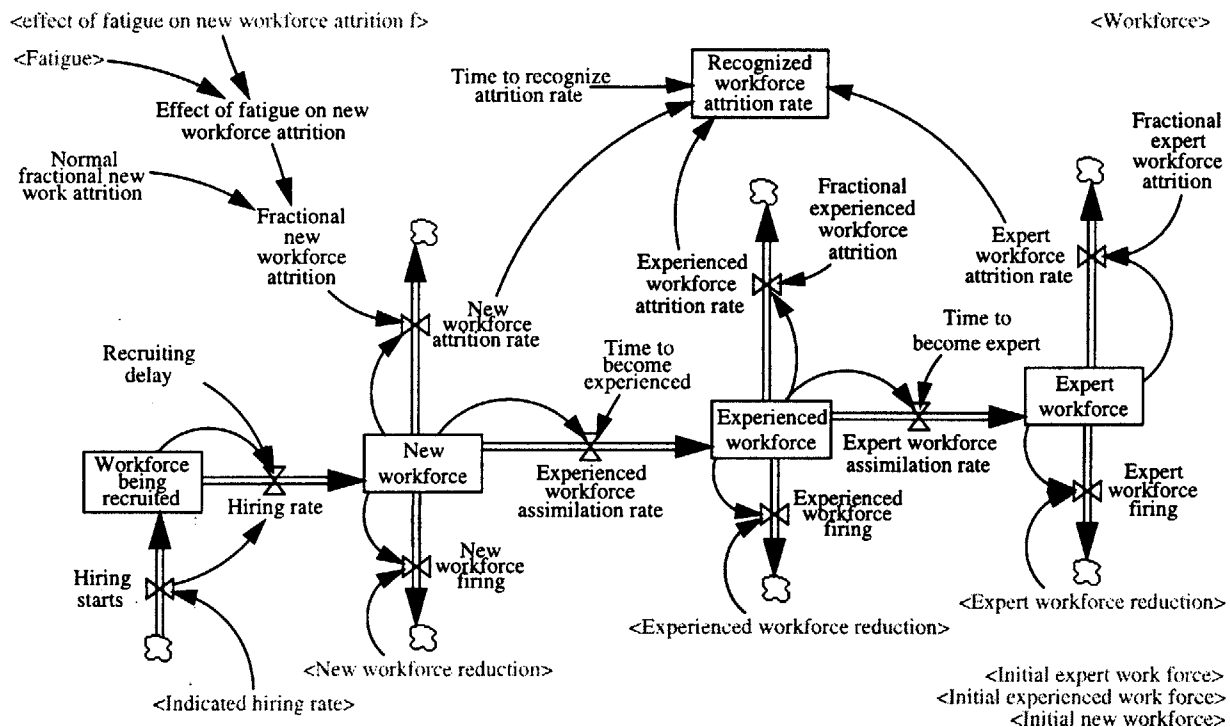


Figure 33: Contractor's Workforce Structure

<sup>68</sup> Three levels are typically adequate to capture the dynamics of such a process. See: Hines, James H., *Molecules of Structure Building Blocks for System Dynamics Models*, LeapTec and Ventana Systems, 1996, Version 9/3/96, Page 19.

<sup>69</sup> Cooper describes the potential for prolonged experience dilution possible with high rates of new hire attrition. Cooper, Kenneth G., *THE \$2,000 HOUR: How Managers Influence Project Performance Through the Rework Cycle*, Project Management Journal, Vol. XXV, No.1, March 1994.

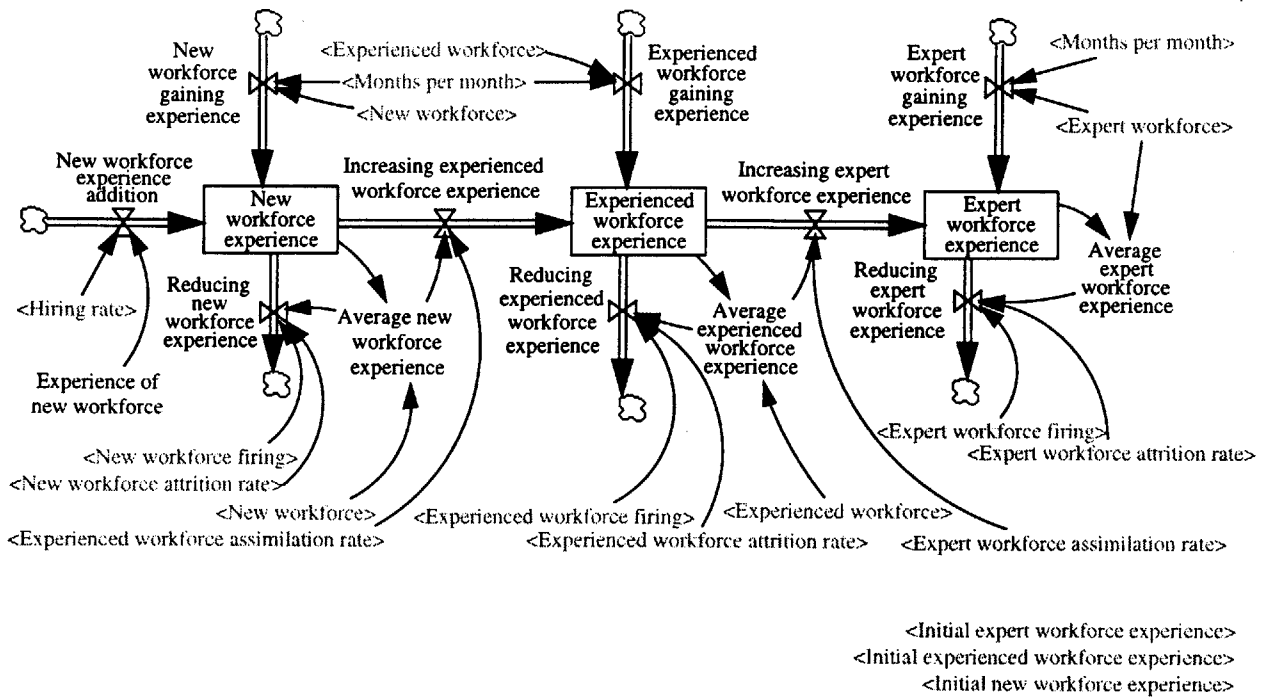


Figure 34: Workforce Experience Structure

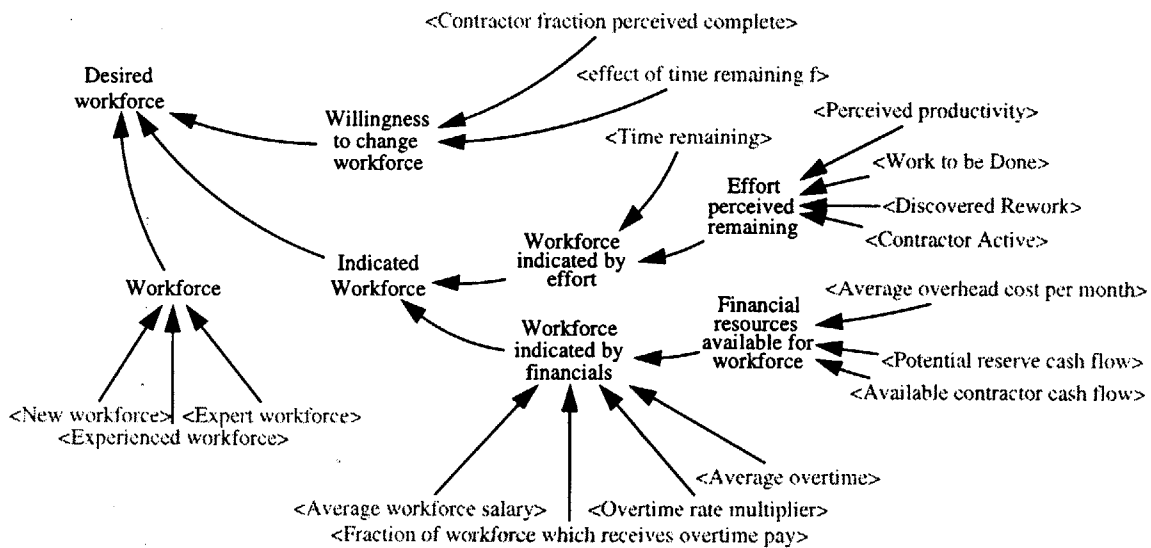
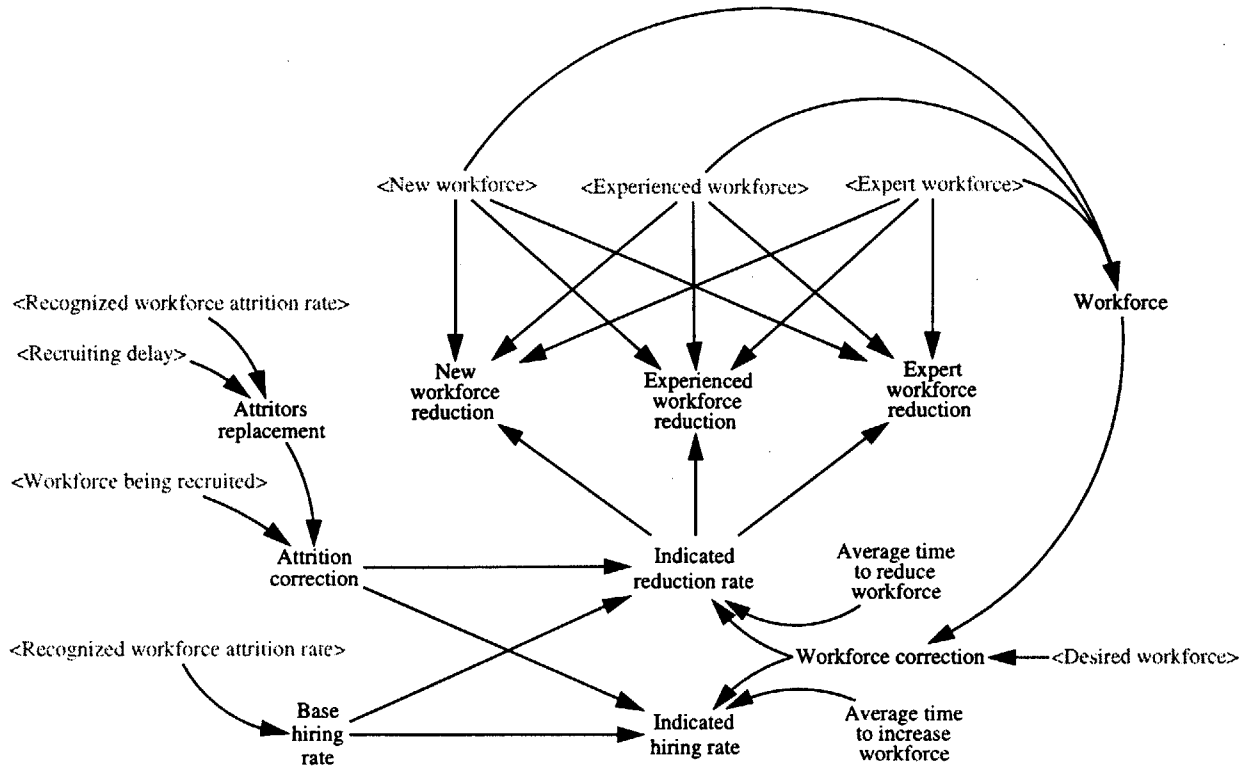
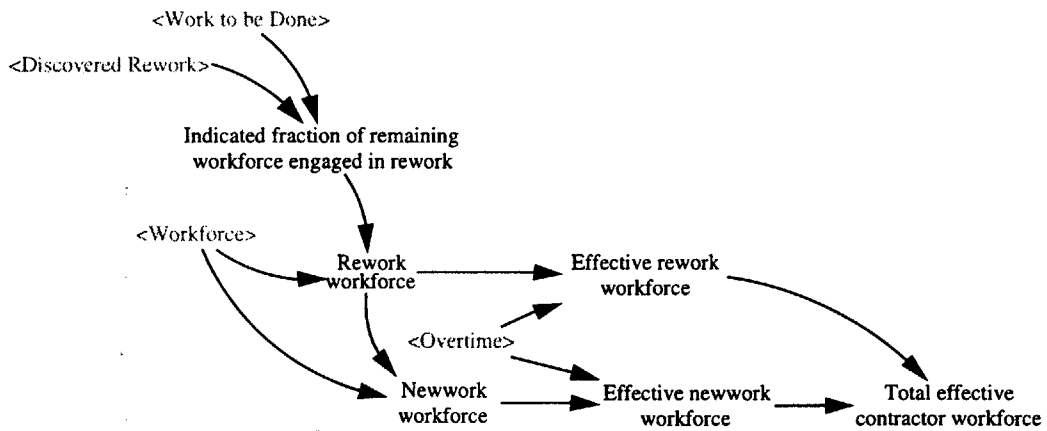


Figure 35: Workforce Sizing Structure





**Figure 36: Workforce Size Control Structure**



**Figure 37: Distribution of Effective Workforce Structure**

### 3.1.9 Schedule

Two additions have been made to the basic schedule structure. Schedule adjustment time has been made dynamic, increasing the frequency of adjustment as schedule pressure mounts<sup>70</sup> and structure has been added which allows simulation of a program forced to pause due to limited financial resources – the effect of restart structure. In effect it slides the scheduled completion date month for month while the program is suspended.

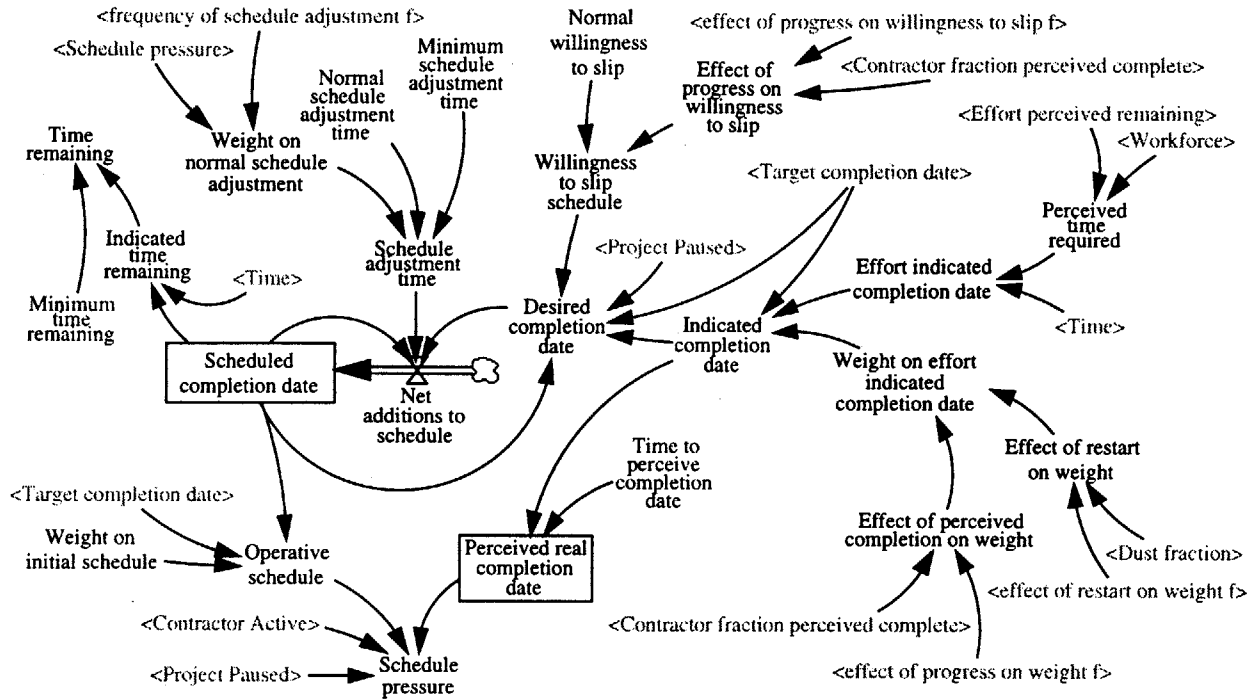


Figure 38: Project Schedule Structure

<sup>70</sup> Interestingly, sensitivity testing indicated that this change had very little effect on the system's dynamic behavior.

### 3.1.10 Management Reserve

Management reserve is a standard tool for risk management, which entails internally withholding a fraction of the resources bid for a project.

“Management reserve is initially created after the contract has been awarded, based upon an agreed to level of effort required to complete the stated contractual tasks. It is not legal for a contractor to bid management reserve as a task or element in his proposal. Therefore, when a program manager creates management reserve at the start of his program, he, in reality, simply negotiates with some line organizational entity to accomplish a set of tasks for a lower amount of funding than the organization originally estimated they needed to do the work; this is literally taken as an organizational management challenge.” [Milauskas]

Not only is rework not included in the effort calculus, but the internal organizations must work with less than the initially estimated resources in a low-cost-wins-bid environment.<sup>71</sup>

Management reserve is released to a line organization only if new, in-scope work is added to its task description. At the end of the program each organization’s over or under-run is netted against the management reserve pool. In effect, management reserve is released only at the end of a project in response to dwindling financial reserves. Figure 40 is this process reduced to model structure.

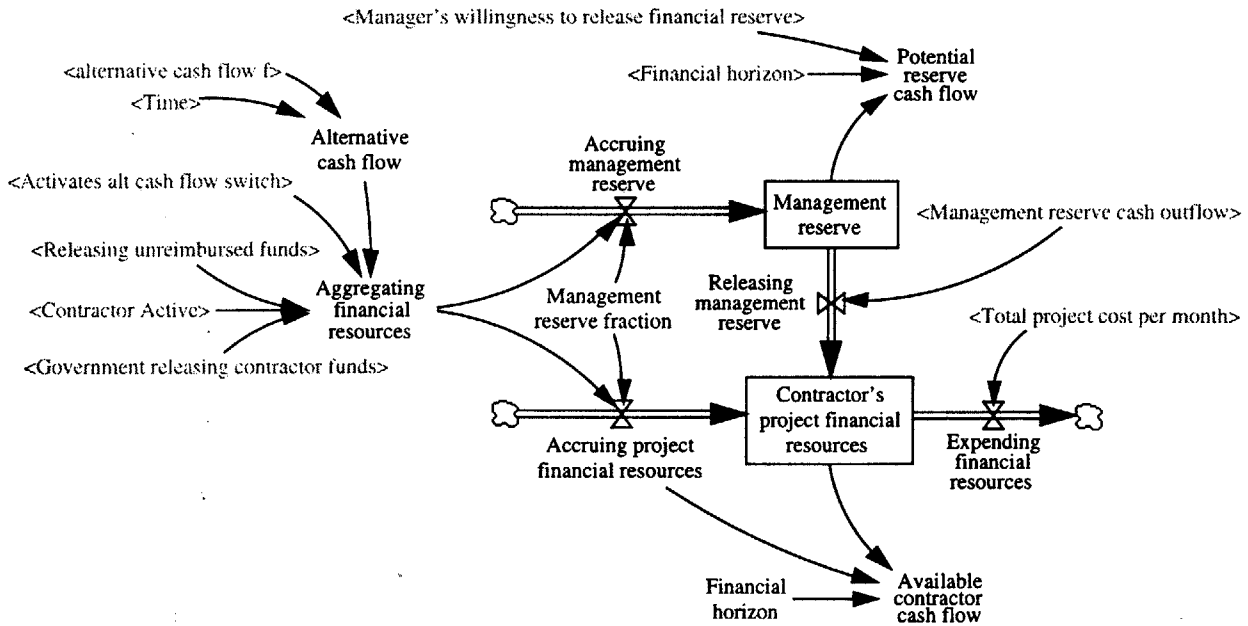
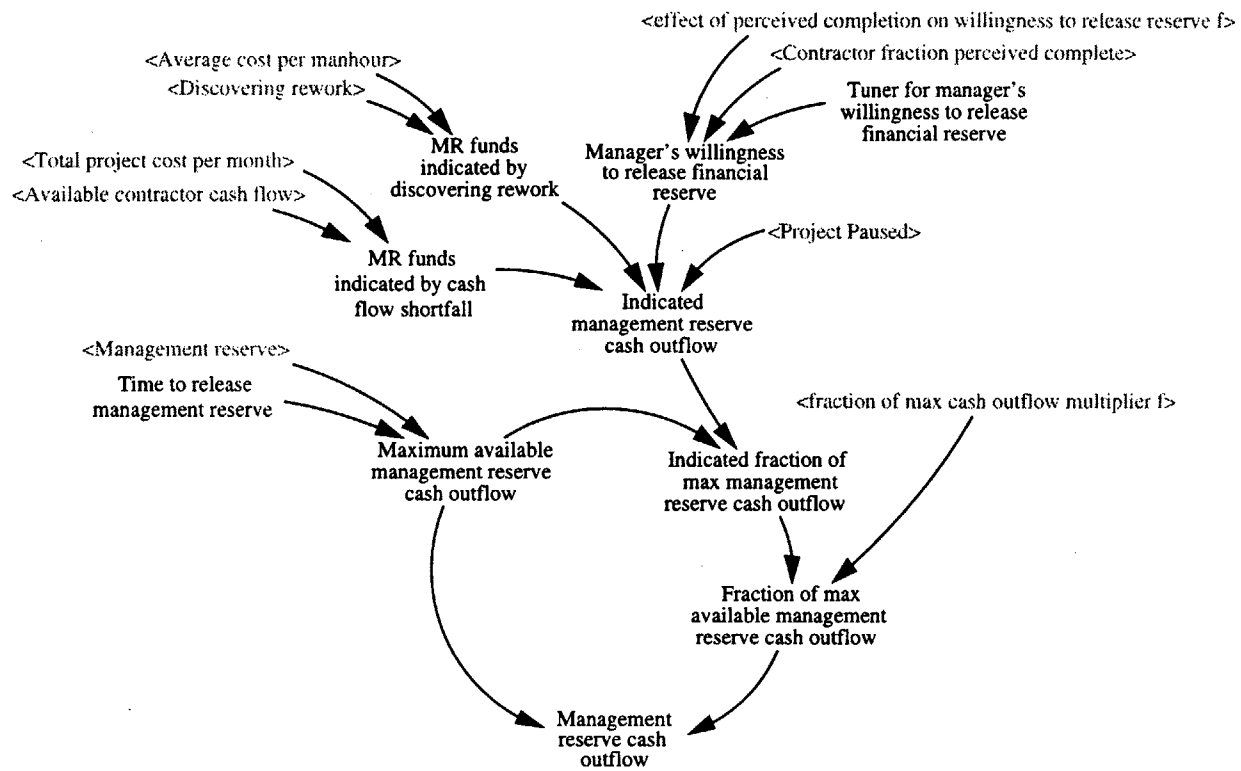


Figure 39: Management Reserve Structure

<sup>71</sup> Management reserve is probably counterproductive, if for no other reason than the adversarial gaming induced between program management and line organizations.



**Figure 40: Decision Rule for Management Reserve Release**

### 3.2 Modeling The System Program Office – Key Differences from The Contractor

Similar to the contractor structure in most respects, the SPO portion of the model requires incorporation of several additional unique features.<sup>72</sup> These include the military workforce, personnel allocations, and multi-source, limited use funding. The last, included because of the potential cost and schedule implications of their misalignment,<sup>73</sup> are exogenous inputs to the system under study and thus their structure is not presented here.

#### 3.2.1 Military Workforce

Total SPO personnel is composed of two separate workforces, military and civilian, with different career paths and retention dynamics. For example, while the SPO civilian workforce tends to mirror its contractor counterpart in terms of attrition and tenure, the military workforce has minimal attrition, but much lower average tenure. On average, officers remain in positions for a scant 24 months. [Rutley, Niiya] This has clear cost and schedule implications – high turnover in positions with significant learning curves will dilute the overall quality and productivity of the SPO’s personnel. Though not explicitly modeled for this study, military personnel that are in leadership positions within the system would have even greater leverage over quality and productivity.

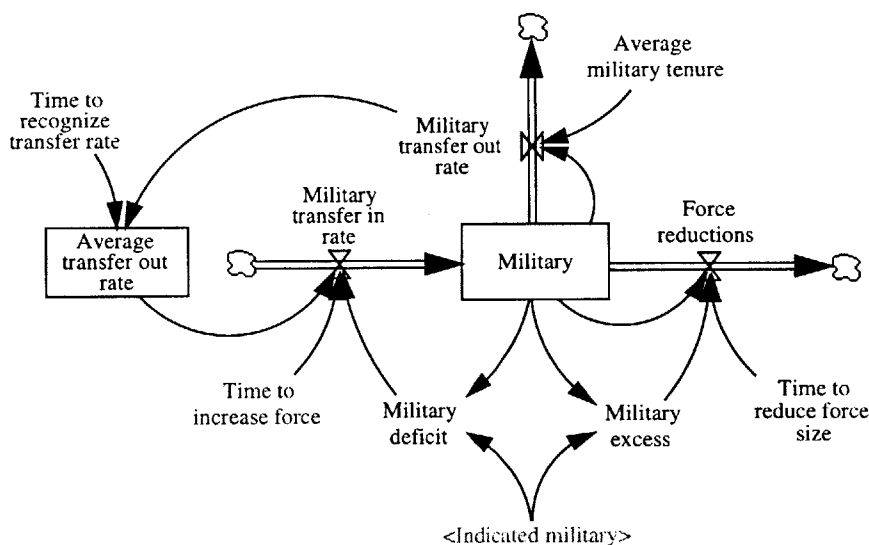


Figure 41: SPO Military Workforce Structure

<sup>72</sup> All the structures presented in Sections 3.1.1 through 3.1.10 are present in the SPO model. Of course, the variable names and parameter values are different.

<sup>73</sup> Misalignment can result in the “standing army” problem. That is, funding provided for payroll, but not for the non-human resources required for task completion.

### 3.2.2 Determination of Manpower by Allocation Rather than by Scope

Determination of workforce size by allocation, rather than estimated effort is the most unique feature of the SPO. Air Force Headquarters allocates a specific number of personnel slots for both military and civilian personnel. These numbers are the upper limit of civilian and military staffing at the SPO. While there have been efforts to determine the “correct” size for a SPO, consensus has yet to be achieved – currently there is no formulaic way to size a SPO. [Sutton] History and program importance play as large a role as effort in its determination. Current efforts are directed toward a 50% reduction in SPO size.

Allocation alone does not determine the manpower at a SPO – available funding is also a limiting factor. The rule used by directors is: staff to the lesser of allocated slots or available funding. This rule is depicted in Figure 42, which shows the specific structure for the civilian workforce. When the authorization switch is activated the number of civilians workers indicated by effort is ignored and the indicated value is the minimum of authorized slots or that indicated by financial resources. There is of course, a similar structure for military workforce. Interestingly there is no formal link between the number of slots and the level of funding.

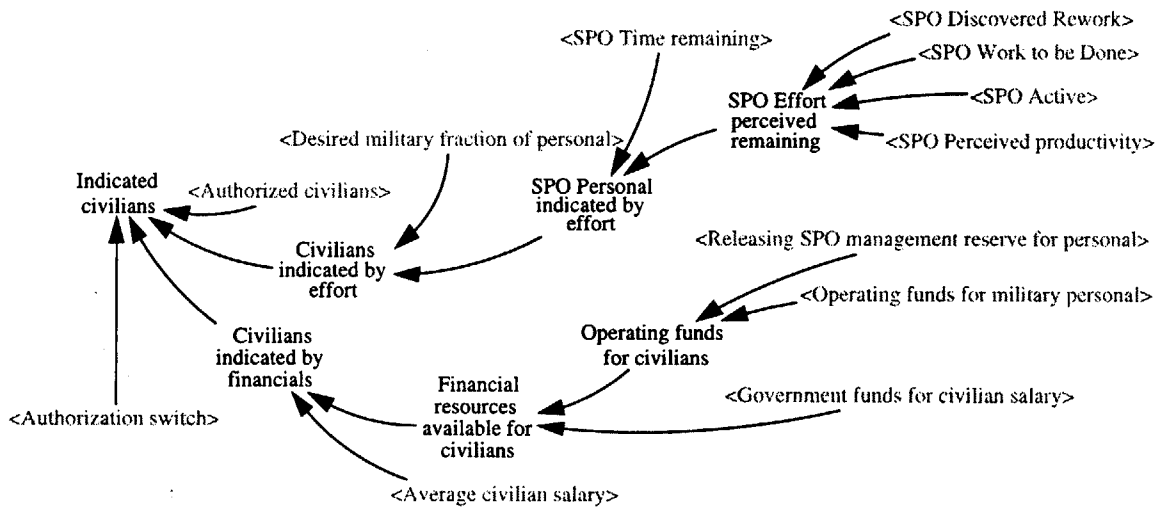


Figure 42: SPO Civilian Workforce Sizing Including Civilian Authorization

### 3.3 Validation Of The SPO-Contractor Model

Any model is a simplification of the system it seeks to represent, with its validity ultimately determined by utility and consistency.<sup>74</sup> This model is no exception. And, while a determination of its utility is left to the reader, the model does pass numerous tests that confirm its consistency.

The most basic test is unit consistency. Every variable has units corresponding to the real world quantity it represents and unit consistency is maintained when variables are combined in equations. The units for each variable and equation are shown in the Appendix, Section 8.5.

Another important test is that of structural consistency – the variables in the model should be central to the problem under study and must be interconnected properly.<sup>75</sup> This was confirmed in several ways; first, the SPO-contractor model is based upon the basic project model structure, which is well documented in the project management literature.<sup>76</sup> Second, unique structures, pertinent to this study, were developed through extensive discussions with participants in the real system, from both SPO and contractor, as well as other acquisition experts.<sup>77</sup> In addition to providing the information necessary for structural development, system participants were also the prime source of parametric values and functional relationships.<sup>78</sup> All serve to ensure that the variables in the model are both relevant and meaningful and that their combinations are representative of the real SPO-contractor system.

Extreme value testing, a technique particularly useful for discovering formulation errors, is an integral part of developing a model. It involves investigating model behavior under extreme parameter values to determine if the response is in accord with both physical laws and common sense. For example, if there are no workers does production continue? If it does, there is a problem with the model formulation that must be corrected. Extreme value testing is typically employed throughout the modeling process, as new structures are added, to ensure continued validity; this model was no exception.

Similar to extreme value tests, sensitivity testing is another technique used throughout model development. By examining the response to a parameter's reasonable range values, a model's sensitivity to a particular parameter or structure may be investigated. High sensitivity suggests additional exploration of the system to determine the reason for its efficacy. The variable *Quality* is a good example. Because the SPO-contractor model exhibits extreme sensitivity to the value of *Quality*, its major influences had to be explicitly modeled. Often disaggregation of a parameter provides important insights into the feedback structure of a system. If however, the structure is adequately defined, the parameter could be an important leverage point for the system. Of course, this too is an important insight, as these points are the tools for controlling the behavior of the system. The last tool used for testing the model's validity was mode comparison.

A variable's mode shape is its pattern of behavior over time. S-shaped growth of profit from a particular product is a familiar example. The comparison of model's modal behavior with that of the real system often provides the most compelling evidence of validity. Of course, any number of models can be constructed which will match a given data set. Moreover, if the model bears no resemblance to the real system or is not robust,<sup>79</sup> it has little power to improve

<sup>74</sup> Richardson, George P., Pugh, Alexander L., *Introduction to System Dynamics Modeling with Dynamo*, Productivity Press, Portland, OR, 1981.

<sup>75</sup> Forrester, Jay W., *Industrial Dynamics*, Productivity Press, Portland OR, 1961. Page 118

<sup>76</sup> See References listed for Cooper, Lyneis, and Roberts.

<sup>77</sup> A complete listing of those who contributed to the development of the model is given in Section 7.

<sup>78</sup> In instances where minimal data were available to facilitate development, plausibility arguments and external data sources were used. An example is the development of functional relationship between fatigue and productivity: *effect of fatigue on pdy f*, shown in Figure 31. While the data were not taken specifically from the system under study, it is reasonable to assume the aggregate affects of fatigue on individuals would be applicable.

<sup>79</sup> A model is robust when changes in its parameter values, within their normal, real world ranges, do not induce qualitative behaviors which can not be explained or are unobserved within the system being modeled.

the manager's ability to control the project. On the other hand, if the model is robust, is structurally similar to the real system, and replicates behavior, qualitatively similar to that observed, confidence in the model's validity grows. The SPO-Contractor model's ability to replicate behavior modes is shown in Figure 43.<sup>80</sup>

Of course, model building is an iterative process and the tests discussed above were run many times throughout development of the SPO-contractor model. The last and most exciting phase of the modeling process is policy analysis. In the next section, the policies, which govern the SPO-contractor system, are investigated and their influence on cost and schedule explained.

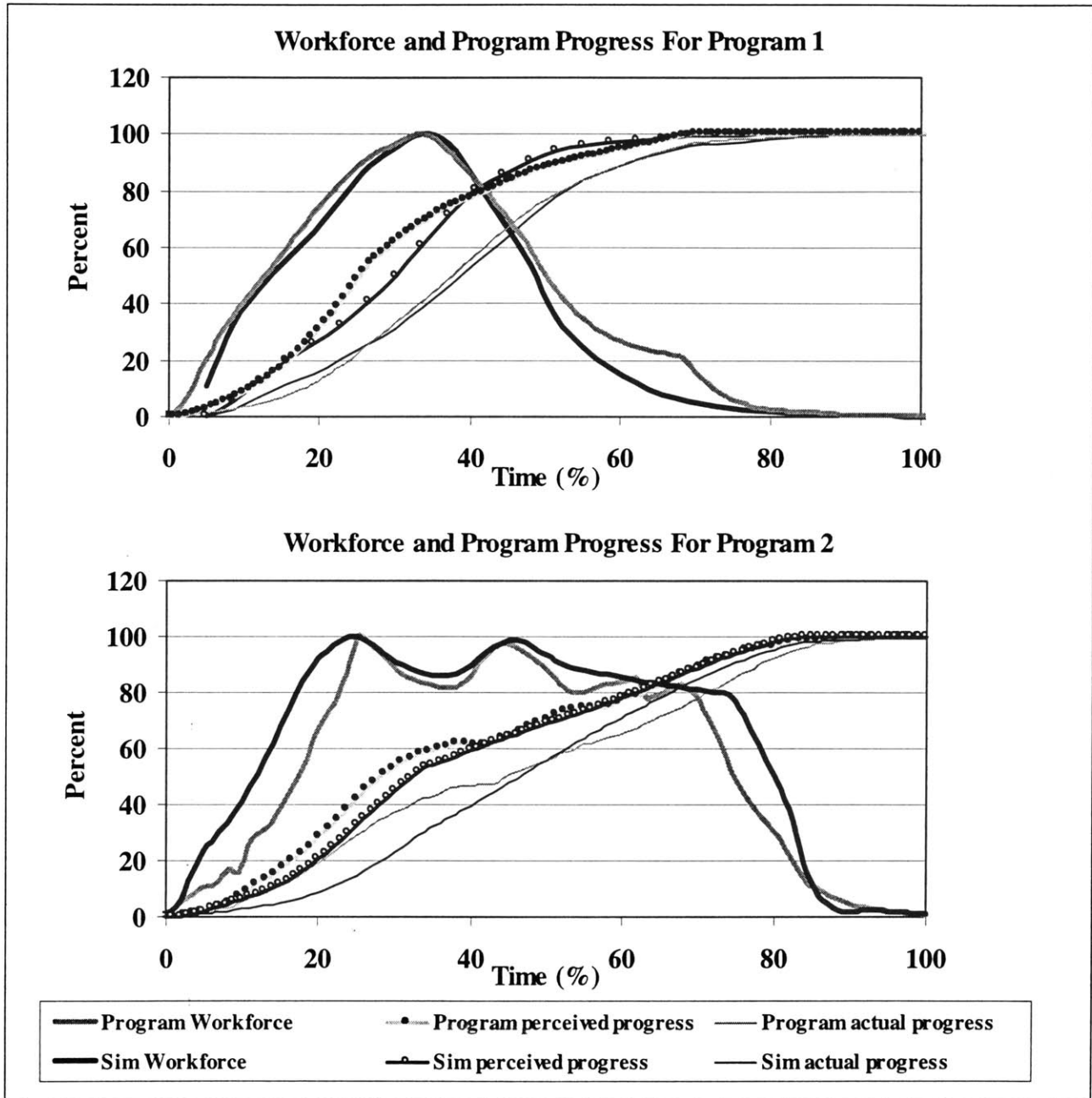


Figure 43: Comparison of Real and Simulated Data

<sup>80</sup> Program data was supplied by James Lyneis and has been normalized to preserve proprietary information.



## 4 ANALYSIS

In this section, the management implications of specific SPO-contractor system policies are discussed in the context of the cost<sup>81</sup> and schedule performance resulting from their implementation. First, the isolated dynamic behaviors of both contractor and SPO are investigated. This serves to develop intuition, useful in understanding the behavior of the complete SPO-contractor system, which is then examined.

### 4.1 Contractor in Isolation

One of the important goals of this study is developing a deeper understanding of Air Force aircraft development project dynamics. Building on the insights distilled from the basic project model developed in Section 2, several contractor specific phenomena are investigated. These include the notion that given two projects of similar risk, but with one having a scope which is 50 percent of the other, the smaller project can be accomplished 50 percent faster for 50 percent less cost. Workforce management issues are revisited with discussions of the consequences of process consistency, workforce skill, and overtime. Finally, the effects of management reserve policies are considered.

#### 4.1.1 Half the Work in Half the Time Doesn't Cost Half as Much

If a fixed relationship between project scope and the desired completion interval is assumed, *ceteris paribus*, intuition would suggest that project cost should scale linearly with project scope. However, Figure 44 demonstrates that managers are not well served by this intuition. It shows that in some instances the cost/scope relationship is very non-linear. Perhaps more importantly, it illustrates that there are potential program configurations, in which a reduction in scope<sup>82</sup> will not reduce cost.

Figure 44 was derived as follows: Within series, holding the scope / desired completion interval ratio constant, project scope was varied for each simulation. Across series, the rapidity with which the workforce traverses the learning curve was the distinguishing characteristic. In the *baseline* series, it was assumed that an employee requires 60 months to achieve full productivity and quality. For the other two series, *quick* and *slow*, employees required 30 and 90 months respectively to reach full potential. To facilitate cost comparison, the results were normalized to a base project with scope of 125 thousand man-months, desired completion interval of 60 months, and learning curve duration of 60 months. Finally the simulations were not financially constrained. Figure 45 presents the same information; but normalized within series to a scope of 125 thousand man-months and a desired completion interval of 60 months. To assist the explanation of this behavior, Figure 46 and Figure 47 were prepared. They are time series comparison of specific simulation runs, cross sectional and within series respectively.

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<sup>81</sup> All simulated costs are in real dollars and thus do not include the effects of inflation.

<sup>82</sup> Recall that in this case the relationship between scope and completion interval has been held fixed. Thus here, a reduction in scope is accompanied by a reduction the desired time to complete the project.

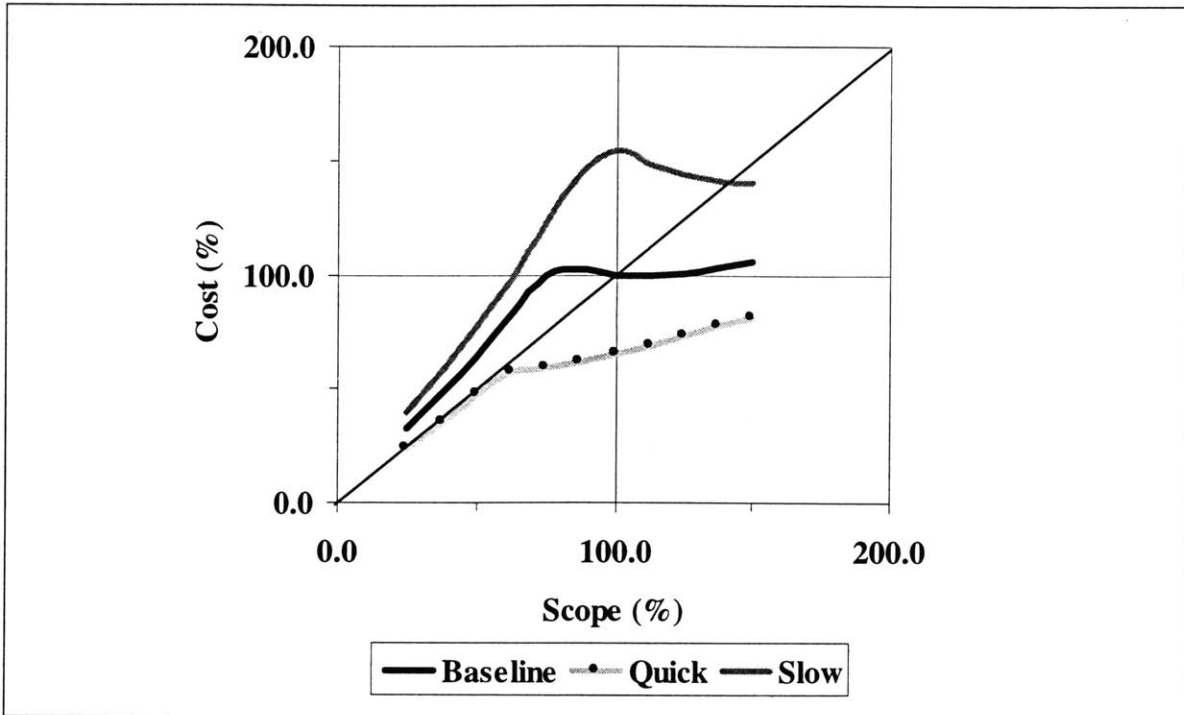


Figure 44: Non-Linear Effects of Proportional Variations In Scope And Desired Completion Interval For Different Workforce Learning Curves, Normalized Across Series

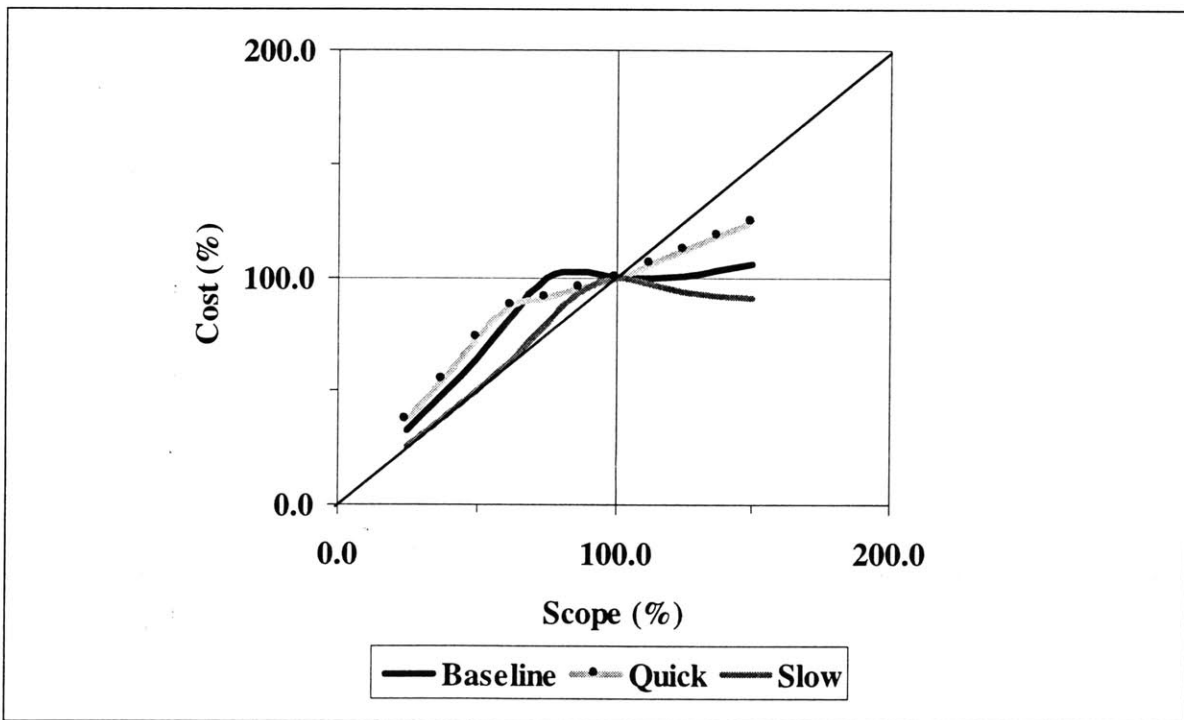


Figure 45: Non-Linear Effects of Proportional Variations In Scope And Desired Completion Interval For Different Workforce Learning Curves, Normalized Within Series

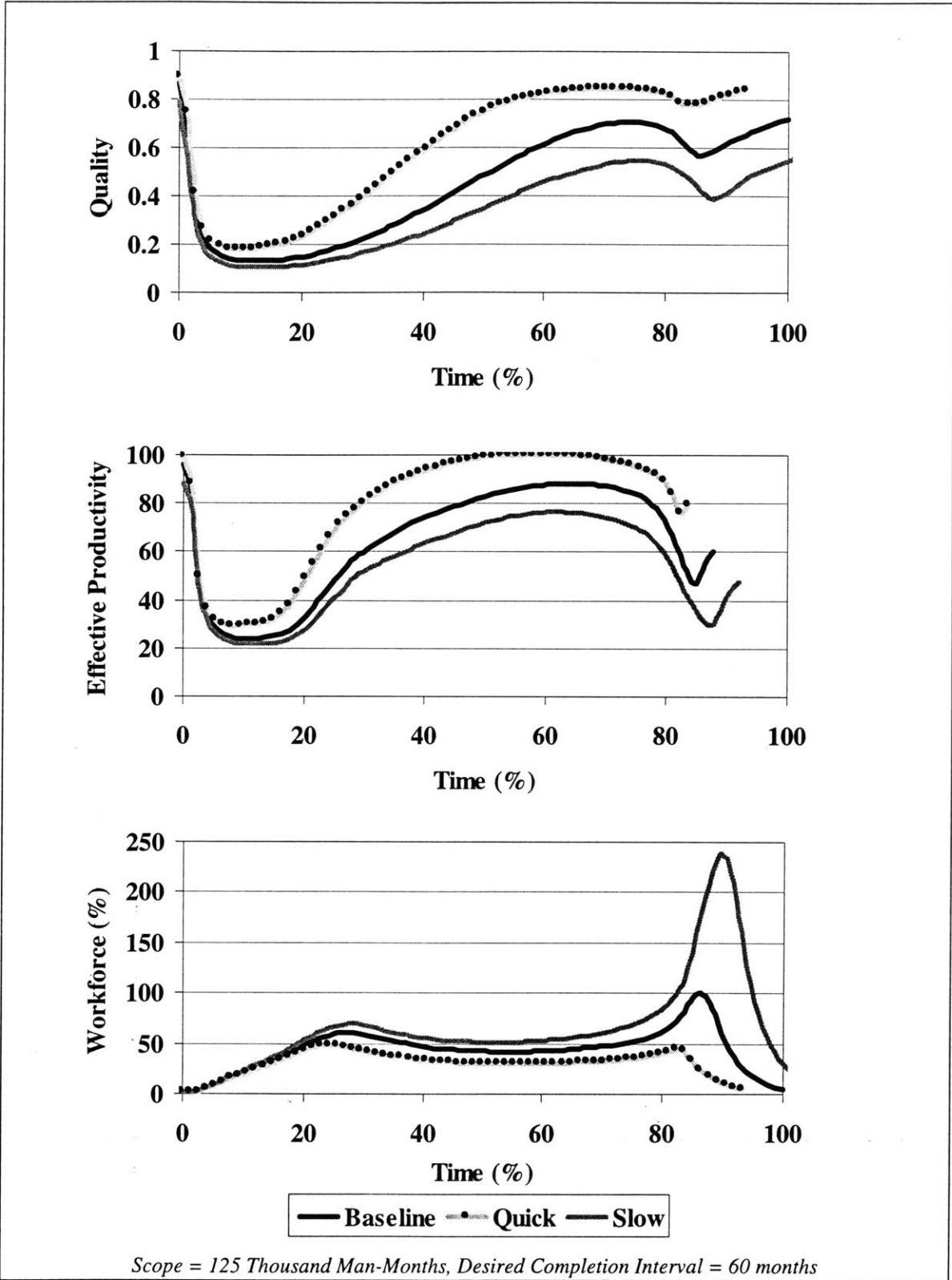
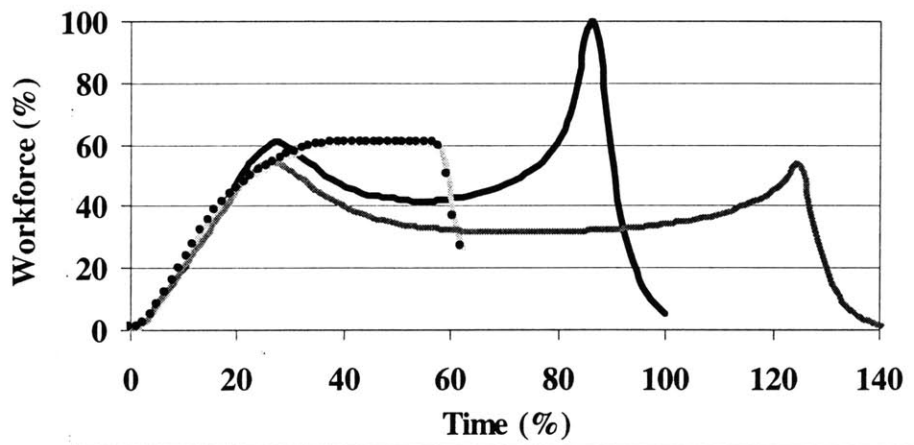
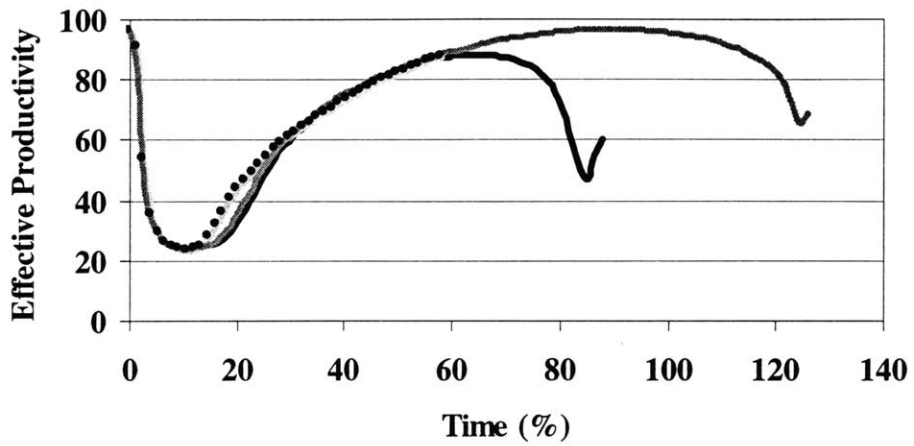
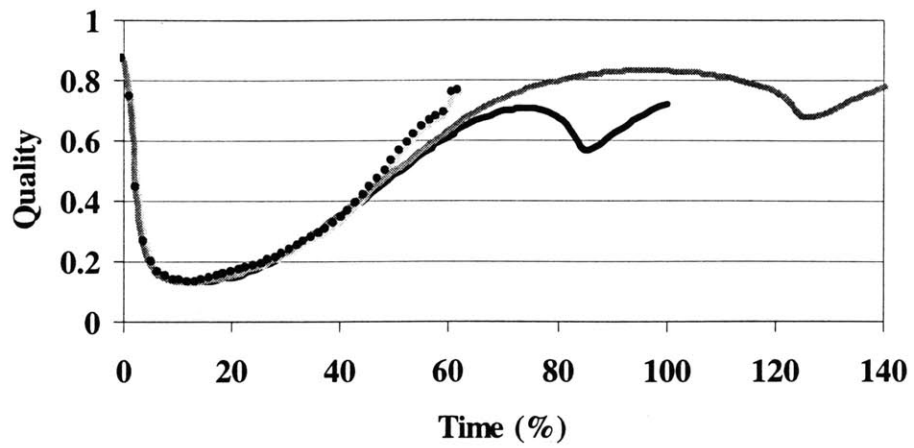


Figure 46: Cross Sectional Effects of Learning Curve Variations, Time Series Comparison



— Base Scope    ••••• 50% Base Scope    - - - 150% Base Scope

*Learning Curve Duration = 60 Months, Base Scope = 125 Thousand Man-Months*

**Figure 47: Within Series Effects of Scope Variations, Time Series Comparison**

Close inspection of the time series comparisons reveals an important insight: for the first five to fifteen percent of the project, the time series trajectories are nearly indistinguishable. During the start-up phase the initial conditions<sup>83</sup> determine the initial program behavior. Because the relationship between scope and desired completion interval is fixed, in all cases the initial desired workforce is identical. Thus *under this set of assumptions*, regardless of the project's scope, initially the same number of workers are being hired at the same rate and therefore there is a constant period of time required to launch the project. It is this initial period that pushes the project cost intercept above the origin. Naturally, this effect is less pronounced for simulations in which the workforce takes longer to traverse the learning curve because this period constitutes proportionally less of the total project cost. This can be gleaned by observing that in Figure 44 the *Slow* series is more expensive than its counterparts, and yet in Figure 45 it is nearly linear for the projects of smaller scope. Essentially, the longer it takes the workforce to become skilled, the more work they do at low quality, thus increasing the amount of rework and accordingly project cost. This is reiterated in Figure 46, which demonstrates the value a steep learning curve.

An examination of the workforce portion of Figure 47 reveals another important characteristic. As the period allotted for the project decreases, the initial overshoot in hiring, the result of lower than expected productivity, merges into the end-of-project hiring spike, the result of trading cost for schedule. In as much as there is not a workforce reduction, the foreshortened projects benefit from higher sustained quality and productivity. But, notice that longer running project benefit from completing a larger portion of the work at higher levels of quality and productivity – levels never reached in the small projects because building those attributes takes time – which reduces the end-of-project spike. It is this increased fraction of the project at higher workforce experience that causes the reduction in cost with increasing scope. For very long projects, the trend reverses to some extent, as fixed costs become a larger percentage of the total cost.

Clearly, the initial intuition that half the work in half the time will cost half as much is misleading. A better intuition may be summarized as follows: A steeper learning curve reduces costs. For a given learning curve, costs will tend to decrease with increasing scope, if the project is long enough to allow a reasonable fraction of the work to be done after the workforce has begun to recover from the skill dilution effect. Potentially, the most expensive proposition is to draw down the workforce after an initial hiring binge and then immediately begin to add workers in the face of unexpected rework under pressure to meet the completion date. It is just this scenario which creates the local maximums in Figure 44.

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<sup>83</sup> The important initial conditions are: estimated scope, desired completion interval, initial workforce level, experience of workforce additions, and the rate at which those additions are made to the project.

#### 4.1.2 Schedule Compression

Section 4.1.1 demonstrated the nonlinear characteristics of a proportional reduction in project scope and desired completion interval. If however, project scope is held constant and the desired completion interval is increased, intuition would suggest that project cost should stay constant or perhaps increase if fixed costs are sufficiently large. The simulation results however, demonstrate that costs and schedule slip decline as the desired completion interval is lengthened. It should be pointed out again that all simulated costs are in real dollars and thus do not show the effects of inflation. Clearly if those effects were included, the project costs would tend to exhibit an increase with increased project duration. However, for the purposes of this study, including inflation effects would only obscure the underlying system dynamics.

Figure 48 displays the cost and schedule slip trends under several program configuration assumptions. In all cases, project scope was assumed to be 625,00 man-months. For the *Learning* series, workers traversed the learning curve 50 percent faster than the 60 months of the *Baseline* series. In the *Experience* series, new workers had an average of 30 months experience, half that required to become proficient, as compared to zero for the *Baseline*. Two things are evident, the value of tools and processes which are easy to master, and the overwhelming value of a pool of experienced workers who are already familiar with the project's tools and processes.

The reasons for these results become apparent with a careful inspection<sup>84</sup> of Figure 49 through Figure 51. For each scenario, the trajectories of quality and productivity are very similar. Nevertheless, for those with a longer completion interval, more of the project work is executed with the workforce at higher levels of quality and productivity – less rework generation and more work completed in a shorter period of time. In addition the maximum number of workers employed is reduced. First because given with constant scope fewer workers are needed with increasing completion time.<sup>85</sup> But also for reasons similar to those in Section 4.1.1 – with increasing completion time, fewer workers are being hired initially reducing the start up period required to launch the project. Longer projects have more time to recover from the inevitable detrimental effects of the startup period. This is why the shorter intervals experience more schedule slip – the startup period becomes a larger fraction of the total project period.

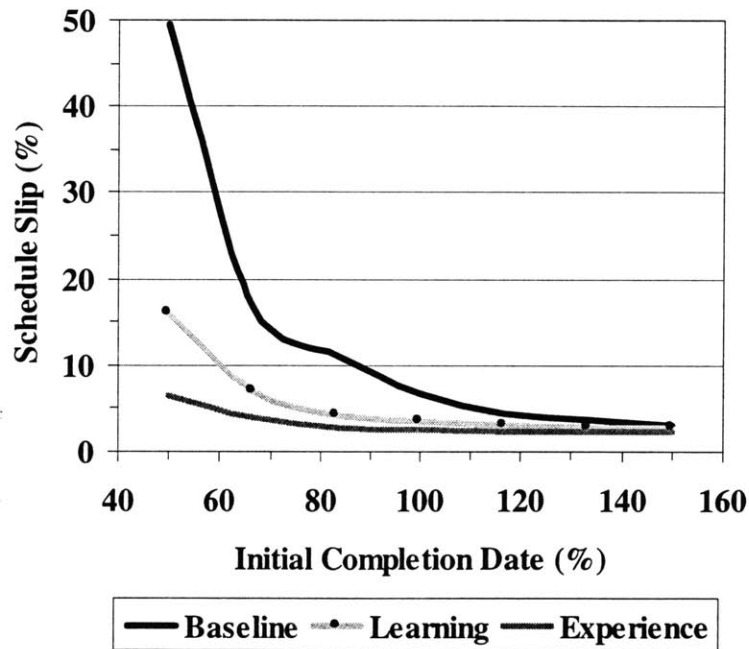
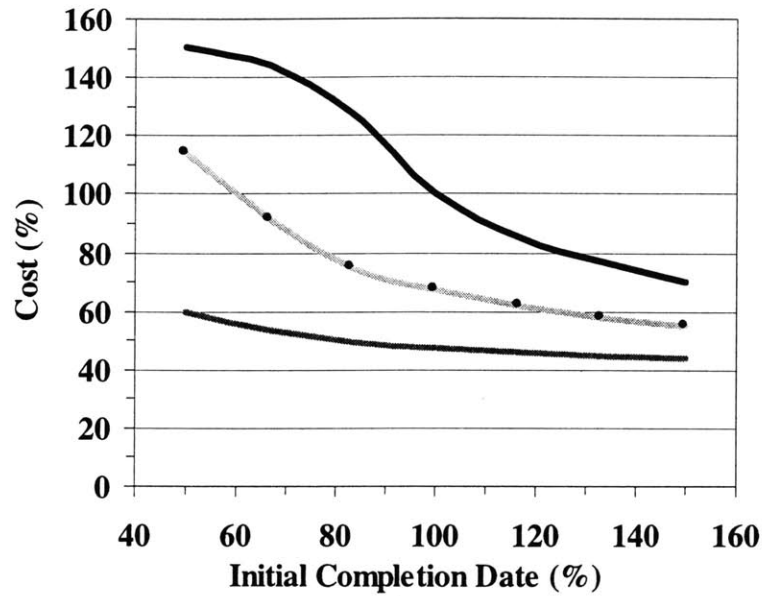
Figure 52 presents a cross-sectional view of the different scenarios and highlights the impact that faster learning and workforce experience can have on a project. Increasing the rate at which the workforce can traverse the learning curve pulls quality and productivity off the *Baseline* trajectories sooner, but they still drop to nearly the same levels. However, increasing the experience of the newly hired workers sends the project on a very different course. Quality and productivity stay higher and recover sooner. Also, the peak workforce is reduced dramatically. These results suggest that retaining experienced workers, rather than laying them off during slack periods will reduce the cost and schedule slip on the next project – the cost of retention is less than the incremental cost of additional workers. Of course, this assumes that actions are taken to mitigate experience obsolescence of the existing workforce.

This section is then a continuation of the previous – the underlying causal mechanisms are the same. Certainly, a more experienced workforce reduces costs and schedule slip. For a given experience profile, costs will tend to decrease with increasing completion interval because a higher fraction of the work is done after the workforce has begun to recover from the skill dilution effect. The cyclical hiring patterns of many aerospace contractors are then potentially large sources of cost and schedule underperformance.

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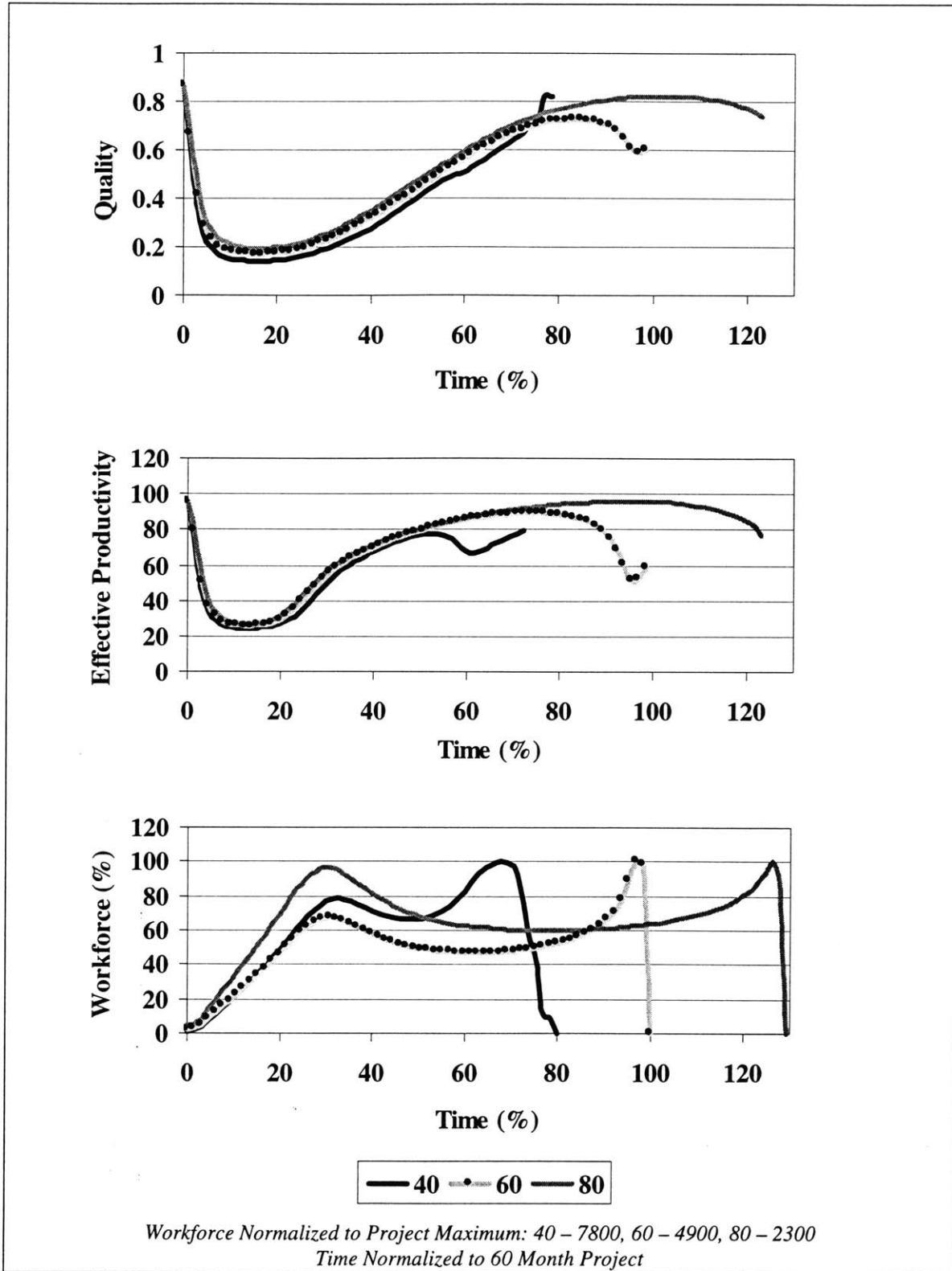
<sup>84</sup> Some care must be used in the interpretation of the workforce size charts because each time series has been normalized to its own maximum. This allows an easy comparison of the distribution of workers over time, but makes comparison of hiring rates more difficult.

<sup>85</sup> With a scope of 62500 man-months, the expected staffing requirements would be approximately 1560, 1040, and 780 men for completion intervals of 40, 60, and 80 months respectively.



Within Series: Initial Completion Dates Normalized to 60 Months  
 Across Series: Costs Normalized to Baseline With Initial Completion Date of 60 Months  
 Simulated Costs are in Real Dollars

**Figure 48: Effects of Schedule Compression on Cost and Schedule Slip Trends**



**Figure 49: Time Series Comparison of Schedule Compression Effects for Baseline Configuration**



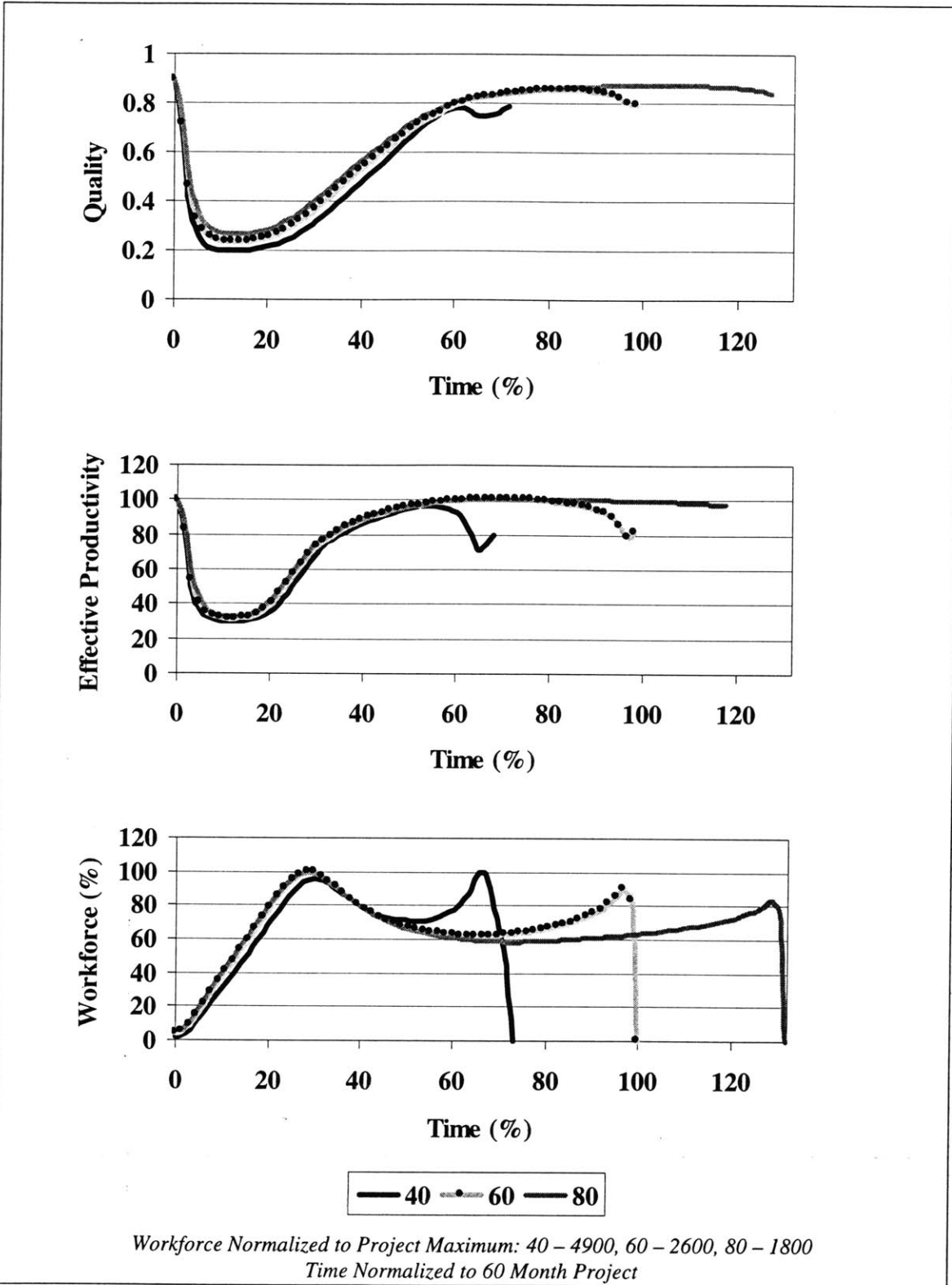
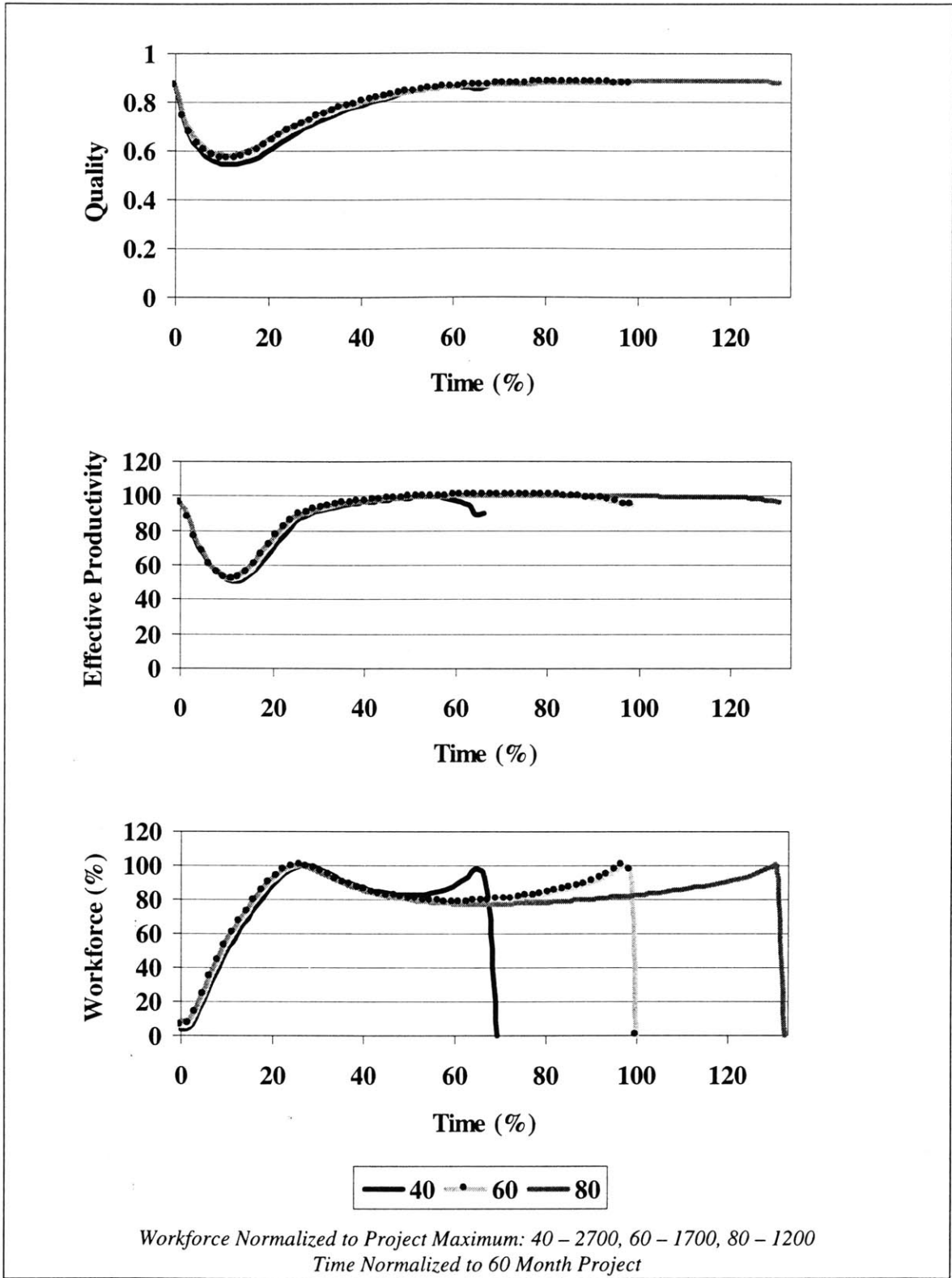


Figure 50: Time Series Comparison of Schedule Compression Effects With Faster Learning Curve Traversal



**Figure 51: Time Series Comparison of Schedule Compression Effects With Hiring of More Experienced Workers**

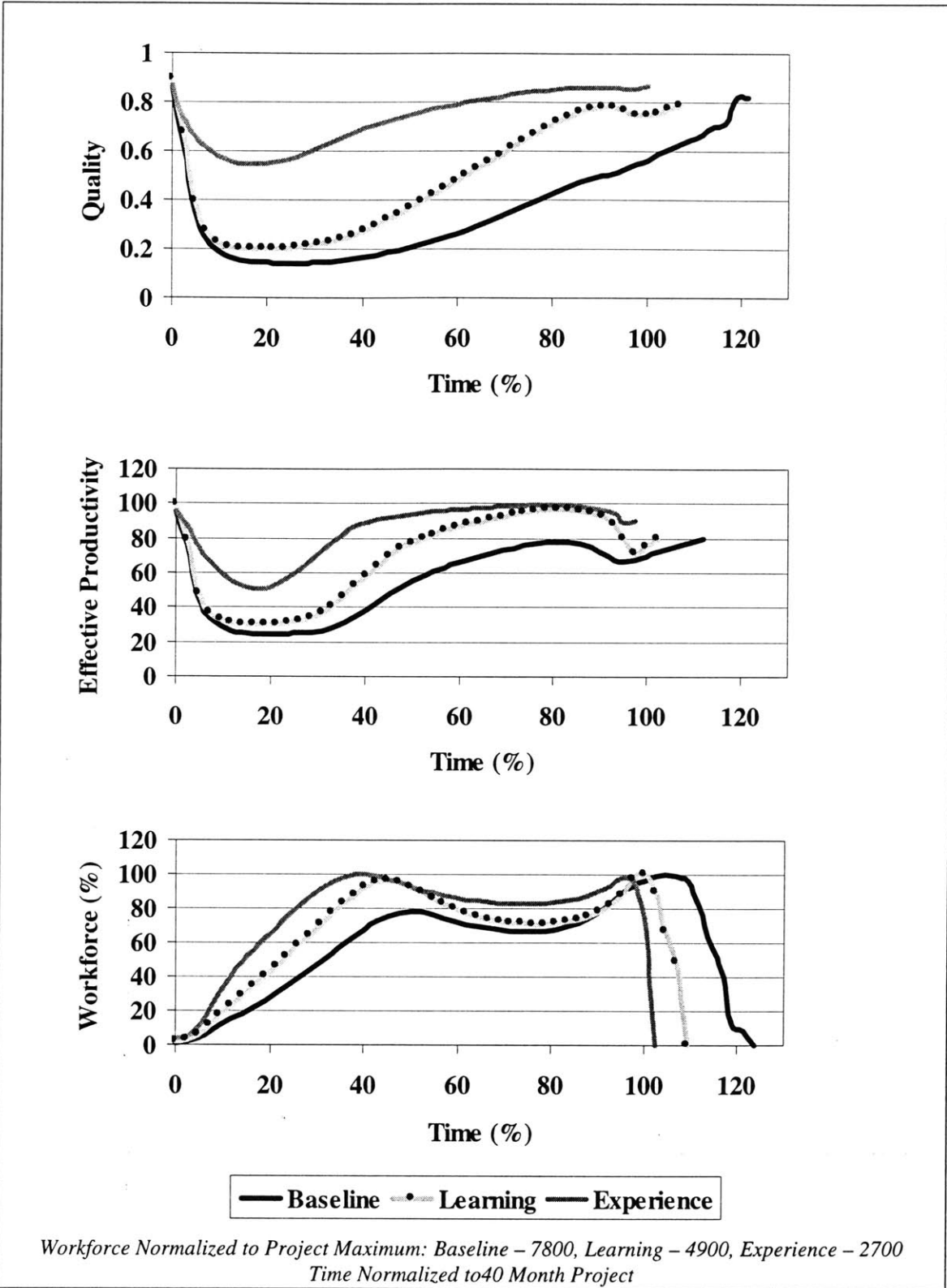


Figure 52: Cross Sectional Comparison of Learning Curve and New Worker Experience Effects

### 4.1.3 The Hidden Costs of Overtime

Another popular management tool used to keep a project on schedule is overtime. It is assumed to be a cost effective way to increase the output per worker. However, overtime is a two edged sword. Section 3.1.5 explained the link between extended periods of overtime and reductions in quality and productivity, whereby the very mechanism designed to increase productivity, resulted in exhausted workers who make more mistakes and who's productivity declines in spite of the extra hours worked. Of course, fatigue affects not only the workforce; it affects the bottom line.

Figure 53, compares quality, productivity, and cumulative contractor cost for simulations of three project scenarios. In the first, *Real*, overtime hours are limited to 50 percent of the normal workload hours per week and prolonged overtime results in workforce fatigue. The second, *No Fatigue*, is identical to the first, with the exception that overtime does not cause fatigue. The last, *No Overtime*, is again identical to the first, but no overtime is allowed. Obviously, the *No Fatigue* scenario is what the manager has in mind when instituting overtime. However, the *Real* scenario is what he actually gets. Figure 54, demonstrates the effects on various workforce measures<sup>86</sup> of overtime and fatigue under these three scenarios.

The startling insight from simulating these effects is that the use of overtime may not cause the project to be completed any faster and tends to increase its cost. The reason is clear; fatigue reduces quality and productivity. From the discussion of the rework cycle, remember that reduced quality creates more rework, increasing the total amount of work needed to complete the project. Fatigue also reduces productivity. Yes the workforce is working more hours, but those hours are less productive. The net result is to increase the total effort that must be expended to complete the project with, at best marginal increases in daily production. Naturally, costs go up. By comparing the *No Fatigue* and *No Overtime* simulations in Figure 53, it is clear the added cost comes not just from the higher wages paid for overtime hours. Figure 54 shows that the added cost is a result of increased workforce size – in response to the increase in effort required.

Because overtime is a response to a perceived lack of manpower, it is used early in a program, during the staff up stage, and again toward the end of a project during the push to finish on schedule. The initial use is probably the most detrimental – when quality and productivity are already being depressed by workforce dilution, fatigue just makes a bad situation worse. In the this case the *Real* project never catches up to the others in terms of quality – remember the effect of past work quality on present quality from Section 2.2. Moreover, lowered productivity increases the estimates of required effort, which induces more hiring – and overtime – lowering productivity even more. Finally, prolonged overtime increases new hire attrition, which prolongs the recovery of both quality and productivity.

Consequently, overtime should be used sparingly, and never for prolonged periods. In particular, it should be avoided during the startup period of a project. Lastly, as suggested by the Nevison study,<sup>87</sup> an employees total work hours per week should not exceed 50.

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<sup>86</sup> Recall that the effective workforce is the theoretical number of workers required if all overtime hours were worked by additional individuals rather than the existing workforce.

<sup>87</sup> Reference Footnote 65. See, John N. Nevisons graph in the Appendix, Section 8.2.

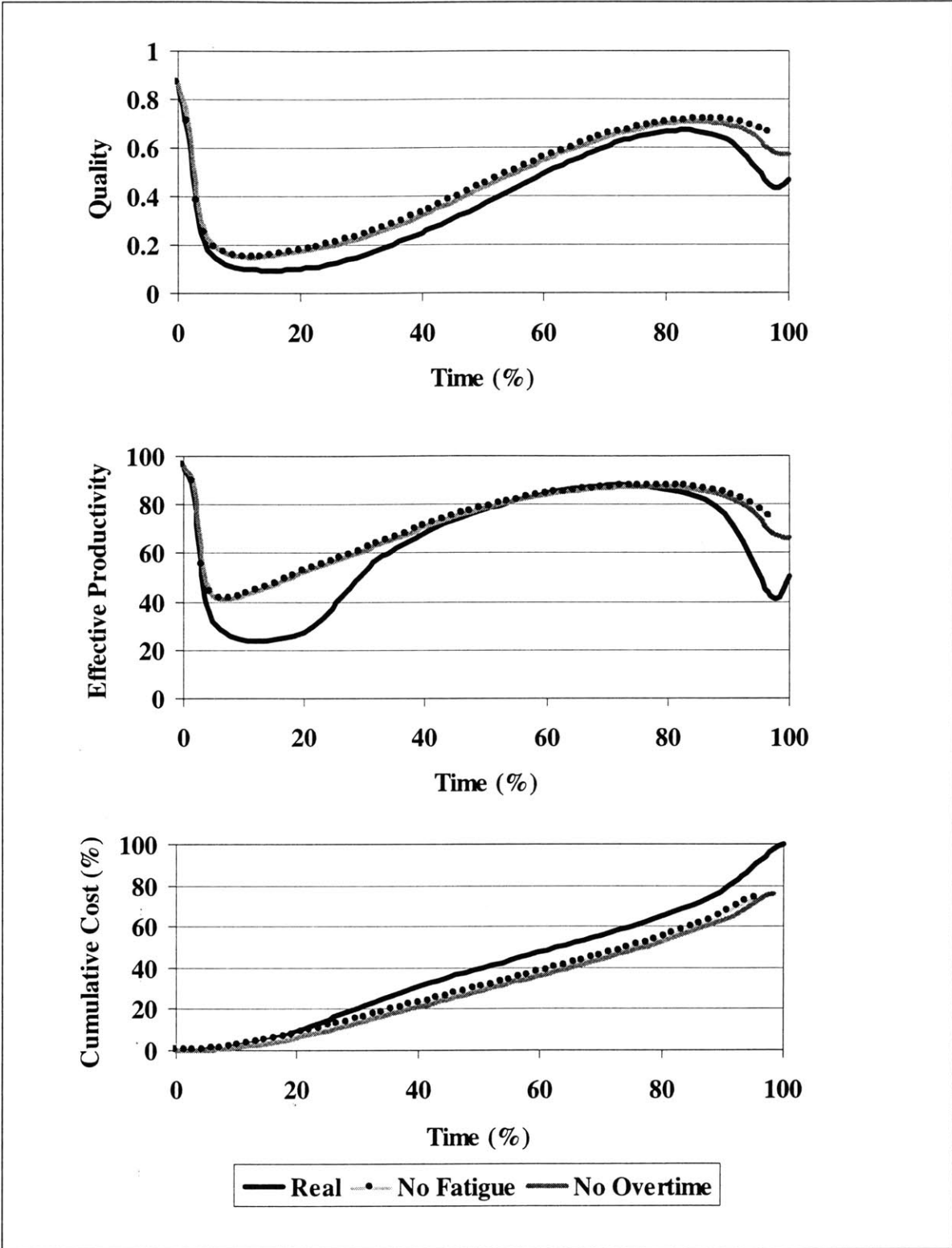


Figure 53: Effects of Fatigue And Overtime On Project Performance

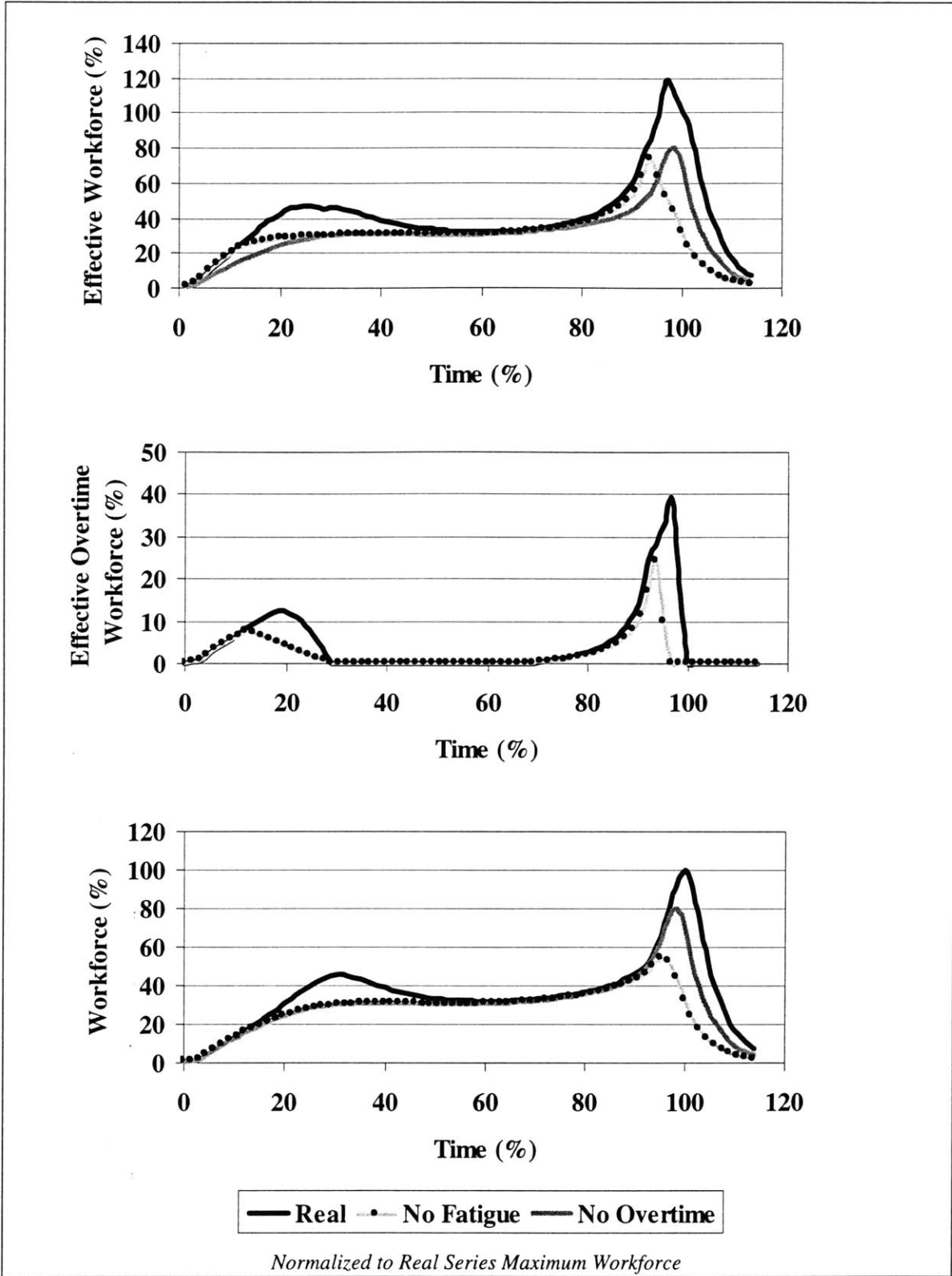


Figure 54: Effects of Fatigue And Overtime On Workforce Numbers

#### 4.1.4 Workforce Management Revisited

In the introduction, it was suggested that part of the misfortune of the C-17 program could be attributed to workforce churn, a direct result of the company's union contract. While no attempt has been made to model the specific experience of the C-17, the general results of such an episode lead us to the conclusion that great care should be taken to prevent workforce disruptions of this sort. Figure 55 and Figure 56 compare the effects on two different program configurations of a nine month period during which approximately 50 percent of the workforce is replaced by inexperienced individuals – indicated by the prefix *High*. In the first program configuration, *Baseline*, workforce size is unconstrained by financial considerations. In the second, *Baseline Constrained*, workforce size is limited by a monthly spending limit. As on the C-17 program, the workforce disruptions occur toward the middle of the programs.

Figure 55 clearly demonstrates the unfavorable effects of high workforce replacement on quality and productivity. This behavior is caused by the same mechanisms that were responsible for the initial drops in quality and productivity seen during the program startup phase – workforce experience dilution. Notice the effects of the workforce disruption appear almost immediately and linger long after the period of high turnover is terminated.<sup>88</sup> In this case, because the disruption is mid-program and the workforce had stabilized, overtime induced fatigue and schedule pressure are not factors initially.

It is a familiar story; workers who had developed program-specific processes and knowledge are being replaced by program novices. Even if the new workers come from other programs, as was the case on the C-17, to the extent that processes are dissimilar and the project unique, learning by doing must occur. Unfortunately, this means the number of mistakes made, and not immediately caught, goes up, and the time spent making those mistakes is longer than with the previous experienced workers. In effect, the workforce must traverse some portion of the learning curve twice.

Two facts are apparent from an inspection of Figure 56, which portrays the workforce dynamics resulting from the high turnover as well as its costs. First, with or without the workforce disruption, constraining workforce growth near the end of the project, while increasing schedule slip slightly, reduces the project's cost. Second, regardless of the workforce growth policy, a massive, mid-project disruption of the workforce increases both cost and schedule slip.

An episode of high turnover increases cost because more effort must be expended to complete the project. Low quality results in the creation of more rework which increases the total effort required. Schedule slips as well because the rework is not discovered immediately. When it is discovered, either more workers are added which takes time and creates even more rework, or the existing workforce begins to work overtime which leads to fatigue, creating more rework. Both fatigue and the addition of new workers decrease productivity, which augments the schedule slip because less real work is done per hour of effort.

Constraining the workforce size reduces cost by keeping quality and productivity high. By not adding more workers, experience is not diluted. However, because there is some rework to be corrected, with the same size workforce, a bit more time is needed to complete the project.

These results suggest that labor contracts and other human resource management policies be designed to maximize the stability of the workforce over the life of a program. Clearly, neither the C-17 program managers nor the Air Force had an inkling that a labor contract would affect the program. However, given the potential disruptive impact of workforce instability, all such contingencies should be considered.

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<sup>88</sup> The high turnover was modeled by adding a square wave input to the base workforce attrition rate.

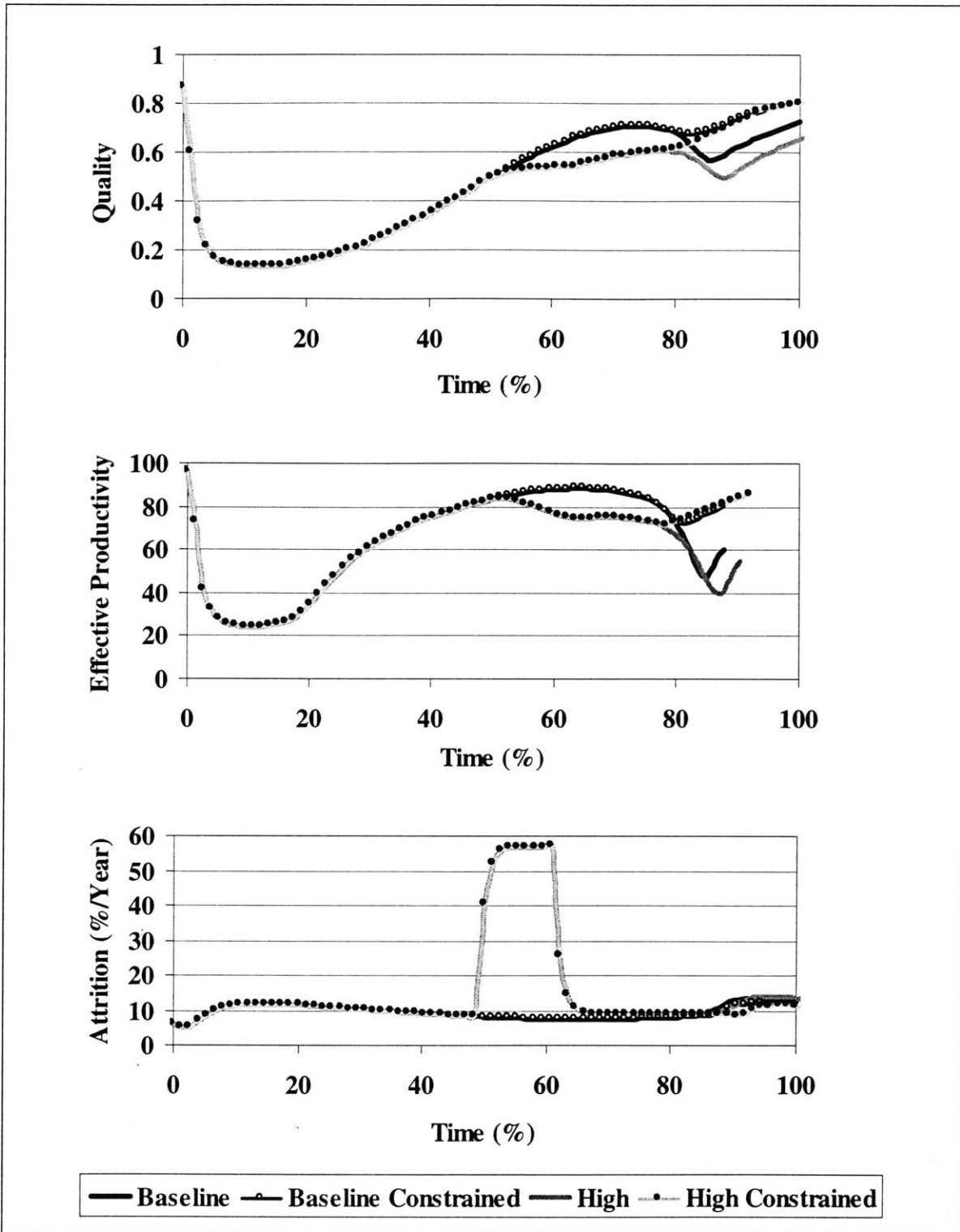


Figure 55: Effects Of Punctuated High Workforce Turnover On Quality And Productivity



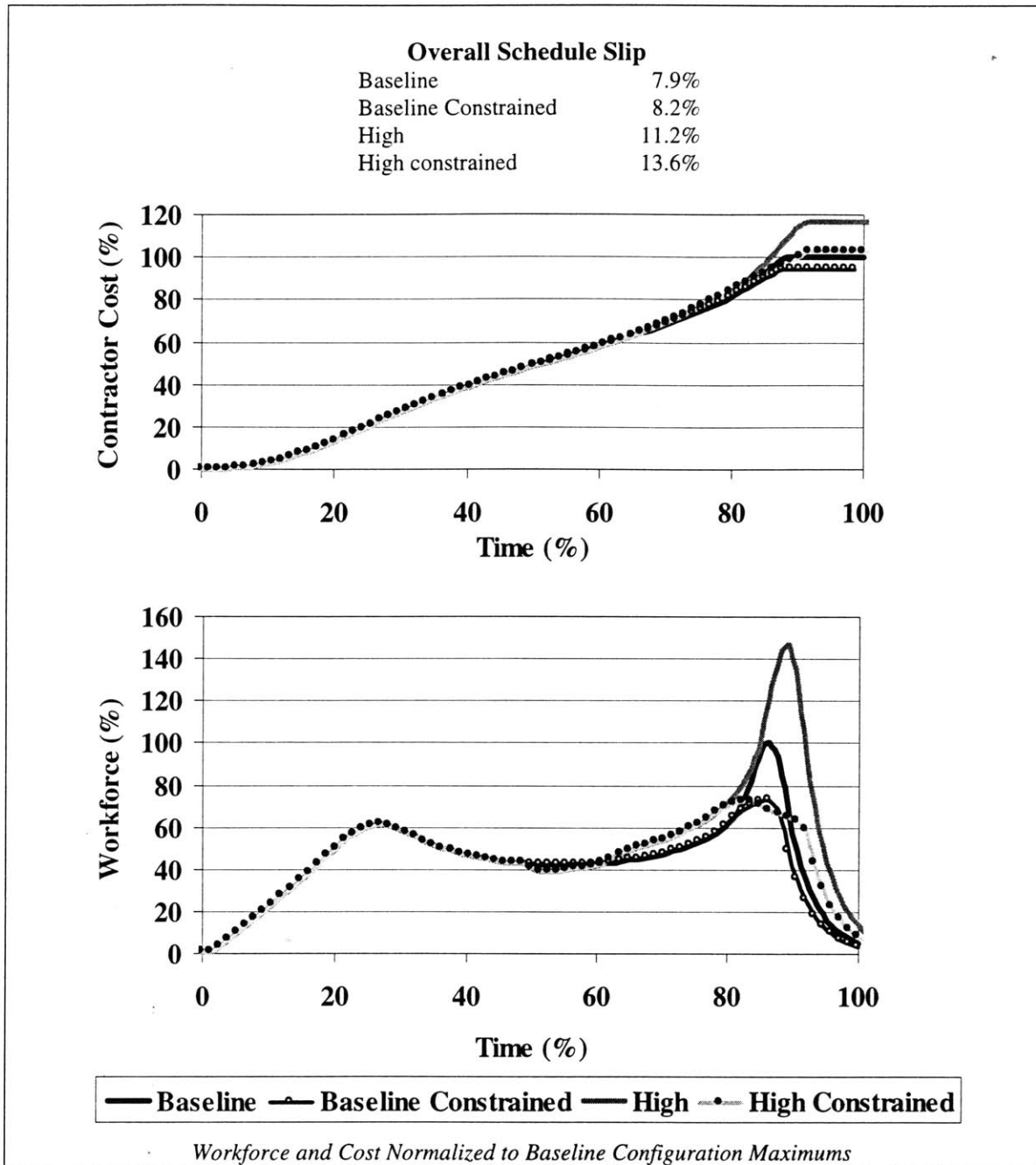


Figure 56: Effects Of Punctuated High Workforce Turnover On Contractor Schedule, Cost, And Workforce Size

#### 4.1.5 Management Reserve

Section 3.1.10 introduced the practice of maintaining a management reserve – withholding a portion of the available project funds until near the end of the project, which is essentially a redistribution of the funding profile. To explore its effects on program cost and schedule performance, various levels of management reserve under several different release scenarios were simulated. The release scenarios differed with respect to the fraction of the project which had been completed before management reserve funds were released, where *Early*, *Middle* and *Late* scenarios indicating no release of management reserve funds until 25, 50, and 75 percent of the project is perceived to have been completed respectively. Remember that release of management reserve funds is indicated by the project’s net requirement for additional funds, which becomes apparent through the discovery of rework and funding shortfalls. However management’s willingness to release reserve funds determines whether the demands for additional funds will be answered. Figure 57 displays the cost and schedule trends for the three scenarios over a range of management reserve fractions.

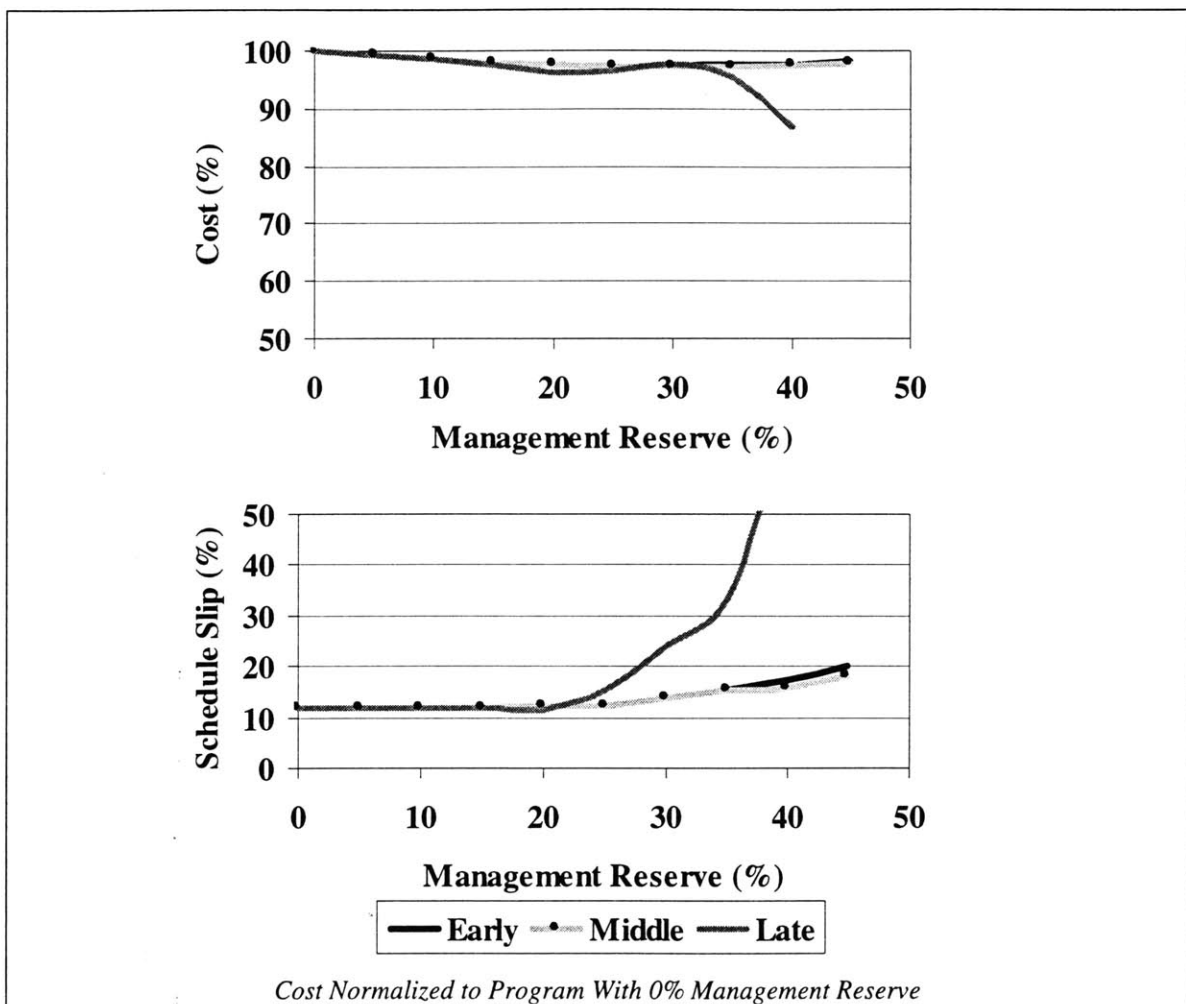


Figure 57: Management Reserve Effects On Cost And Schedule Slip Trends

For low levels of management reserve, the net program effect is negligible to slightly positive. As the reserve fraction increases, cost savings plateau and schedule slip begins to increase. Though, the delayed onset of increased slip suggests a cost advantage may be obtained through a limited use of management reserve. The magnitude of schedule slip increases with higher reserve fractions, the longer the manager waits to release the funds. The mechanism of this behavior becomes clear with an examination of quality, productivity and workforce time series for different scenarios. Figure 58 and Figure 59 allow a comparison between the *Middle* and *Late* scenarios, presenting the behavioral progression as management reserve fraction increases.

Management reserve artificially creates a financially constrained environment. Under these conditions, workforce size is determined primarily by the funding available. This can be seen in the workforce curves in both figures. As the management reserve fraction was increased, the rate at which individuals were added to the project decreased. This lessened the impact of the now familiar, workforce dilution effect. Quality and productivity do not drop as low and begin to recover more quickly. In all the scenarios investigated, moderate reserve fractions initially resulted in higher quality and productivity. However, a close inspection of figures reveals that the series in which no management reserve was maintained, recover more quickly and eclipse the other series by mid-project. This is because having a larger workforce initially gives the impression that much progress is being made, and the project is on schedule. This reduces the use of overtime and lessens schedule pressure. With fewer workers, it seems that less work is being done – though in fact because of the higher quality more real progress is being made – which increases the use of overtime and increases schedule pressure. These two are the slight drag that slows the recovery of quality and productivity. The conundrum then is; reducing the rate at which new workers are added to the project reduces the dilutive effects on quality and productivity, however, fewer workers give the impression that insufficient progress is being made and so overtime and schedule pressure increase, both of which ultimately reduce quality and productivity.

The value of management reserve comes from slowing the initial workforce surge, which reduces the dilution effects on quality and productivity. Of course, restricting hiring too much can be counter productive, resulting in excessive schedule slip – insufficient human productive capacity causes work to be pushed into the future. Moreover, as shown in Section 4.1.2, bringing more experienced workers onto the program or using processes which have a steeper learning curve provide a more direct mechanism that creates even greater cost saving. Finally, this model has not included any morale or gaming effects, which the use of management reserve might elicit. Clearly, these could eliminate all gains from the use of management reserve – inflated cost estimates and reduced productivity could result.

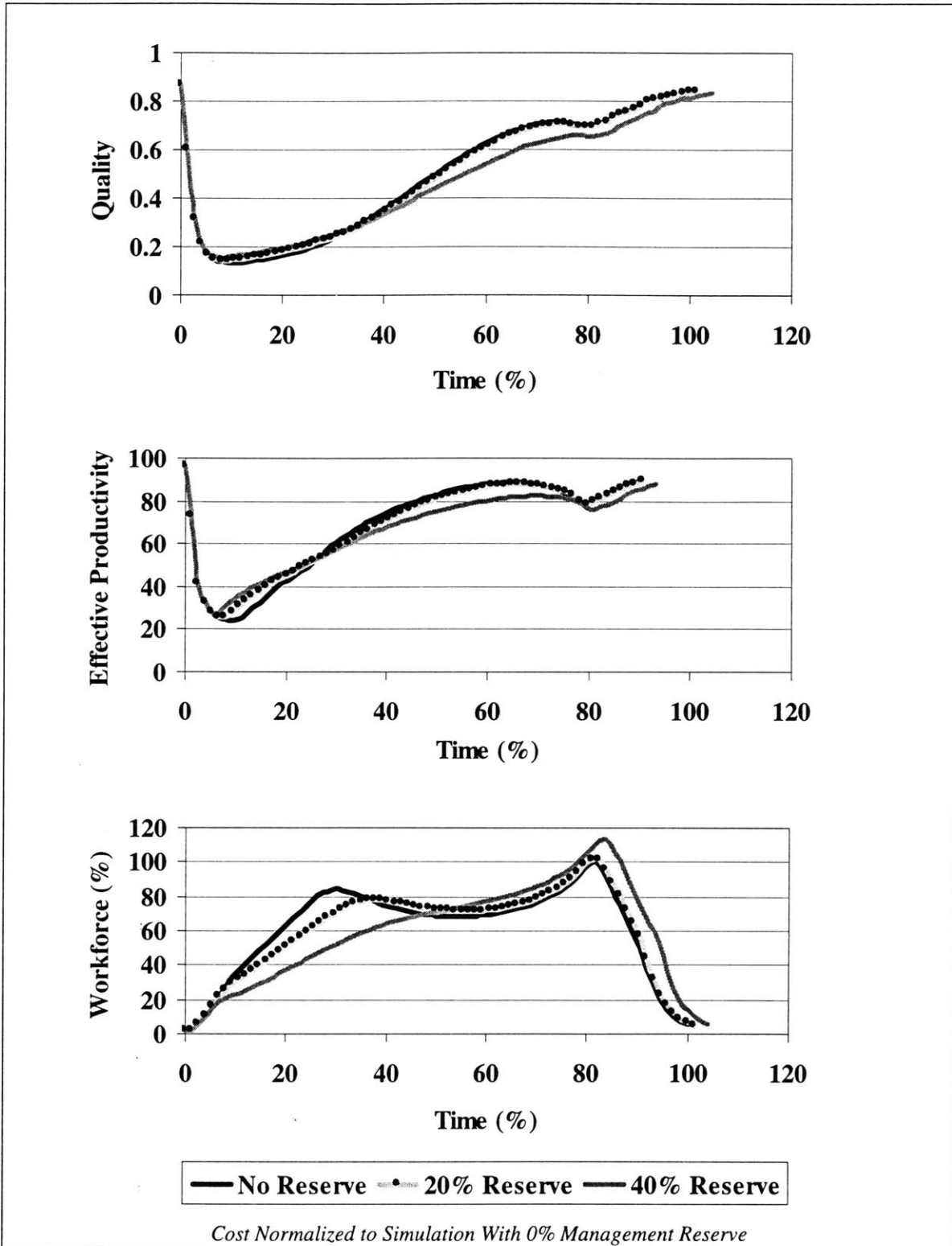


Figure 58: Time Series Comparison For Middle Scenario, Management Reserve Released Only After 50 Percent Completion

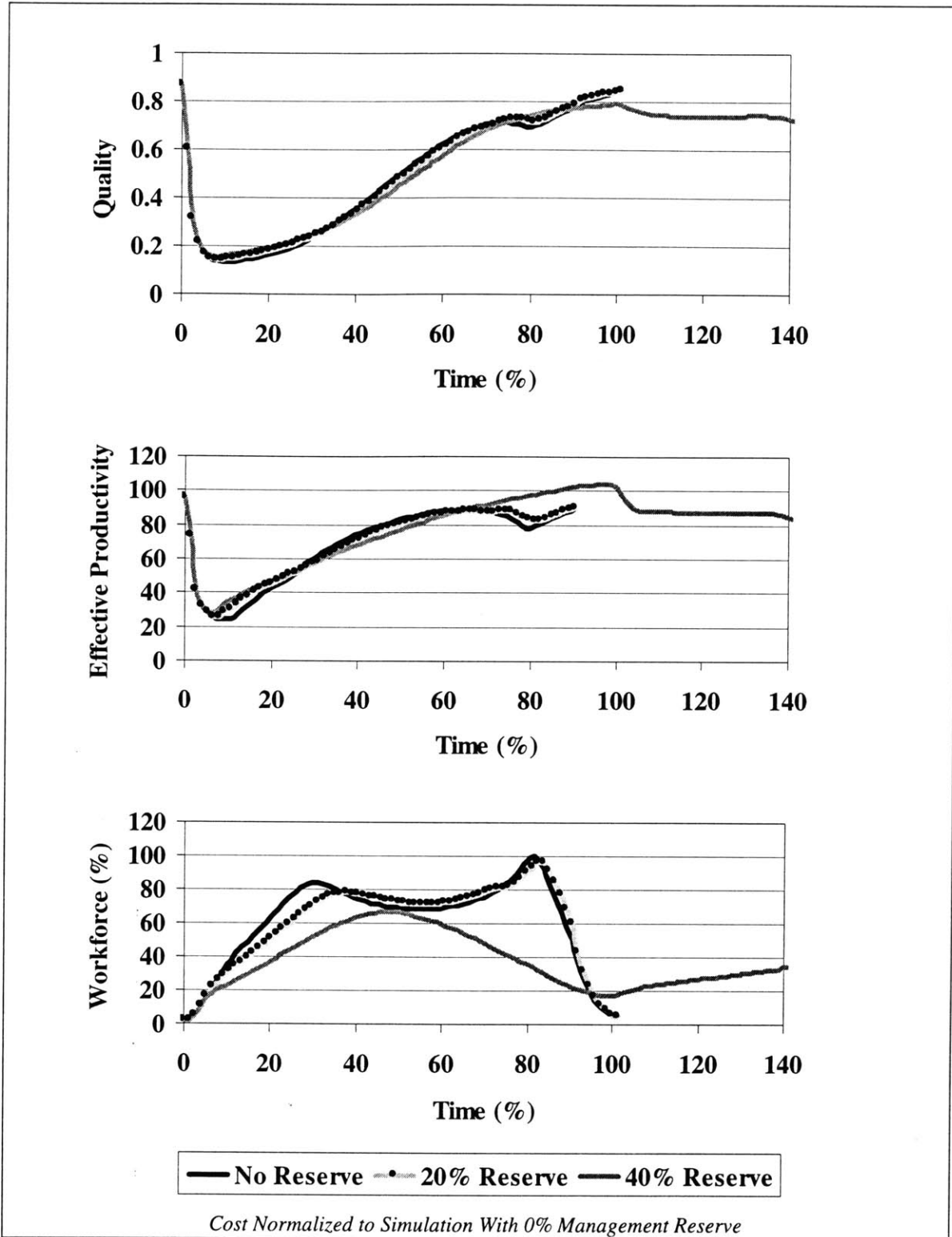


Figure 59: Time Series Comparison For Late Scenario, Management Reserve Released Only After 75 Percent Completion

## 4.2 Contractor and Program Office Interaction

In the previous sections, the behavior of the contractor system, independent of the SPO's influence was investigated. Now, the dynamics of the combined SPO-contractor system will be explored. The cost and schedule implications of officer tenure and other SPO human resource management policies, SPO-contractor coordination, as well as the potential value of explicitly including quality estimates in the initial estimates of program cost and schedule are presented. In addition, the effects of government funding profiles on program performance are addressed.

### 4.2.1 High officer turnover is expensive

In Section 4.1.4 the disruptive payoff from replacing experienced workers with novices was exposed. There it was demonstrated that the ensuing drop in average workforce experience depressed quality and productivity, increasing cost through the generation of additional rework and ultimately the total effort required to complete the project. This coupled with the reduced productivity demands that either the schedule slip, more workers are hired, or both. Of course, it is now understood that adding additional workers will dilute workforce experience even more – continuing the now familiar spiral. Clearly, the same mechanisms operate within the SPO's workforce. However, because the quality and productivity of the two are inter-related, if the average experience of SPO officers is reduced or not allowed to develop because of the Air Force's promotion process, one would expect cost and schedule slip benefits to accrue from increased officer tenure. This is exactly what is confirmed in Figure 60.

For the figures in this section, average officer tenure as a fraction of the time required for officers to achieve their full potential was varied under several different scenarios. The *No Interaction* scenario captures the results of completely autonomous operation of both the SPO and contractor – no feedback. *Medium* and *High* scenarios illustrate the effects of increasing SPO-contractor dependency<sup>89</sup> – essentially increasing the feedback gain. The *Learning* scenario shows how the *Medium* results would change under a learning curve that is more uniform – a linear rather than a concave function of time.

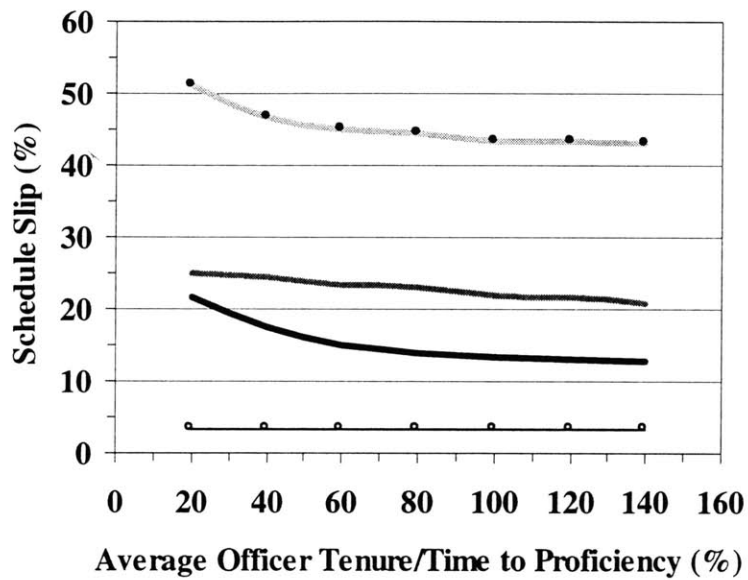
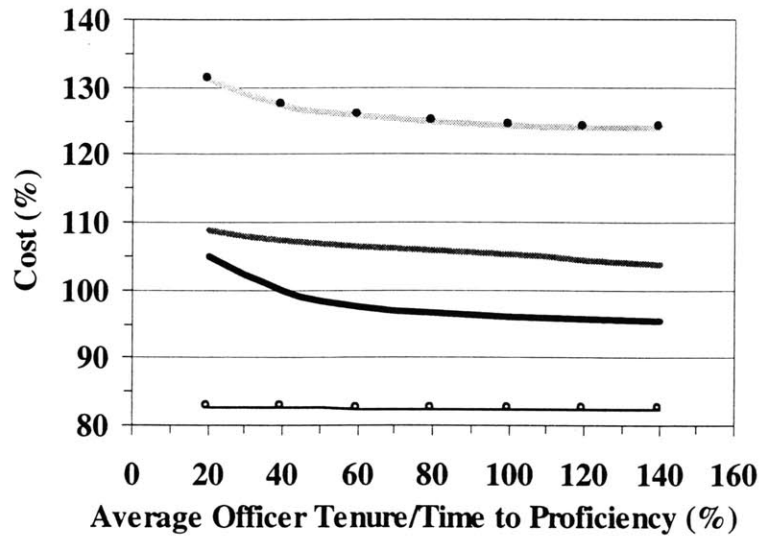
Figure 61 confirms the workforce dilution hypothesis – SPO quality and effective productivity recover more quickly and achieve higher levels as the average officer tenure increases from 12 to 48 months. The mechanisms that bind the SPO's performance are exactly those described in a previous section on workforce management, in which skilled workers were replaced with inexperienced transfers.

However, unseen before are the consequences of the feedback between the SPO and contractor under these conditions. Remembering that the two influence each other primarily through the quality of their work products and the timeliness of the delivery of those products, Figure 62 and Figure 63 are a cross sectional comparison of the scenarios showing quality, effective productivity,<sup>90</sup> and workforce. Several features of these time series require explanations, as their modes differ significantly from those seen previously.

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<sup>89</sup> In this context, dependency is indicative of the effect poor work quality of one has on the work quality of the other. The higher the dependency, the greater the effect.

<sup>90</sup> Effective productivity is the gross productivity of the workforce reduced to reflect what they actually produce in a given day. So while the workforce could produce 10 units in one day, if they lack a critical input and can only produce 5 units, their effective productivity would be 50 percent of their gross.



Medium
  High
  Learning
  No Interaction

*Average Officer Tenure Normalized by 60 Months Time to Proficiency*  
*Costs Normalized to Baseline Scenario with 24 Months Average Officer Tenure*

**Figure 60: Effects of Average Officer Tenure on Cost and Schedule Slip Trends**

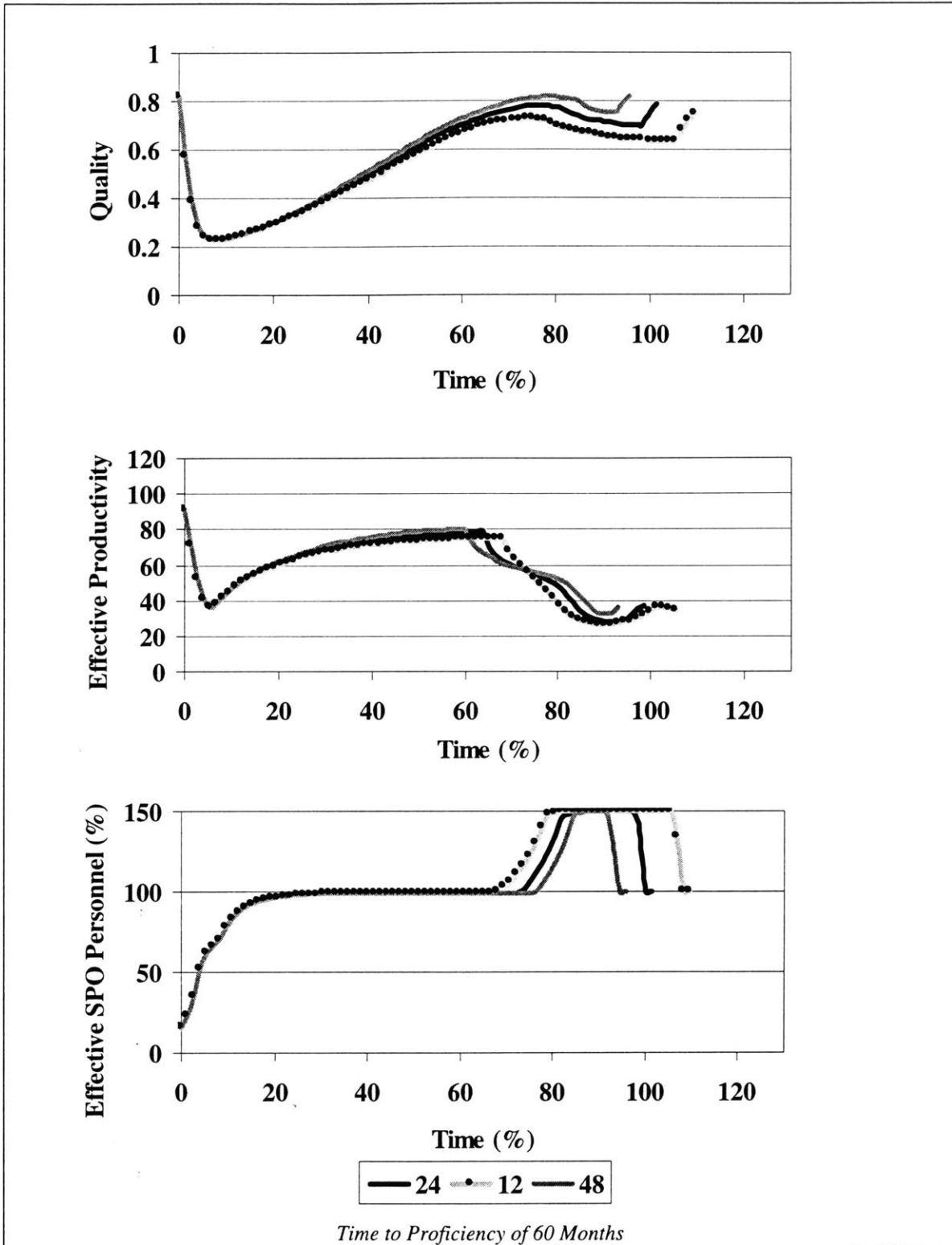


Figure 61: Time Series Comparison of Average Officer Tenure Effects for Baseline Configuration



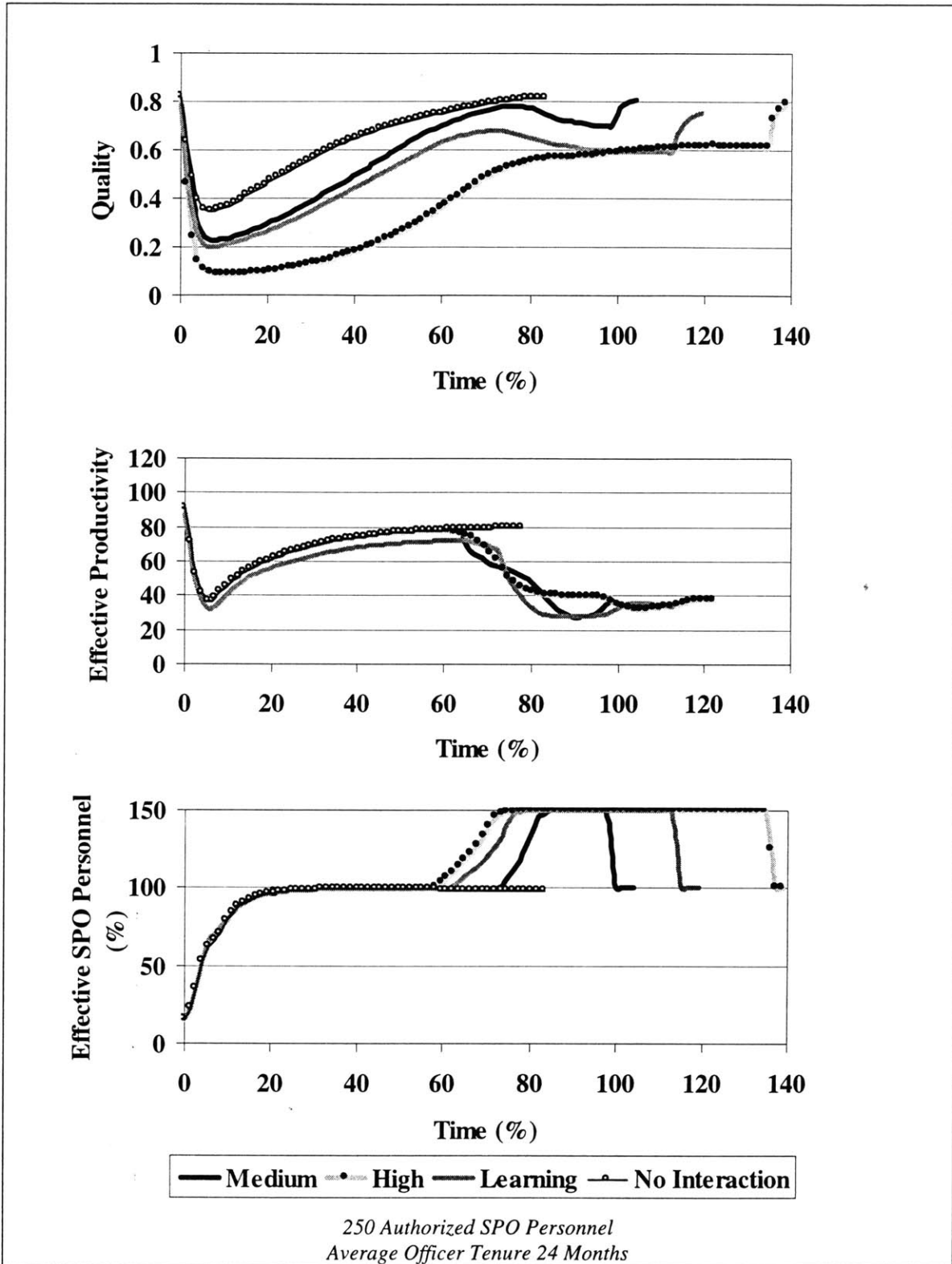


Figure 62: Cross Sectional Comparison of Learning Curve and Interconnectivity Effects On SPO

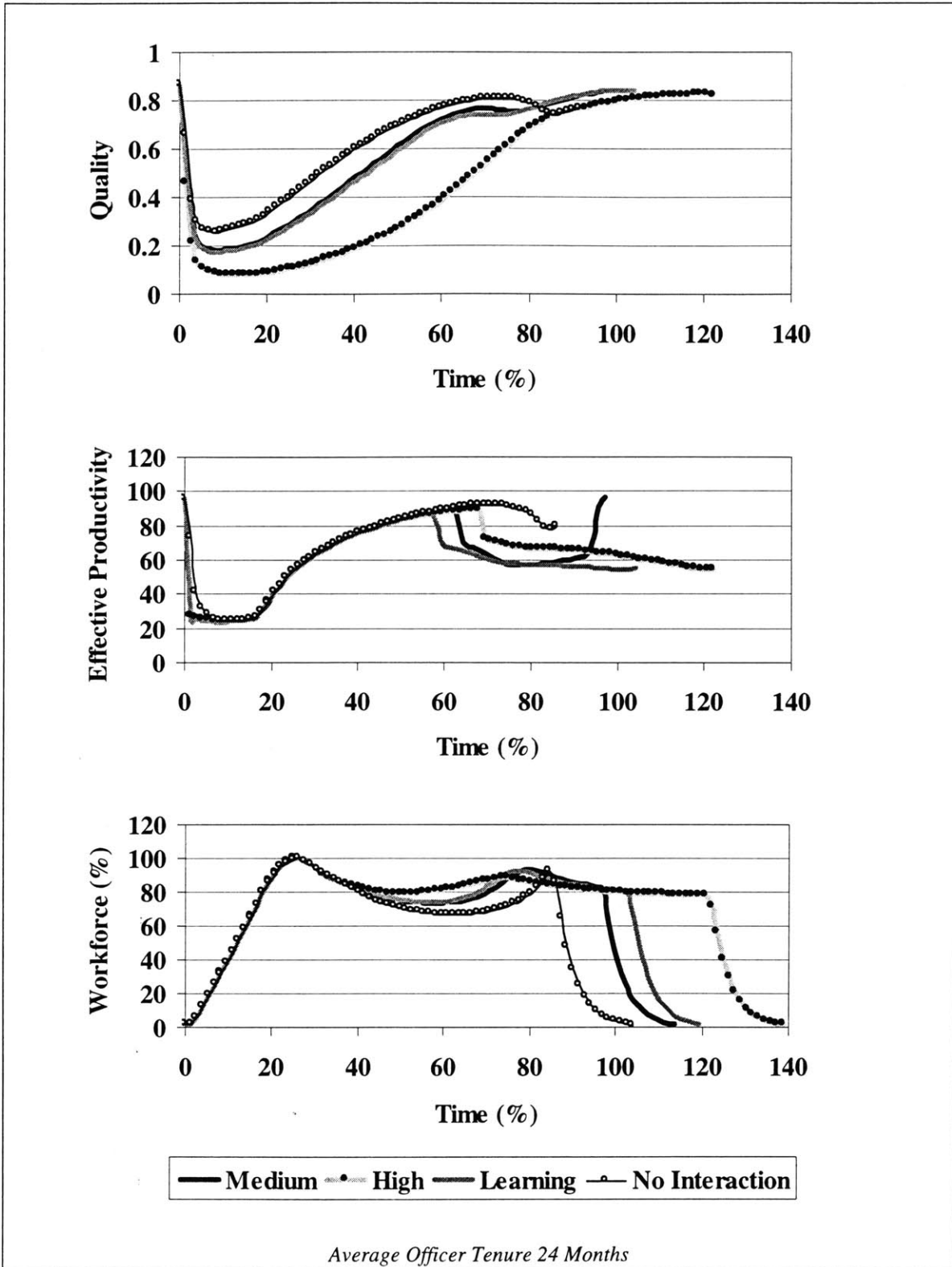


Figure 63: Cross Sectional Comparison of Learning Curve and Interconnectivity Effects on Contractor

Effective productivity of both parties declines more abruptly toward the end of the project. Of course, some decline was expected reflecting end of project fatigue, due to an increase in overtime, and experience dilution, if additional workers are added to the project. However, here effective productivity is also reduced by holdup – the unavailability of required inputs. For example, assume the SPO requires data from the contractor to finalize flight test plans and the contractor is late providing the information, while the workers at the SPO are waiting for the data, their effective productivity declines. This is sometimes referred to as the “standing army” problem – the workers are in place but there is insufficient work to keep them working at full productivity. This problem can be particularly acute for the contractor at the end of a project if they must wait for SPO approval of changes – a day for day slide in schedule can result. [Weiss] A comparison between the *No Interaction* and other scenarios demonstrates the potential magnitude of these impacts.

Real productivity also plummets with the drop in quality. Under the pressure to meet schedule, this induces the use of overtime. The result is a “hurry up and wait” environment. In the scenarios simulated, the contractor is held up by the SPO at the end of the project. Ironically, this gives the contractor time to catch up and actually reduces the use of overtime by the contractor, in part because more workers are retained after the project ramp-up peak – the response to management’s perception of low productivity. The same is not true for the SPO. Rushing to catch up, overtime use increased. In the last graph in Figure 62, effective SPO workforce, this burst of overtime is visible. The peculiarities of the SPO workforce were discussed in Section 3.2.2, and it is hiring to the personnel authorization limit that creates the flat-line mode. In this case, the only mechanism for the SPO to increase productivity is to use overtime and hence the step increase in effective personnel in the figure. Naturally, the use of more overtime leads to fatigue, which cascades into lower quality and productivity – holdup becomes persistent and increasing cost and schedule slip are the payoff.

These results suggest that real cost and schedule benefits would result from increasing the general level of SPO officer experience. Obviously, those benefits increase with as the gain on SPO-contractor feedback increases and the time required for officers to traverse the learning curve increases. To effect this, the average officer experience could be increased either through in-transfers of officers having greater experience with the program’s processes, developing processes which require less time to learn, or both. These have the benefit of not requiring structural changes in the Air Forces’ promotion process. Alternatively, promotions could be structured such that officers could remain on programs for longer periods while still making satisfactory progress up the ranks. A third alternative might be to reduce the number of officers on projects, reducing their project leverage. Of course, the secondary effects of any of these alternatives warrant additional study before enactment.

#### 4.2.2 Unrealistic initial estimates

Two important issues related to program cost are investigated in this study. The first, understanding how management policies contribute to total program cost has been the focus of many previous sections. The second, the accuracy of initial program cost predictions, important for the determination of a project's true cost/value proposition and for the Air Force wide management of development budgets, is investigated here.

Government regulations do not allow estimates of quality to be factored into the initial cost calculations. In effect, no allowance can be made for rework. Given the additional effort quality induced rework generates this oversight must reduce the odds of a program finishing on budget to pure chance. In fact, the intuition developed so far would dictate that only a reduction in the project's scope could cause an alignment of actual and estimated cost – assuming the initial estimate was not inflated. Presuming that project scope is not increased, and that the contractor is operating in good faith, Figure 64 indicates that including estimates of average quality and average gross productivity in initial cost estimates improves their predictive power. Of course, if the scope of the project is increased or found to have been underestimated, no amount of adjusting for quality and productivity will improve the initial estimates. However, if cost revisions resulting from those changes include the effects of quality and productivity, it can be assumed that the revised costs will more accurately reflect the real program cost, than those obtained otherwise will.

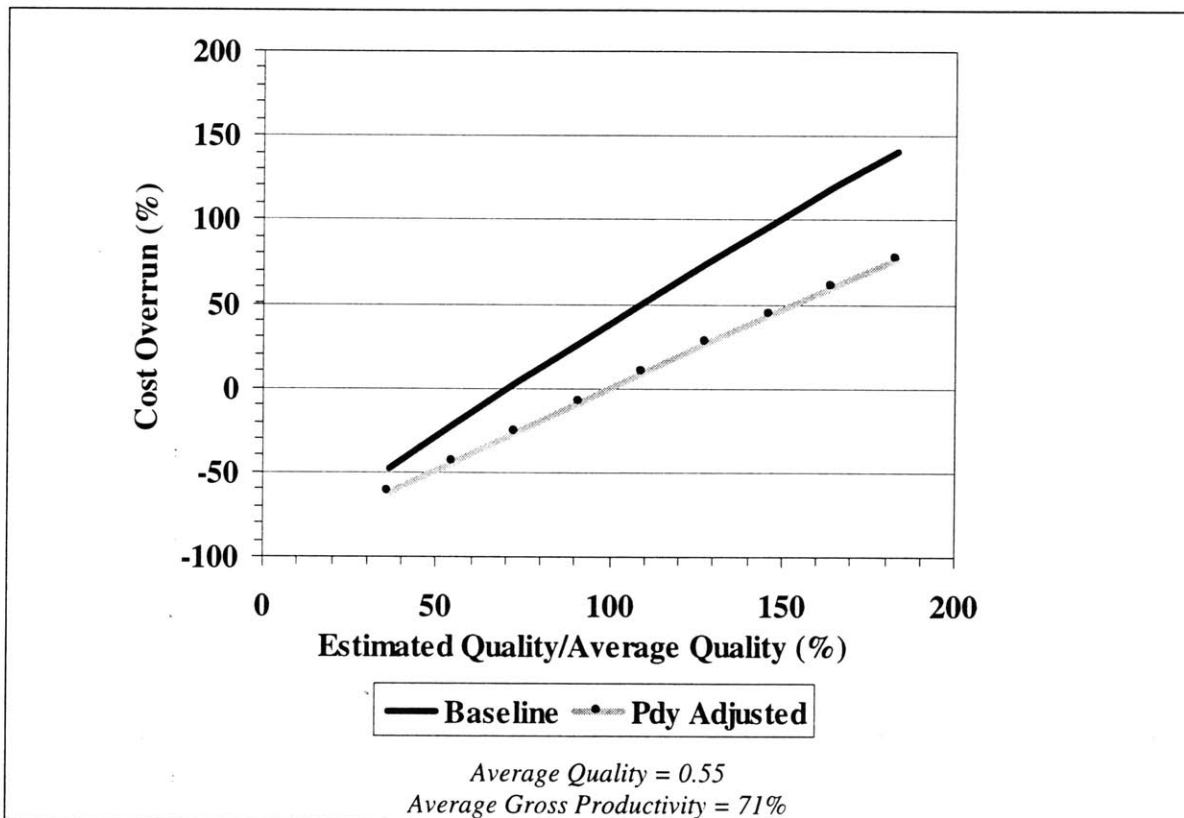


Figure 64: Effects of Quality and Gross Productivity Assumptions on Cost Estimate Precision

In Figure 64, the *Baseline* series shows how the project's cost overrun declines as the estimates of average quality are decreased, the result of an increase in the initial estimated cost – project cost is not changing, only the initial estimates. The *Pdy Adjusted* series improves on the *Baseline* by also adjusting the estimates for average gross productivity.

The reason that both quality and productivity must be adjusted for can be demonstrated from a very simple cost estimation model. Workforce gross productivity ( $P$ ) translates project scope ( $S$ ) into man-hours of effort, which are paid for at an average workforce wage ( $W$ ) giving a total project cost estimate ( $C$ ). For simplicity overhead has been considered a component of the workforce wage.<sup>91</sup>

$$(1) \quad C = \frac{S}{P} W$$

However, because of the rework cycle, if quality is less than perfect, the true effort required is not  $S$ , but  $S^*$  which is equal to  $S/q$ , where  $q$  is the average work quality.<sup>92</sup> In addition, if  $P$  is assumed to be the normal workforce productivity under ideal conditions, previous sections have shown that workforce dilution, schedule pressure, and fatigue conspire to make workforce productivity something lower than  $P$ , perhaps  $P^*$ . The true program cost,  $C^*$ , would then be given by equation (2).

$$(2) \quad C^* = \frac{S^*}{P^*} W$$

If  $\rho$  is defined as the ratio,  $P^*/P$ , then equation (2) may be rewritten in terms of the original variables as equation (3). Finally, the cost estimation error,  $E_c$ , resulting from ignoring reduced quality and productivity becomes as show in equation (4).

$$(3) \quad C^* = \frac{S}{P\rho q} W$$

$$(4) \quad E_c = W \frac{S}{P} \left( \frac{1}{\rho q} - 1 \right)$$

Obviously, low values of  $\rho$  or  $q$  can dramatically increase the cost of a program, and so equation (3) reiterates the importance of making decisions which serve to increase or maintain high values of quality and productivity during program execution. Concurrently, equation (4) stresses that if the goal is to provide more accurate initial estimates of a program's total cost, including the effects of quality and productivity is a necessity. Not adjusting a program's scope to reflect rework is equivalent to intentionally underestimating its true size. Likewise, assuming the workforce will produce at levels unattainable over the course of the project only serves to create false impressions of economy.

The cost estimation error may also be interpreted as the cost increment resulting from the interaction between quality and productivity deficiencies. Dramatic cost escalations can result because the magnitude of the increase is determined by the product ( $\rho q$ ), which appears in the denominator. For example, if average productivity was 71 percent of its expected value and average quality was 55 percent, the resulting cost increase would be approximately 156 percent. The inverse product relationship demonstrates again the

<sup>91</sup> This is consistent with the industry practice of estimating overhead costs to be a fraction of labor cost – the burden rate. In this case, I have combined the wage and burden rate into one variable,  $W$ .

<sup>92</sup> This was derived in Section 2.2, Footnote 49.

non-linear nature of the SPO-contractor system and implies that cost reduction programs must focus on increasing *both* quality and productivity to be successful.

One objection to utilizing a method such as that of equation (3) to make initial estimates of program cost is that it creates the problem of what values of quality and productivity to use *a priori*. Simulation of the project before execution would be one excellent option, in addition to historical values, which could be used. Another objection could be that using such methods only serves to institutionalize low quality and productivity. Rather, the suggestion here is to rationalize the cost estimation process. Clearly, perfect quality and productivity are important goals, with the benefits of improving both demonstrated many times throughout this study. However, to ignore the realities of their behavior over a project's execution is to misrepresent the potential performance of a program. A reasonable objective would then be: Always strive for quality and productivity improvements, while at the same time, fully acknowledge the cost consequences of a program's real quality and productivity.

### 4.2.3 SPO personnel allocation

In a period of declining manpower and budgets there is naturally a question of the correct size for a SPO. One of the difficulties in determining the correct size is the very nature of the task. Certainly, a significant portion of the SPO's work, such as coordinating flight tests, preparing official progress reports and the like, can be forecast at program inception. However, oversight and facilitation activities are not as easy to predict – their levels are related to the perceived health of the program. This can result in significant uncertainty in the level of effort required by the SPO. There is a tension between the desire to reduce SPO costs through workforce reductions and having sufficient manpower for adequate task performance. Under the current system, SPO personnel level is capped by the minimum of either its personnel allocation, or available funding. Further, upward movements in a SPO's allocation can take significant time and are met with varying degrees of resistance. Thus, SPO personnel levels tend to be flat, or follow funding trends.

Because the SPO's function in the SPO-contractor system is management and oversight, it has considerable cost and schedule leverage. If the SPO is unable to provide the required inputs to the contractor, when the contractor needs them, Figure 65 demonstrates the resulting program cost and schedule slip escalation as the size of the SPO is decreased.

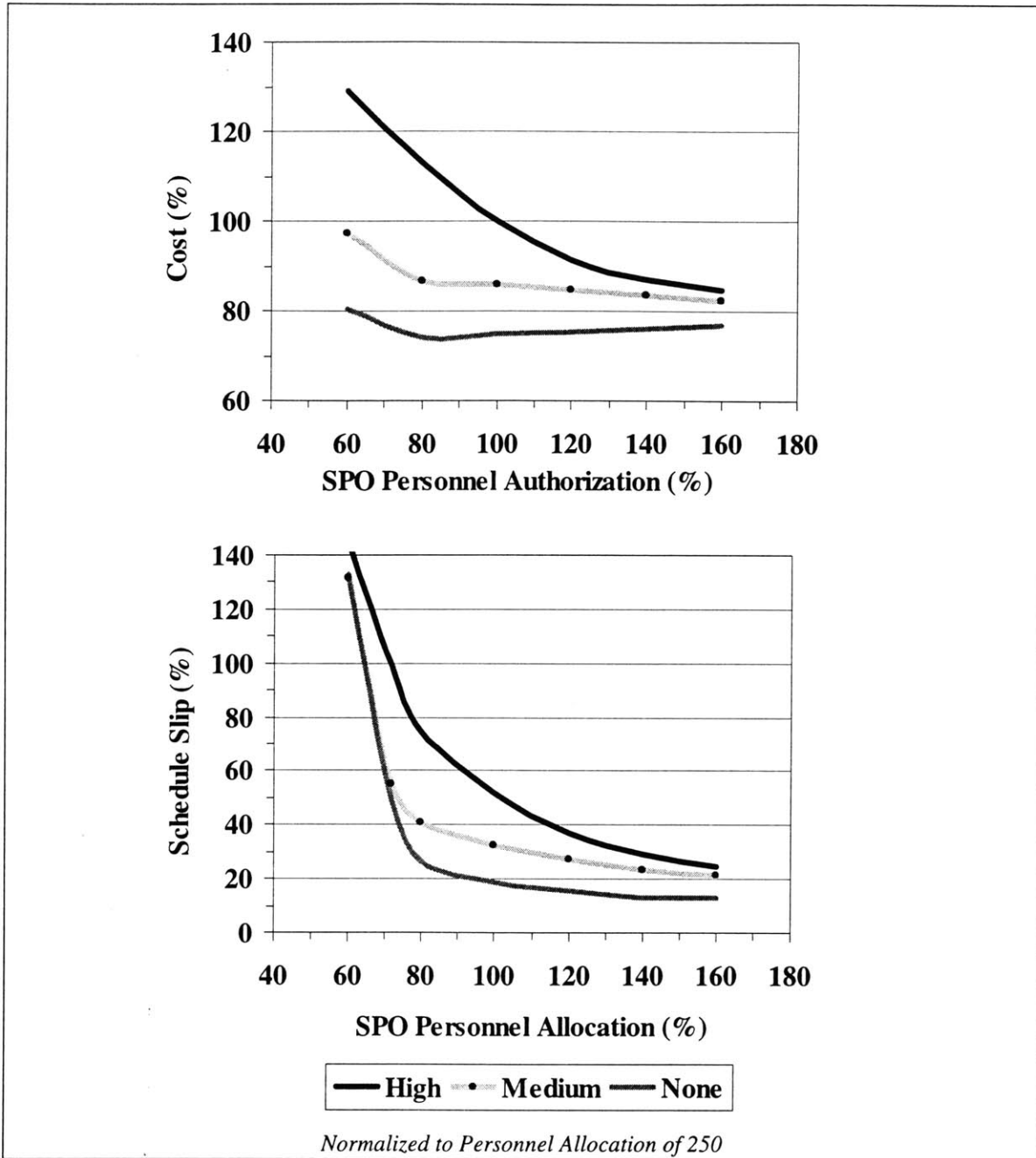
Three program scenarios, representing different levels of the SPO's ability to hold-up the contractor late in the project, were simulated with a range of SPO personal levels. In the *None* series, SPO holdup during the program's later stages did not directly affect contractor effective productivity. However, the contractor still suffers any secondary effects resulting from the SPO being behind schedule – for example low quality related to schedule pressure and fatigue. In the *Medium* and *High* scenarios, the contractor's dependence on the SPO's work products for project completion increases. Finally, in all cases, sufficient operational funding is provided to mitigate any cost or schedule effects due to operational funding shortfalls.

Figure 65 suggests that for almost any level of contractor dependence the marginal savings in program cost and schedule are greater than the marginal cost for SPO personnel – every dollar saved by reducing the number of SPO personnel increases the total cost of the program by more than that dollar. An undersized SPO is very expensive.

There are three mechanisms combining to produce these results. For SPO sizes below a critical threshold, corresponding to the inflection point in the graphs<sup>93</sup>, insufficient manpower results in continuous overtime and schedule pressure. The resulting fatigue and rush drives SPO quality down dramatically, which feeds back through the contractor pushing program cost up and schedule out substantially. Figure 66 shows an example of the quality mode shifts, as SPO personnel allocation increases from 170 to 190 personnel. This pattern of low initial quality fostering poor performance for the duration of the program has been seen before in previous sections, and dominates the left portions of the cost and schedule curves.

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<sup>93</sup> A potential rule of thumb for the threshold is  $S/(DPp)$ , where  $D$  is the initial time interval to complete the project and the other variables are as defined in Section 4.2.2 but for the SPO. That is, the workforce size indicated by the effort required, adjusted to reflect average productivity. Naturally, given the results of Figure 65, adjusting scope ( $S$ ) for quality ( $q$ ) would be a good lower bound for a SPO's personnel allocation. This values are only approximate because a critical parameter is the management's use of overtime. Even with an undersized SPO, if the workforce is rested and not pushed to rush their work, fatigue induce quality problems will be eliminated from the program startup period. Of course, hold-up will then become the issue as the program progress lags.



**Figure 65: Cost and Schedule Slip Trends With SPO Size And Level Of Effectivity On Contractor Late Program Productivity**



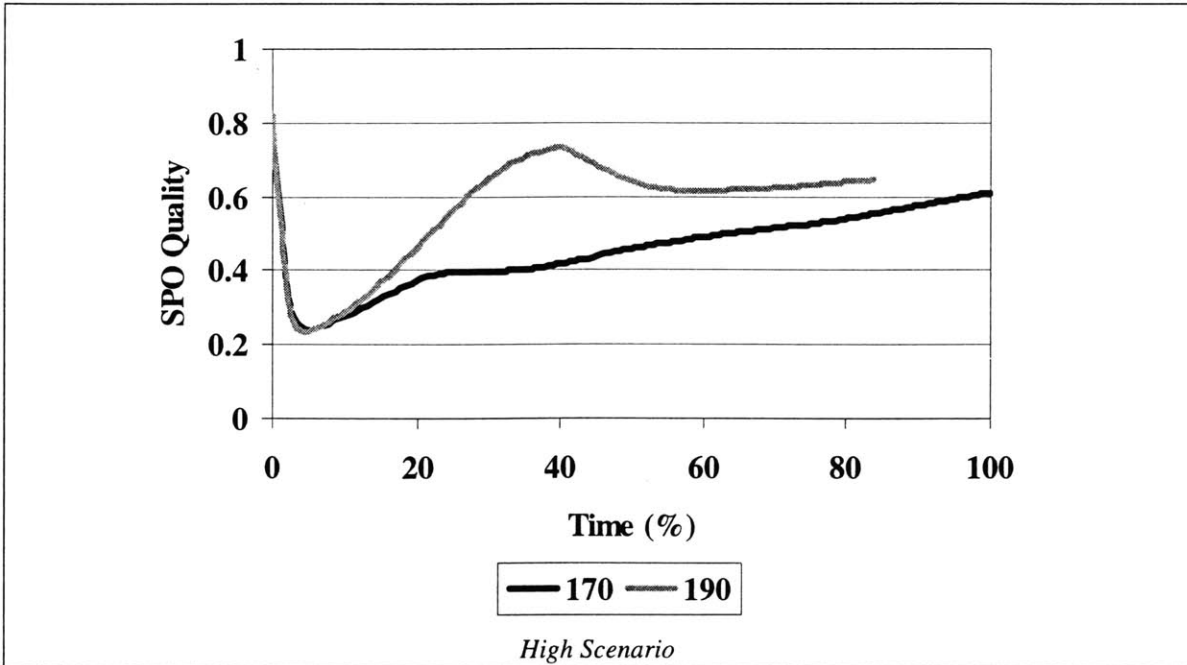


Figure 66: Mode Transformation Of SPO Quality With Increasing SPO Personnel Allocation

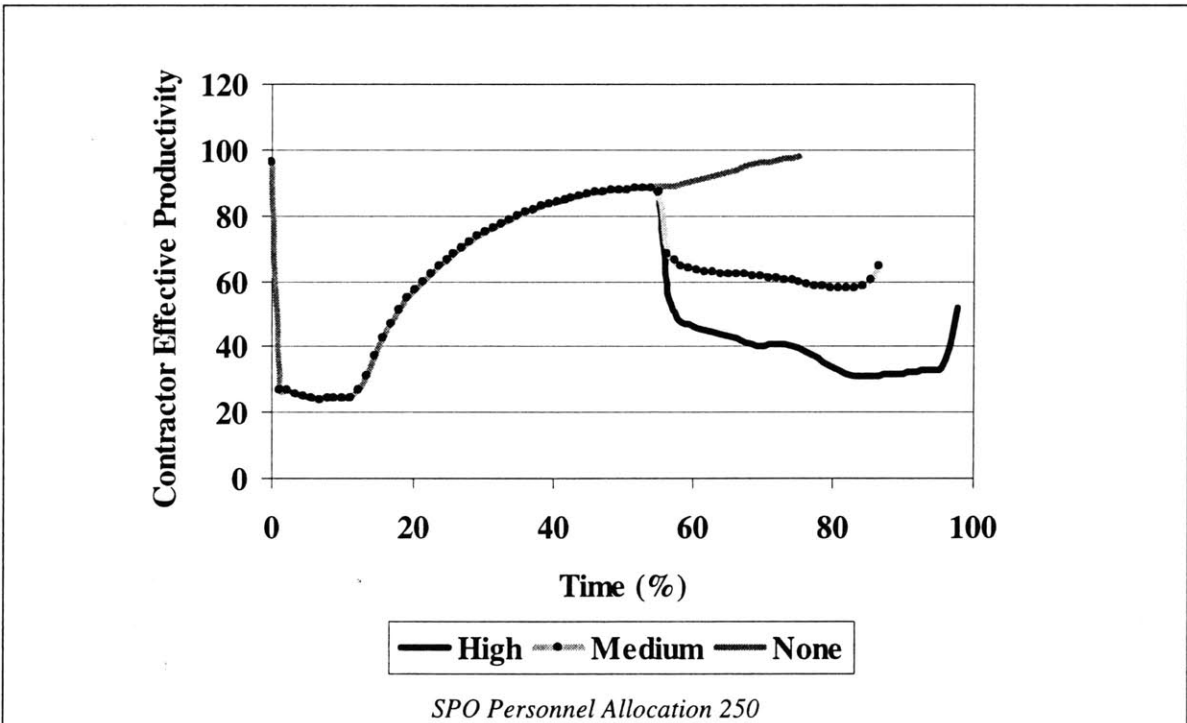
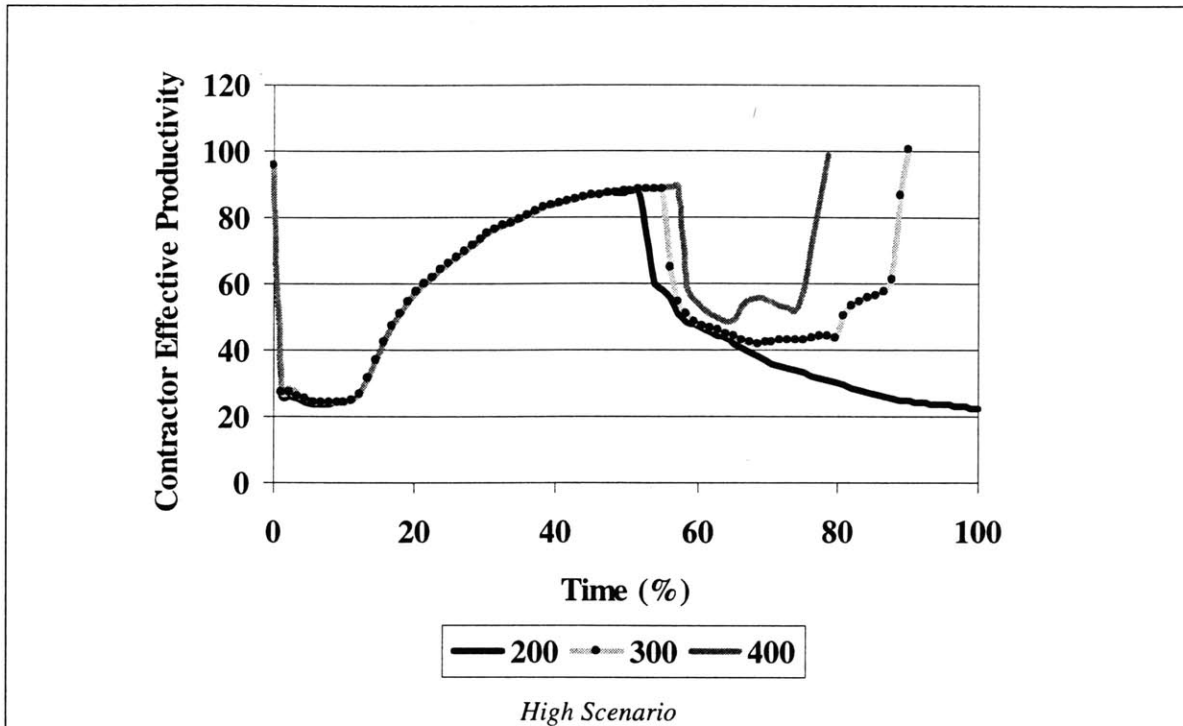


Figure 67: Effects On Contractor Effective Productivity Of Increasing Levels Of Contractor Dependence On SPO Inputs Near Project Completion



**Figure 68: Effect of SPO Personnel Allocation on Onset Of Hold-Up**

Once the SPO is allowed to attain reasonable size, so that the workforce is not suffering excess fatigue and schedule pressure, workforce dilution effects begin to dominate. Given the specific productivity of the SPO personal, progress is made and program tasks are completed. Naturally, a smaller workforce results in more calendar time for equivalent levels of progress and the SPO drifts further behind schedule – relative to that required by the contractor. The important factors here are how critical the SPO’s inputs are to the contractor’s work, increasing in Figure 67 as the scenarios move from *None* to *High*, and how soon the hold-up begins, which quickens as the SPO personnel allocation is reduced. *Ceteris paribus*, a smaller workforce results in the effects of holdup occurring sooner in the program, as shown in Figure 68.

Like a slight increase in drag, these effects reduce the contractor’s average effective productivity – increasing the number of days for which the contractor’s workforce must be paid. Certainly, the contractor can and does have the same effect on the SPO. In fact, it is likely that the contractor gets behind first, reducing the SPO’s productivity which then feeds back to the contractor in a vicious spiral. Again illustrating the importance the management practices discussed in previous sections designed to keep the contractor’s quality and productivity high – thus keeping it on schedule. However, because the magnitude of resources employed by the contractor is many times that of the SPO, the cost of an extra day of contractor activity far exceeds that of the SPO. It is this, which makes understaffing at the SPO so expensive – its leverage with the contractor’s resources. The more leverage the SPO has, the more imperative it becomes that high productive capacity is available at the SPO, ensuring that the contractor’s resources are utilized as effectively as possible. Of course, all the intuition developed in previous sections concerning mitigation of workforce dilution effects are as applicable for the SPO as they were for the contractor.

#### 4.2.4 The importance of a systems approach to managing the SPO-contractor system

In the previous section, the SPO's potential to dramatically increase the cost and time required to complete a program through insufficient personnel was demonstrated. However, there can be another cause of holdup within the SPO-contractor system. Not only can either party have made insufficient progress relative to schedule, but also the schedules they are working to may be incompatible. That is, even if both have made adequate progress relative to the agreed schedule, the schedules themselves may result in critical work not having been completed when optimal for its user.

Figure 69 shows several functional relationships between the contractor's perceived progress and the SPO progress required to support it. For example, using the *S Curve* scenario, if the SPO has completed 20 percent of its work, the contractor can have completed up to 30 percent of its portion of the project without experiencing any hold-up. Likewise, the SPO can complete 45 percent of its work if the contractor has churned through 20 percent of its tasks.

During the research for this study, both SPO and contractor representatives agreed that the SPO Progress curve was roughly S shaped and that the SPO can not finish before the contractor. However, there were divergent opinions about the Contractor Progress curve, both S and inverted S shapes were hypothesized – a linear configuration was added for comparison. Figure 70 presents the effects on contractor and SPO *Effective Productivity* under the three different scenarios. Notice that as mentioned in the previous section, the first to suffer hold-up related productivity reductions is the SPO, not the contractor.

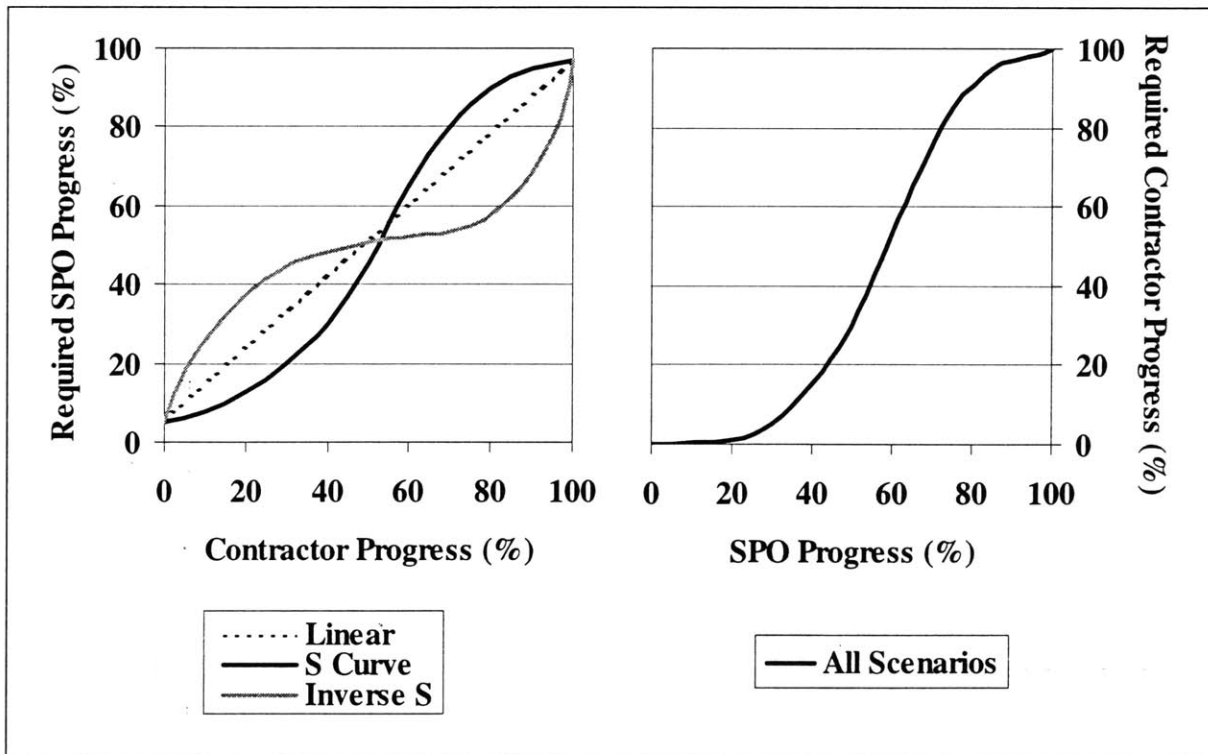


Figure 69: Functional Relationships Between Progress And The Progress Required To Support That Level of Progress

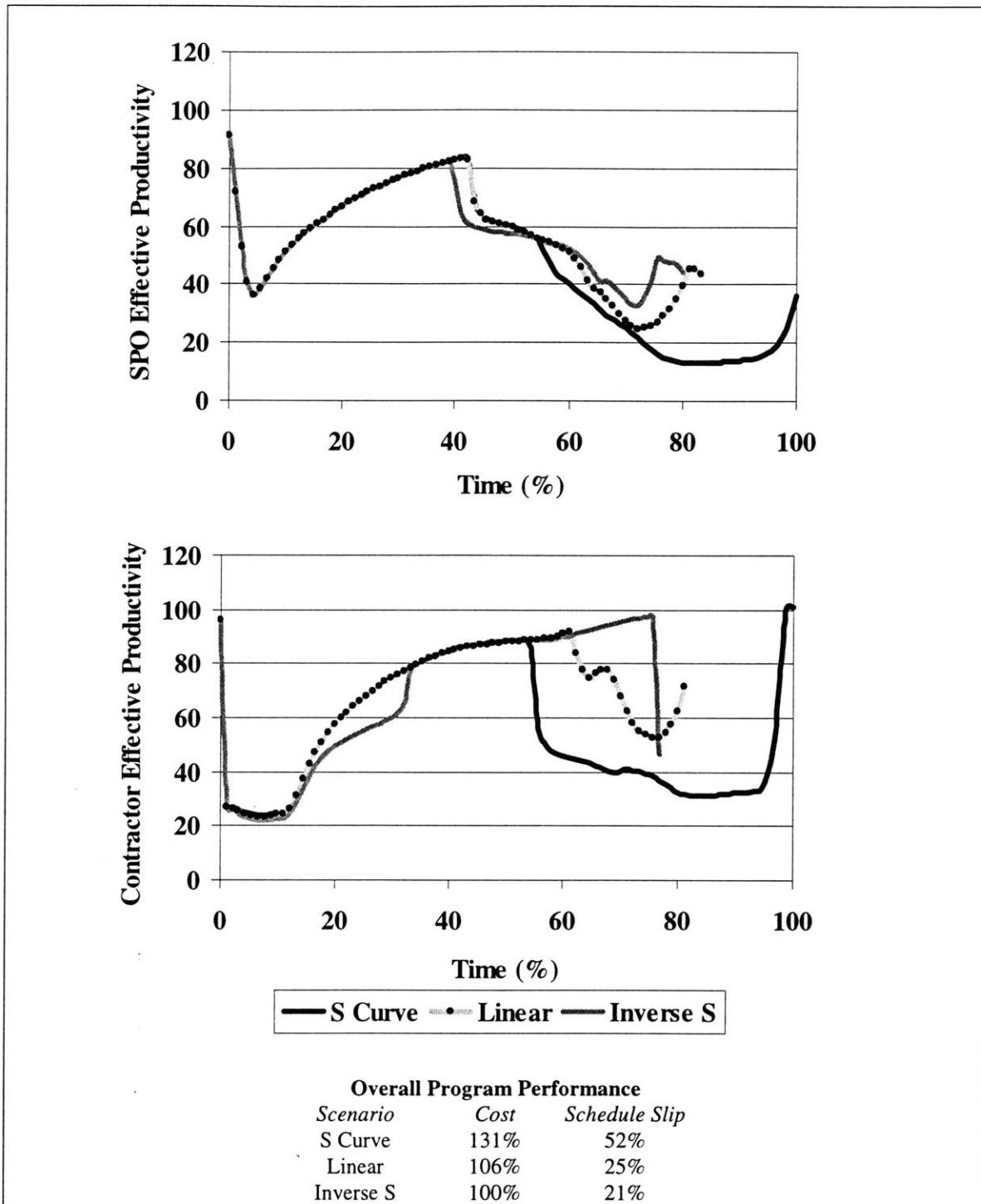


Figure 70: Effective Productivity Ramifications of Different SPO Required Progress Functions

Because the three scenarios differed only in the functional relationship between the amount of progress the contractor can make without being held-up for a given amount of SPO progress, Figure 70 clearly demonstrates that the phasing of deliverables between system participants can lead to increased program cost and schedule slip. Interestingly, the scenario with the best program performance, *Inverse S*, exhibits the earliest disruptions to productivity, but the least hold-up overall. In this case, the early disruption reduces the amount of work done early in the program while quality is low, reducing the total effort that must be expended to complete the project by lowering the total amount of rework generated. Again we see the tension between the value of having a large experienced workforce, capable of quality productivity at the end of a program, and the problems which reverberate throughout the program generated by the low quality productivity that occurs while the workforce traverses the learning curve, early in the program. Here, what is important is when and how the productive capacity is applied.

These simulations suggest that modest amounts of hold-up, early in the program, are not detrimental to a program's overall performance. However, hold-up near the end of a project only increases cost and schedule slip. Thus during the second half of a program, schedule coordination and adherence are far more critical than during initial program startup. This is clearly a complex issue which obviously deserves study in much greater detail. Nevertheless, even this cursory treatment points to the importance of a unified, systems approach to the development process. The requirements and deliverables the contractor and SPO will exchange should be as unified, delineated and coordinated as the aircraft design itself. Indicative that a systems approach would be beneficial is the extent to which differences of opinion exist between the SPO and contractor about their required progress for a given level of the other's progress.

#### 4.2.5 Funding profiles

In the previous section, the deleterious consequences of SPO understaffing were demonstrated – in the context of a constant SPO personnel authorization. To complete the analysis of the SPO-contractor system, the effect of declining SPO personnel authorizations in conjunction with different profiles for funding available to the contractor are investigated.

Figure 71 gives the two SPO personnel profiles used in the initial scenarios. SPO personnel numbers are cut to achieve a 50 percent linear reduction over 120 months. This equates to a 25 percent reduction over the course of the target completion period for the projects simulated. Figure 72 presents the profiles of funds made available to the contractor.<sup>94</sup> In all scenarios, the aggregate funding is equivalent – only the timing of the cash flows changes. The *Sine* scenario uses a sinusoidal cash flow distribution, while the *Flat* scenario provides the contractor with a constant supply over the project funding period.<sup>95</sup> *Trap*, is similar to the *Flat* scenario except that the cash flows ramp up and down over the first and last 25 percent of the funding period. Again similar to the *Flat* scenario, *Sloped* starts with a constant cash flow that begins to decay after 50 percent of the funding period has expired. Figure 73 and Figure 74 compare contractor workforce time series under these different scenarios.

Looking first at the *Sine* workforce time series in Figure 73, it exhibits slower ramp-up in personnel but the highest peak workforce of the scenarios investigated. In this case, improved initial quality is squandered by mid and late project hiring, driven by attempts to stay on schedule – facilitated by the high mid project cash flow. The result: sufficient rework is created such that available funds are exhausted before project completion. That this also transpired when SPO personnel were reduced, is not surprising and Table 1 confirms the increased expense in the earlier termination date – less schedule slip. Thus, the numbers in the table for both *Sine* scenarios are results at program termination rather than at completion, as they are for the other scenarios. Useful predominately to suggest that poor distribution of otherwise sufficient funds could lead to the termination of viable projects. The other scenarios hint what might constitute a better funding distribution.

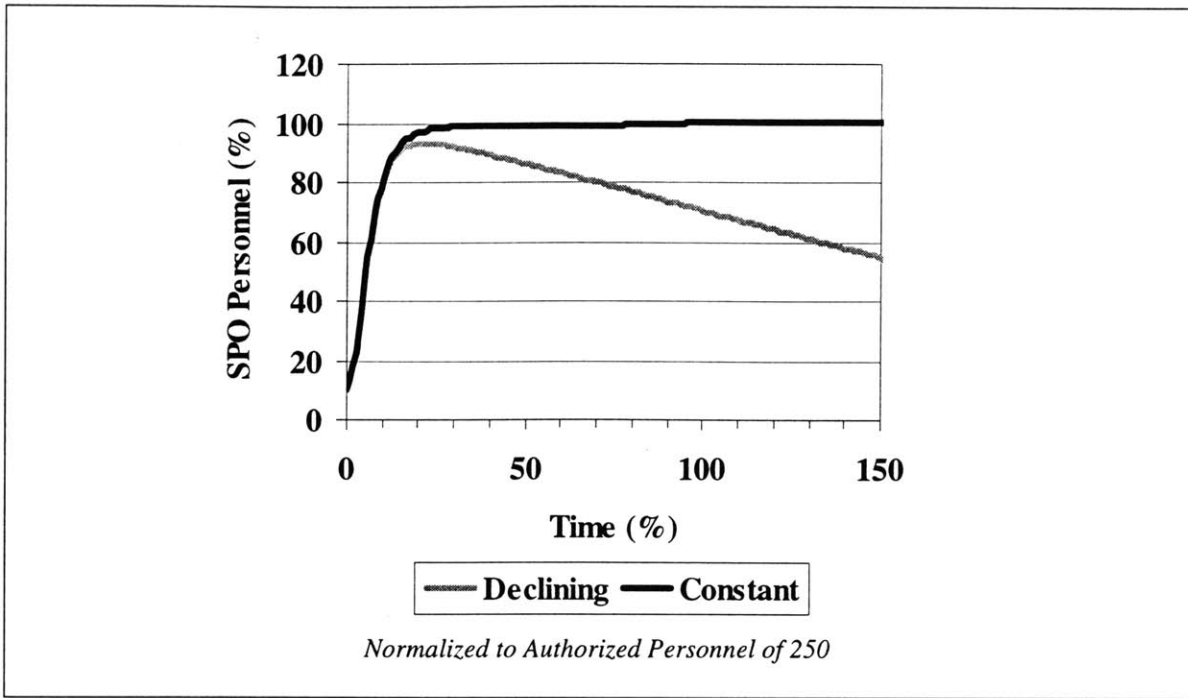
**Table 1: Comparison of Program Cost and Schedule Performance**

<i>Funding Scenario</i>	<i>SPO Personnel Authorization</i>			
	<i>Constant</i>		<i>Declining</i>	
	<i>Cost</i>	<i>Schedule Slip</i>	<i>Cost</i>	<i>Schedule Slip</i>
<i>Sine</i> <sup>96</sup>	105%	116%	105%	109%
<i>Flat</i>	100%	26%	101%	35%
<i>Sloped</i>	96%	35%	97%	45%
<i>Trap</i>	94%	33%	94%	43%

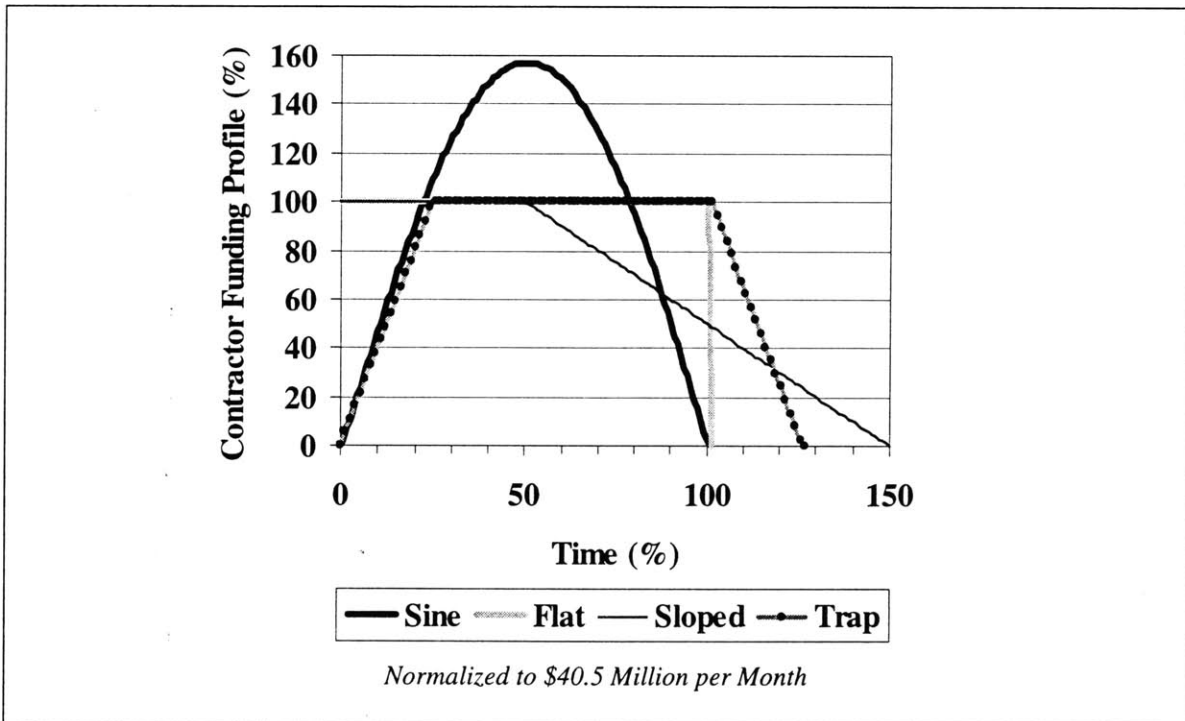
<sup>94</sup> This is not necessarily the rate at which the contractor will utilize the funds, but the rate at which they are made available. Building management reserves, staff-up, and perceived need can result in a divergence of utilization and availability rates.

<sup>95</sup> The project funding period is the time interval over which external sources are willing to supply funds for the project. For example in the *Flat* scenario, the project funding period extended 14 months past the desired program completion date of 60 months.

<sup>96</sup> The cost and schedule slip figures for the *Sine* scenarios are the values at project termination not completion. In both, available funds were exhausted before the projects could be brought to completion. The other table values are at project completion.



**Figure 71: SPO Personnel Profiles**



**Figure 72: Profiles of Funding Made Available to the Contractor**

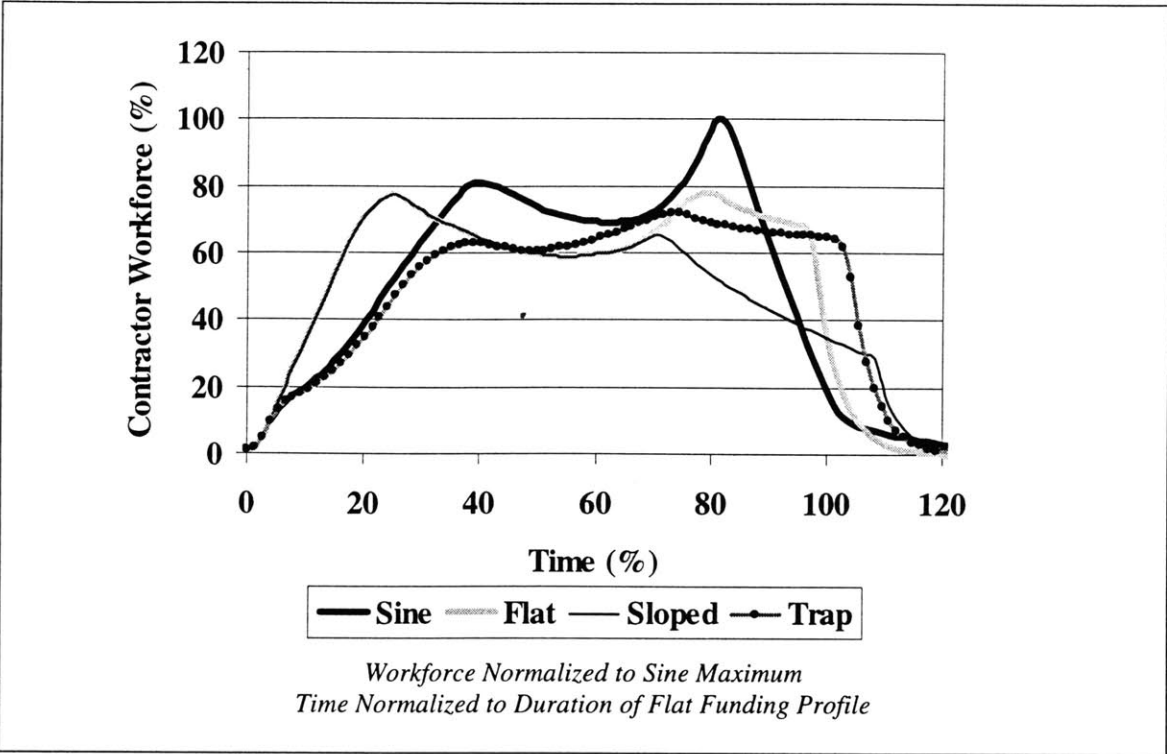


Figure 73: Contractor Workforce Time Series With Constant SPO Personnel Authorization

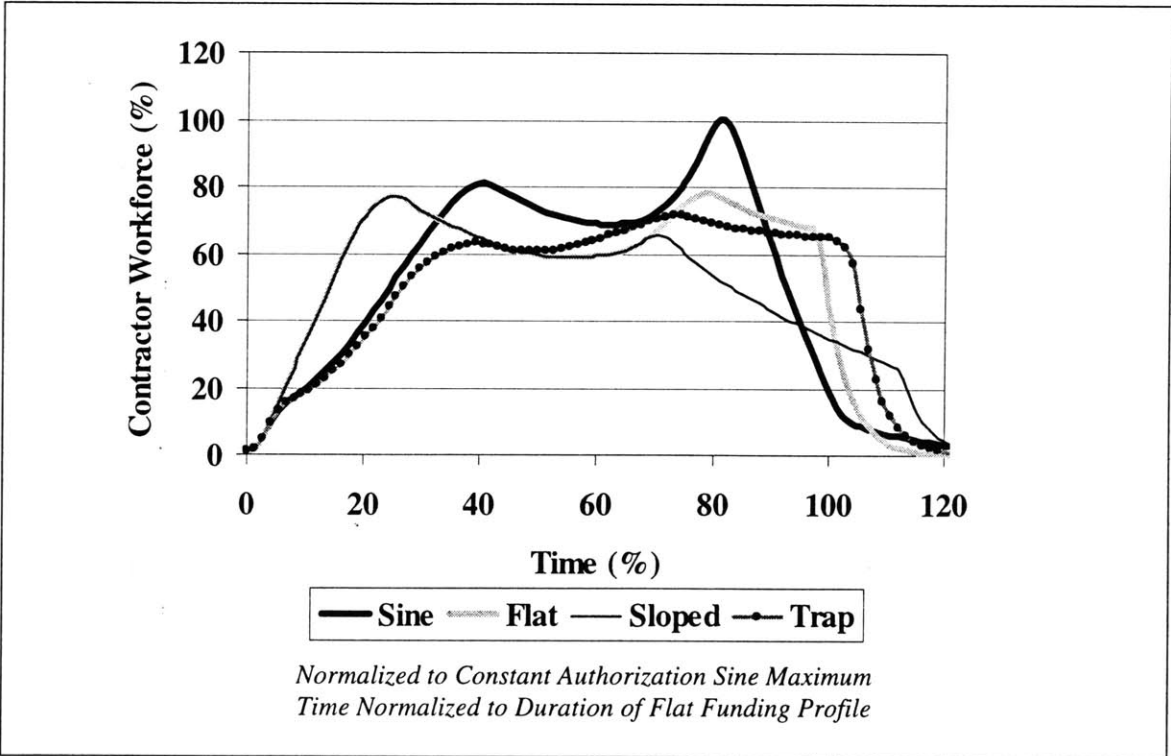


Figure 74: Contractor Workforce Time Series With Declining SPO Personnel Authorization



Inspection of Table 1 shows a trade exists between schedule slip and cost. While the *Flat* funding profile produces the least slip, it is also the most expensive of the projects that reached completion. Clearly, it allows the contractor to ramp up quickly, causing the precipitous drop in quality and productivity associated with workforce dilution. However, the flat profile mitigates late program staff-up, thus the dip in quality and productivity that typically results. It also helps to reduce overtime-induced fatigue effects. Schedule pressure is still a factor, though less important because the skilled workforce does not get as far behind. The result is higher cost, but with less schedule slip.

Comparing the *Flat* and *Sloped* workforce time series in Figure 73 the workforce reduction caused by available funds decline is clear, as is the increase in the time required to achieve completion. Obviously late project quality and gross productivity are higher for the *Sloped* scenario because there is no hiring to dilute the workforce. Likewise, there is little money for overtime, restraining fatigue. Naturally, schedule pressure mounts as the schedule slips. Notwithstanding, the net effect is to reduce the total effort required to complete the project over a longer period.

Table 1 suggests that the funding profile resulting in the lowest cost is trapezoidal. The scenario benefits from a lower staff-up rate enforced by the funding ramp, which keeps initial quality higher. In contrast to the *Sine* run, this initial quality improvement is not squandered by late program hiring. Not coincidentally, schedule slip is lower than in the *Sloped* scenario because the workforce is not subject to funding driven contractions – the project completes just as available funding begins to taper off.

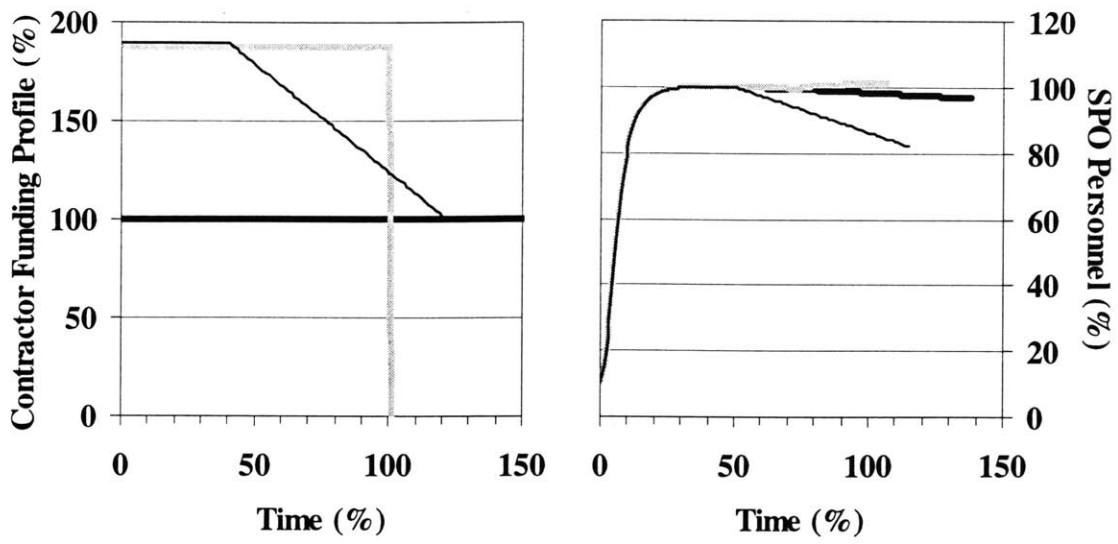
Finally, comparing Figure 73 and Figure 74, the program slip resulting from drawing down the SPO workforce is visibly manifest in the *Sloped* and *Trap* scenarios. The other programs are affected, but dwindling funding obscures the effect. As expected in light of Section 4.2.3, reductions in SPO productive capacity increase both cost and schedule slip. Cost less so in these scenarios because the contractor's operating cost per day is being reduced by funding driven layoffs. This is particularly true for the *Sloped* scenarios. Another important reason is that: even after the contractor has finished its part of the project, there is still work to be done by the SPO, which takes longer with fewer workers. This increases the schedule slip, but has minimal impact on total cost because the SPO's daily costs<sup>97</sup> are such a small fraction of the total program cost. Consequently, we see again that the savings accrued through reducing the size of the SPO are erased by costs incurred by the SPO-contractor system.

In the previous scenarios, the available funding level was sufficient for the programs to finish with moderate schedule slip. It is instructive to test what happens if the contractor is given a flat funding profile that provides, in aggregate, the initial cost estimate delivered over the desired completion interval – essentially what the contractor requested. The *Plan* scenario, in the following figures, is this case with the exception that the profile is extended until program completion is achieved. For comparison, the *Schedule* scenario has sufficient funds to finish with moderate schedule slip and *Reduction* transitions between the two. Figure 75 and Figure 76 present the simulation results from these three scenarios.

Figure 76 exhibits some interesting features driven by funding availability. Comparing contractor quality for the *Plan* and *Schedule* scenarios, as expected, increasing the number of workers hired tends to depress initial quality. However as the desired completion date looms and passes, schedule pressure related quality problems arise and are a major factor in the reduced late project quality of the *Plan* run. Interestingly the *Reduction* quality curve, which mirrors *Schedule*'s through mid project, begins to improve with workforce layoffs. The absence of new hires, even to cover attrition, allows the average experience of the workforce to grow.

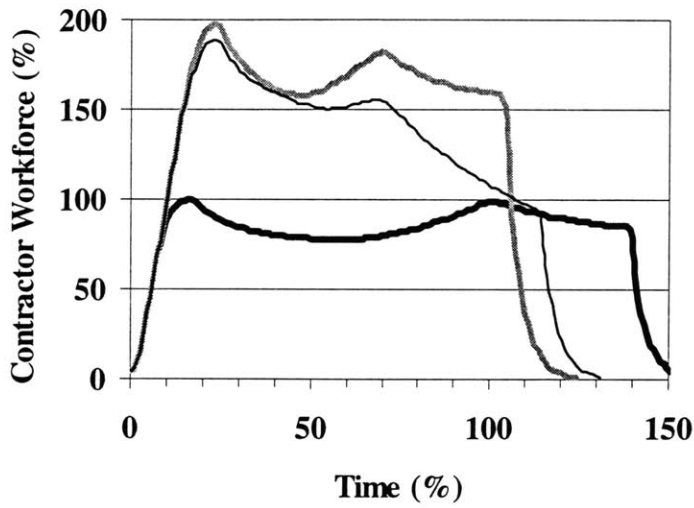
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<sup>97</sup> This includes operational funds as well as pay for both civilian and military personnel.



Normalized to \$17.9 Million per Month

Normalized Personnel Authorization of 250



— Plan — Schedule — Reduction

Workforce Normalized to Plan Scenario Maximum

Scenario	Cost	Schedule Slip
Plan	100%	72%
Schedule	137%	33%
Reduction	130%	43%

Figure 75: Program Effects of Variations in Available Funding Profile Levels

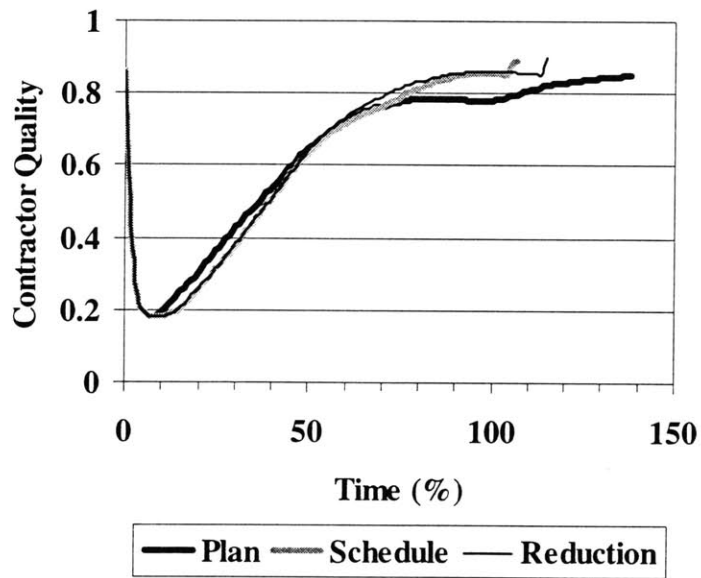
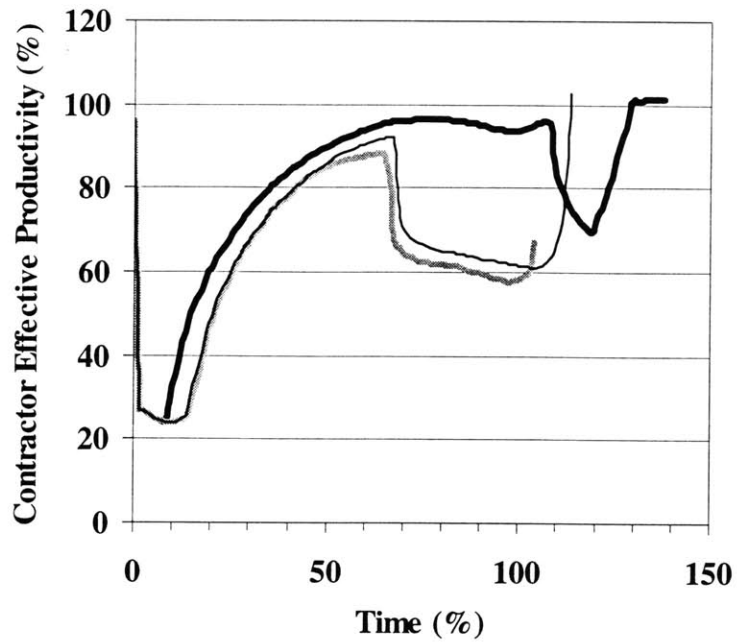


Figure 76: Contractor Quality and Effective Productivity

Contractor effective productivity behaves as expected. The *Schedule* and *Reduction* runs exhibits the effects of increased hiring early in the project and increased schedule pressure gives a subtle late project boost to all runs. Of course, holdup effects dominate the terminal phase. There is a curious trend however with reduced contractor workforce seeming to lower the SPO's holdup of the contractor, especially for the *Plan* scenario. Even in the *Reduction* run, where SPO personnel was drawn down, holdup effects were less. What is important is the relative progress between the SPO and contractor. Slowing the rate of contractor progress, either by cutting available funds or providing constant funds at a reduce level, effectively lowers the progress rate required of the SPO for it to stay in phase with the contractor. Thus in this case, slowing the contractor's progress provides a program benefit by reducing contractor holdup. Of course, SPO holdup by the contractor is increased.

In Figure 75, clearly, the most striking result is the *Plan* scenario schedule slip relative to its cost and the cost of the other two cases.<sup>98</sup> In Section 4.2.2 the need to include quality and real productivity in initial cost estimates was posited. Here the program implications of not doing so are obvious – extensive schedule and cost overruns of 72 percent and 68 percent respectively, based upon initial estimates. There are actually two interrelated issues here. In as much as the available funding profile is based upon the initial cost estimate, as in the *Plan* scenario, schedule slip increases in proportion to the difference between the real cost and the initial estimate. Simply not enough funds are available to maintain the productive capability required for completing projects on schedule. The additional effort that was not accounted for pushes up the time required to finish, if the resources are held constant, the schedule must slide. To hold the resources constant requires additional funding and thus the second issue is the accuracy of the initial estimates – discussed in Section 4.2.2. Obviously, if the initial cost estimates are below that economically possible given the real effort required, cost overruns will be high.

It is important to recognize that the results of this section are a function of the underlying structure of the SPO-contractor system. The availability of funds, as modeled, is predominately an exogenous forcing function to which the system responds. It must be suspected that if the magnitude of system variables were changed, for example increasing the level of new employee experience or shortening the time to traverse the learning curves, cost and schedule slip magnitudes would change – the cost and schedule differential between *Plan* and *Schedule* scenarios would be compressed.

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<sup>98</sup> These numbers are in real dollars. If inflation were included, the differential would be decreased, making the long running *Plan* scenario less attractive.

## 5 CONCLUSIONS AND RECOMMENDATIONS

This study has examined the interactions between the SPO and the prime contractor for a major aircraft acquisition program, in particular how management decisions effect program cost and cycle time. Through the study, based upon system dynamics modeling of the SPO-contractor system, insight has been gained into the program behaviors generated by program coordination structures, human resource management policies, and initial estimates of project cost and size. It has shown that effective use of management reserves and staffing policies, as well as attention to process quality can result in significant cost and schedule performance improvements. It has also confirmed the high degree of interdependence inherent in the SPO-contractor system and has demonstrated the requirement for a systems approach to managing that system.

There were several basic project management insights that underlay many of behaviors exhibited by the SPO-contractor system. They were:

Rework is an intrinsic part of development projects. One of the most important insights of the program model is that a significant fraction of the effort expended on any project, is spent redoing work previously thought to have been completed. Frequently, the rework is not discovered immediately, but remains hidden for some period, often a significant fraction of the time allotted for the project, and requires additional work to reveal its existence. Naturally, to the extent that rework is unaccounted for in cost and schedule estimates, it becomes a major source of cost and schedule overruns. The total effort required to complete a project was shown to be the quotient of a project's scope and average quality.

Quality drives rework. The cause of rework generation is producing work with less than perfect quality. Understandably, quality is not constant over the course of a project; capped by the intrinsic quality of the processes utilized, it is influenced by factors such as workforce skill and fatigue, schedule pressure, as well as the quality of process inputs, all of which change during a program. In the SPO-contractor system, one of those process inputs is the work of the counterpart, in this way the quality of work done by the SPO directly influences that done by the contractor and *vice versa*. Another significant influence comes from the quality of previous work upon which current work is based. Clearly, the complexity of the product and the design architecture determine the extent to which errors cascade through the design over time. This manifold interconnectivity – means that any actions which effect quality must be considered in a system wide context. It also is the underlying reason that continuously striving to improve both the intrinsic quality of process and the capability of the workforce utilizing those processes.

Workforce capability is a prime contributor to project quality and productivity, which if mismanaged, can be a significant source of cost and cycle time growth. Any influx of new workers presents the possibility of diluting the workforce capability and therefore depressing quality and productivity. If they are less familiar with the tools and processes employed on the project than the existing workforce, they dilute quality and productivity in proportion to their numbers. The magnitude and duration of the workforce dilution effect is determined by the shape of the process learning curves and the time required to traverse them – the longer it takes to master a process, the longer quality will remain depressed. The management task over the course of a project is to grow and maintain a workforce which at all times, has acceptable levels of quality and productivity. The value of a highly skilled hiring/transfer pool from which to draw workers and quality processes that are quick to master is clear, as is the value of maintaining consistent processes across related business lines. Naturally, the periods during which workforce dilution can be the most serious are during program ramp-up, hiring binges in response to looming deadlines, and episodes of high turnover. Finally, this behavioral mode suggests

that the cyclical hiring patterns of many aerospace contractors could be the cause of a significant fraction of cost and schedule problems.

Proper management of the workforce is critical for its optimal performance. In addition to workforce dilution, the misuse of overtime and application of undue pressure to achieve deadlines can dramatically reduce workforce quality and productivity. Overtime must be used with care. Studies by others indicate that, under normal conditions of rest, working more than 50 hours per week affords no additional real productivity and that when exhausted, from enduring extended periods of overtime, real productivity can decline by as much as 50 percent.<sup>99</sup> Overtime induced fatigue has two principle effects; it reduces quality – tired workers make more mistakes – and it reduces gross productivity – tired workers can not work as fast. These two effects, can easily eliminate any benefit derived from the additional hours spend on the job, or worse, can actually result in less progress being made than had overtime not been used at all. Overtime should be used sparingly in short bursts, but not to compensate for organic deficiencies of workforce or processes. Analogously, pushing the workforce too hard, even without resorting to overtime, to meet a schedule deadline for example, despite the increment to productivity, it also reduces quality – rushed workers make more mistakes – and increases the time required to find those mistakes – in the rush things get missed. Of course, more productivity at lower quality increases the volume of rework and thus effort required, which translates into higher cost and more time required to complete the project. Again, just opposite the intended effect. Pushing the workers to perform above their natural capacity is a sure means to lower performance. When it becomes clear that the schedule can not be achieved, slipping the schedule is likely to be the most cost-effective solution.

With the added insight these mechanisms provide into the behavior of large development programs, analysis of specific SPO-contractor system phenomena, particularly their cost and schedule implications is possible. Clearly, this is a preliminary work and additional study would be required before significant policy changes could be implemented based upon these finding. That notwithstanding, the results of this investigation imply:

**System feedback.** The contractor and SPO are interconnected; they do not operate in isolation but as a complex system. Quality, productivity, and rework discovery effects feed back and forth between the system participants. For example, a drop in contractor quality reduces quality at the SPO, which further depresses quality at the contractor which.... This interconnectivity means that locally optimum solutions may not be optimum for the system at large. Consequently, the system wide ramifications of management actions and process modifications, by either contractor or SPO, must be investigated to ensure that unintended consequences do not negate the intended benefits.

**Project compression.** The intuition that half the work in half the time will cost half as much is misleading. Under such a scenario, although the project scope has been reduced, because the time to complete the project has shrunk as well, the workforce required remains the same. In both cases, the startup periods will be identical in terms of duration and workforce quality and productivity. Because more of the smaller project is completed while quality is low, its costs will be proportionally higher than the larger project because of the additional rework which is generated. A better intuition is that a steeper learning curve reduces costs. For a given learning curve, if the project is long enough to allow a reasonable fraction of the work to be done after the workforce has begun to recover from the skill dilution effect, costs will tend to decrease with increasing scope. Potentially, the most expensive proposition is to draw down the workforce after an initial hiring binge and then immediately begin to add workers in the face of unexpected rework under pressure to meet the completion date.

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<sup>99</sup> See Footnote 65, or Section 8.2 in the Appendix.

Schedule compression. If project scope is held constant and the desired completion interval is increased: real dollar costs decline, to the extent that fixed costs are not a significant fraction of variable costs and schedule slip declines. The underlying causal mechanisms are the same as those above – a more experienced workforce reduces costs and schedule slip. For a given experience profile or learning curve, costs will tend to decrease with increasing completion interval because a higher fraction of the work is done after the workforce has begun to recover from the effects of skill dilution.

Schedule focus. The combined insights from schedule compression, project compression, and the cost and schedule slip implications of schedule pressure, intimate that making schedule adherence the prime focus of a program will ultimately increase its cost above that which could be obtained with a more systemic approach. Almost any action taken to force a program back on schedule will have negative implications for program cost.

High workforce turnover. During periods of high workforce turnover, a large fraction of the workers who have specific project experience are replaced by workers who have none. The result is workforce dilution with all the attendant cost and schedule implications. Regardless of how well the workforce growth policy has been managed, a massive, mid-project disruption of the workforce increases both cost and schedule slip. Labor contracts and other human resource management policies should be designed to maximize the stability of the workforce over the life of a program – and beyond.

Low military tenure. If military tenure is insufficient, the SPO's workforce will never achieve its potential quality or productivity. For example, if the average tenure of military personnel is two years, but an average of five years experience is required to achieve full potential, their quality and productivity are effectively depressed far below potential. Because they represent a significant fraction of the SPO workforce, low tenure is effectively a continuous dilution of SPO workforce capability. It is as if the quality and productivity potential of SPO processes were incrementally reduced. What makes this particularly pernicious is the feedback of these effects to the contractor, depressing quality and productivity throughout the system. The net result is increased cost and schedule slip. Naturally, the magnitude of the increase depends upon the shape and duration of the learning curve as well as the relationships governing the SPO's impact on the contractor's quality. Clearly the more dependent the contractor is on the SPO for critical information, the more expensive reduced SPO quality and hence low tenure will be. If other system requirements preclude an increase in military tenure, modifications should be made to SPO/Air Force processes to compress the learning curve, to allow full potential be achieved during the available project tenure.

Management reserve. For low levels of management reserve, the net program effect is negligible to slightly positive. As the reserve fraction increases, cost savings plateau and schedule slip begins to increase. However, the delayed onset of increased slip suggests a cost advantage may be obtained through a limited use of management reserve. The value of management reserve comes from slowing the initial workforce hiring surge, which reduces the dilution effects on quality and productivity. Of course, restricting hiring too much can be counter productive, resulting in excessive schedule slip – insufficient human productive capacity causes work to be pushed into the future. However, bringing more experienced workers onto the program or using processes which have a steeper learning curve provide a more direct mechanism that creates even greater cost saving. Finally, because this investigation has not included any morale or gaming effects that the use of management reserve might elicit – which could eliminate all gains from its use – this area requires additional study.

Initial cost and schedule estimates. Unrealistic initial estimates exacerbate cost and schedule overruns through the misrepresentation of a program's potential performance. Because government regulations do not allow estimates of quality to be factored into the initial cost calculations – in effect ignoring the additional effort due to quality induced rework – those estimates are hopelessly inadequate. Likewise, if an unrealistically optimistic productivity figure is used in cost derivations, additional error is introduced. By not accounting for these two, the resultant cost estimate error can be shown proportional to the inverse product of the average program quality and the ratio of achieved to expected average productivity minus one.

$$E_c \propto \left( \frac{1}{\rho q} - 1 \right)$$

Obviously, it is necessary to include estimates of average quality and average gross productivity in initial cost estimates to improve their predictive power. The equation also quantifies the cost of low quality and productivity, insinuating the necessity of improving both. Consequently, while always striving for high quality and productivity, program management must fully acknowledge the cost consequences of a program's real quality and productivity when estimates are made.

Holdup. Any time either the contractor or SPO suffers reduced productivity because they are waiting on the other for process inputs, costs and schedule risk increases. This can arise not because there is insufficient workers, but because the deliverables between system participants are not properly phased. During research for this study, a difference of opinion between SPO and contractor representative about the relative levels of SPO progress required relative to the contractor's progress was discovered. While this could be an isolated incident, it nevertheless, points to the importance of a unified, systems approach to the development process. The requirements and deliverables the contractor and SPO will exchange should be as unified, delineated and coordinated as the aircraft design itself.

SPO workforce size. An undersized SPO is very expensive if it results in contractor holdup. For almost any level of contractor dependence on the SPO, the marginal savings in program cost and schedule are greater than the marginal cost for SPO personnel – every dollar saved by reducing the number of SPO personnel increases the total cost of the program by more than that dollar. Consequently, it is imperative to define clearly the scope of the SPO's participation in an aircraft development program and then fund sufficient staff to ensure its tasks are completed as required to keep the contractor progressing without holdup. This implies that the actual effort required, including rework, should be used to determine the SPO's manpower requirements, rather than an arbitrary allocation, as is now the case.

Contractor funding profiles. The shape of the available funds profile can contribute to a program's demise. A sinusoidal funding profile was found to be the least efficient of those tested, while the lowest total cost was found with a profile trapezoidal in shape. It benefits from a lower staff-up rate enforced by the funding ramp, which keeps initial quality higher. And, this initial quality improvement is not squandered by late program hiring as in the sinusoidal case. Finally as expected, funding profiles which are based upon poor initial estimates, are quickly overrun and contribute to schedule slip due to insufficient funds – despite high quality, there is insufficient productive capability.



Table 2, beginning on the page 106, has been developed to provide an easy reference for the interactions resulting from important system variables and functions. To reduce duplication, variables which appear in both SPO and contractor models are entered as designated in the contractor model.

Finally a comment about using the system dynamics for analysis of complex systems. It is clearly a powerful tool. By making explicit, the structural assumptions and causal relationships of system participants, those participants intuition about the system's behavior can be enhanced – the first step toward improving the performance of that system. However, it can be a difficult tool to master and no model can be better than the information used to construct it. For this reason, it is absolutely necessary that, at every stage of the model development process, system experts are engaged. In addition, it is extremely beneficial if the model builder is also intimate with the system. Obviously, developing a simulation model parallels an aircraft development program in that the learning curve must be traversed, rework will be present, and productivity reductions due to holdup by information suppliers are a real possibility. Thus, the more experienced an organization becomes in the use of system dynamics, the more satisfactory the results will become – the quality of information derived will increase, while both development effort and time will decline. There is no substitute for experience, skill, and hard work.

**Table 2: Important System Variables and Their Impact on the SPO-Contractor System**

System Variable	System Implications
Quality	<p>Controls the creation of rework.</p> <p>An increase in quality reduces the generation of rework which:                      Reduces the total effort that must be expended to complete a project. Reducing total effort improves program performance by:</p> <ul style="list-style-type: none"> <li>- Lowering cost because either fewer workers are needed or a given workforce is not needed as long.</li> <li>- Reducing schedule slip because given a particular workforce and its productivity, the less effort which must be expended, the less time the project will require to complete.</li> </ul>
Rework Discovery Time	<p>Controls the buildup of undiscovered rework.</p> <p>A decreasing the time to discover rework reduces the buildup of undiscovered rework which:                      Tends to reduce schedule slip because the slower than expected progress rate is detected earlier.                      Tends to improve quality because rework is discovered sooner and so less work is done based upon the original error thus less rework is created. This also helps to lower program cost.</p> <p>However, in the early stages of a program, when the design is in flux, obsolescence can flush rework from the system and thus effort is saved by not fixing errors in designs that will be abandoned. Nevertheless, because early errors in the final design have tremendous cost, quality, and schedule leverage over the rest of the program, it is important to discover those errors early.</p>
Schedule Pressure	<p>Controls the workforce's response to pressure to meet the scheduled completion date</p> <p>As the difference between the scheduled completion date and date at which, with the current workforce, the project could be finished increases, schedule pressure increases. An increase in schedule pressure:</p> <ul style="list-style-type: none"> <li>Increases the gross workforce productivity because the workers work faster to meet the deadline.</li> <li>Decreases quality because workers make more mistakes when working faster than normal.</li> <li>Increases time to discover rework because in the rush to finish mistakes are missed.</li> <li>Tends to increase cost and schedule slip because the rework generated by the reduction in quality outweighs the increased rate of productivity. The product would also be delivered with more defects.</li> </ul>

**Table 2 Continued**

<b>System Variable</b>	<b>System Implications</b>
Fatigue	<p>Controls the workforce's response to periods of overtime.</p> <p>Fatigue accumulates as the number of weeks of overtime increases, and becomes more severe as overtime hours per week mount. Fatigue diminishes with time, after a return to normal hours. An increase in fatigue:</p> <p>Decreases quality because an exhausted sleepy workforce makes more mistakes.</p> <p>Decreases productivity because a tired workforce works slower.</p> <p>Tends to increase cost and schedule slip because of the additional rework generated by lower quality and compounding of additional time required to complete work because of decreased productivity.</p>
Process Potential Quality	<p>Determines the maximum quality possible for the project.</p> <p>An increase in process potential quality increases the level of quality that can be obtained by a workforce with a given level of experience, fatigue and schedule pressure.</p>
Effect of Past Quality on Present Quality	<p>Determines the extent to which existing errors propagate through the design over time.</p> <p>The complexity and architecture of the system being designed determine the shape of this function.</p>
Gross Productivity	<p>Controls the potential rate at which work could be done.</p> <p>An increase in gross productivity increases the potential rate at which work could be completed. Its value is increased by increases in workforce's productivity and schedule pressure. And, decreased by fatigue.</p>
Effective Productivity	<p>Controls the rate at which work is completed.</p> <p>An increase in effective productivity increases the rate at which work and rework are processed. Its value is increases by the workforce's Gross Productivity and decreased by holdup – the unavailability of required work inputs from a system partner.</p>
Effect of Experience on Workforce Skill	<p>Determines the relationship between a worker's experience and the quality of their work – the shape of the quality learning curve.</p> <p>The steeper the learning curve, the more quickly a worker's potential quality improves. A worker's location of the curve is determined by their experience level – the fraction of Average Time to Attain Normal Quality.</p>

**Table 2 Continued**

<b>System Variable</b>	<b>System Implications</b>
Effect of Experience on Workforce Productivity	<p>Determines the relationship between a worker's experience and their productivity– the shape of the productivity learning curve.</p> <p>The steeper the learning curve, the more quickly a worker's potential productivity increases. A worker's location of the curve is determined by their experience level – the fraction of the Average Time to Attain Normal Productivity.</p>
Average Time to Attain Normal Quality	<p>Determines the average time required for a novice to traverse the skill (quality) learning curve.</p> <p>The time constant that sets the length of time required to attain the normal level of quality. The longer the time constant, the longer a worker takes to develop full quality potential.</p>
Average Time to Attain Normal Productivity	<p>Determines the average time required for a novice to traverse the productivity learning curve.</p> <p>The time constant that sets the average length of time required to attain the normal level of productivity. The longer the time constant, the longer a worker takes to develop full productivity potential.</p>
Maximum Allowed Overtime	<p>Limits the maximum number of overtime hours a worker can work per week.</p> <p>If overtime is being used to supplement workforce productive capability, an increase in the maximum allowed overtime increases the overtime worked per worker, which increases the rate at which fatigue develops.</p>
Experience of New Workforce	<p>Determines the impact of hiring on average workforce experience</p> <p>If new workers enter the system with higher levels of experience, their skill and productivity are higher. This tends to reduce the dilutive impact on workforce quality and gross productivity of staff-up and other instances when large numbers of workers are added to a project.</p>
Effect of SPO Progress on Contractor Rework Discovery	<p>Controls the SPO's effect on the contractor's rework discovery time.</p> <p>As the SPO progresses, and errors are discovered, this information is transmitted back to the contractor. Near the end of the project, the nature of the work transitions such that the time required to discover errors is reduced. Of course, the contractor has the same effect on the SPO</p>

**Table 2 Continued**

<b>System Variable</b>	<b>System Implications</b>
Effect of SPO Quality on Contractor Quality	<p>Controls the SPO's effect on the contractor's quality</p> <p>The contractor relies on information and other inputs from the SPO. Errors in these inputs generate additional errors in the contractor's work and thus diminish contractor quality. As the complexity of the project and criticality of the information increases, the magnitude of the effect mounts. Naturally, the contractor has the same effect on SPO quality.</p>
Effect of SPO Progress on Contractor Gross Productivity	<p>Controls the SPO's effect on the contractor's productivity.</p> <p>The contractor relies on information and other inputs from the SPO. If these inputs are not available when required, the contractor's productivity is inhibited. As the criticality of the inputs increases, for example near the end of the project, the magnitude of the holdup potential grows. As expected, the contractor has the same effect on SPO productivity. The cost of holding up the contractor tends to be high because of the magnitude of resources employed.</p>
Required SPO Progress	<p>Determines the SPO's effect on the contractor's productivity through the phasing of SPO progress relative to that of the contractor.</p> <p>Given the succession of project tasks, the contractor will require SPO inputs at specific points in the project. This function captures the required level of progress the SPO must have achieved so that the contractor can proceed unimpeded. Of course, the contractor is subject to a similar schedule. The potential for holdup increases to the extent they lag their required progress.</p>
Initial Completion Date	<p>Determines the initial period allowed for project completion.</p> <p>The initial completion date is integral to the determination of the project's initial cost and workforce size. As the time remaining before the completion date shrinks, workforce size is re-evaluated, and the potential for schedule pressure grows. For a project of given scope, decreasing the initial completion date (reducing the time allowed for execution of the project) increases cost and schedule slip. Cost increases because the project startup period becomes a larger fraction of the total program period – more work is done at low quality. Schedule slip increases because more effort is required to complete a project when more work is done with lower quality.</p>
Intrinsic Project Size	<p>Determines the minimum effort required to complete the project.</p> <p>Intrinsic project size is the project's true scope if quality were perfect. Cost and workforce size are calculated based upon estimates of this parameter.</p>

## 6 FURTHER INVESTIGATIONS

The simulation model, as constructed, allows a high level investigation of SPO-contractor interaction. Based on a generic representation of the system, the results should have broad applicability across a range of projects. However, because all projects must have limits, some potentially important and interesting aspects of the system have not been explored. Continuations and extensions of this work would include:

**Holdup.** The phasing of deliverables between SPO and contractor was found to have profound cost and schedule implications if it cause the contractor's progress to be held-up. In addition, it was found that the SPO and contractor had different expectations of each other's required progress. The two make this an excellent topic for further study.

**Team work.** An important requirement for the coordination of SPO-contractor interactions, team work should be add to the simulation model. It is expected that teamwork would increase the project's scope, but at the same time reduce holdup, time to discover rework, and improve quality. Thus, it should have a net positive influence on cost and schedule performance.

**Government sector.** As currently modeled, government funding of the program was exogenous. A natural extension would be to expanding the government section to include program performance feedback for the determination of continued funding and other program decisions. This would provide insight into the lingering death of some programs, as well as give government decision makers insight to the ramifications of their management practices.

**Other system participants.** Because the SPO and contractor are not the only participants in the system, the model could be expand to include other first tier suppliers such as engine and avionics manufacturers. In addition, subcontractors and other supply chain members could be included. This would provide a richer depiction of the interaction between all members of the system and help to answer questions about supply chain management and program coordination.

**Management reserve.** A further investigation to determine the workforce response to the imposition of management reserves. It is suspected that a consistent pattern of being asked to complete a project for 90 percent of the estimated budget would induce gaming of the system and foster adversarial relationships which would decrease cooperation and ultimately quality and productivity.

**Technology obsolescence.** Including technology obsolescence in the rework cycle would allow the investigation of policies to mitigate its effect on program cost and schedule.

**Quality on quality relationships.** Because the model was quite sensitive to the shape of the quality on quality relationships, further study of the functions subtitles is warranted. This would include resolving what factors determine the function and how the function change over the life of a project and could lead to improved system architecture.

**Learning curves.** Program performance was determined in large part by the shape and duration of the various learning curves. Investigations should be undertake to determine what factors control the shape of these functions, how they differ across organizations, and how they could be contoured to reduce costs.

**Inflation.** Adding inflation to the model would provide visibility of nominal cost growth.

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## **8 APPENDIX**

### **8.1 Acquisition Community Organization Chart**

The organizational chart presented on the next page was developed from information published on the world wide web by various acquisition community members. Clearly, the extent of each member's involvement in the acquisition system varies greatly. The goal was to capture the breadth and depth of the community on a single chart and to suggest the potential diversity of objectives and concerns of the various participants.

Chart is consistent with web published organizational charts as of May 1997  
 Compiled by Sean Morgan

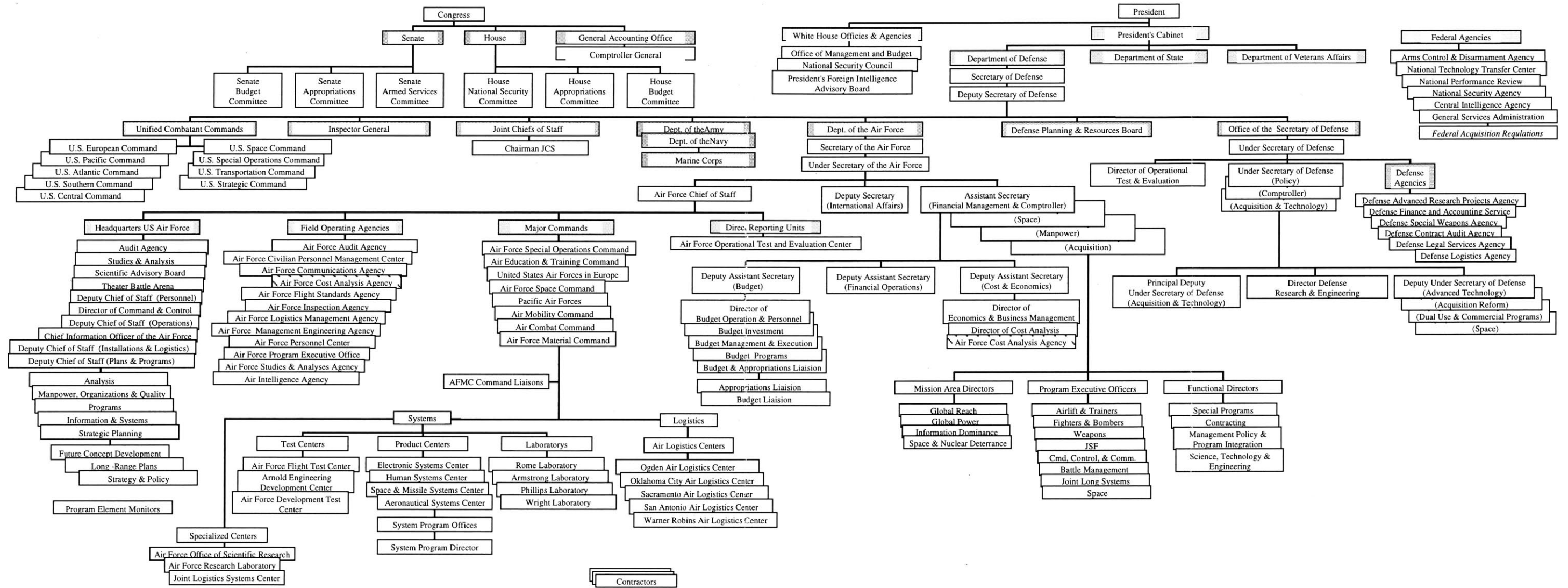
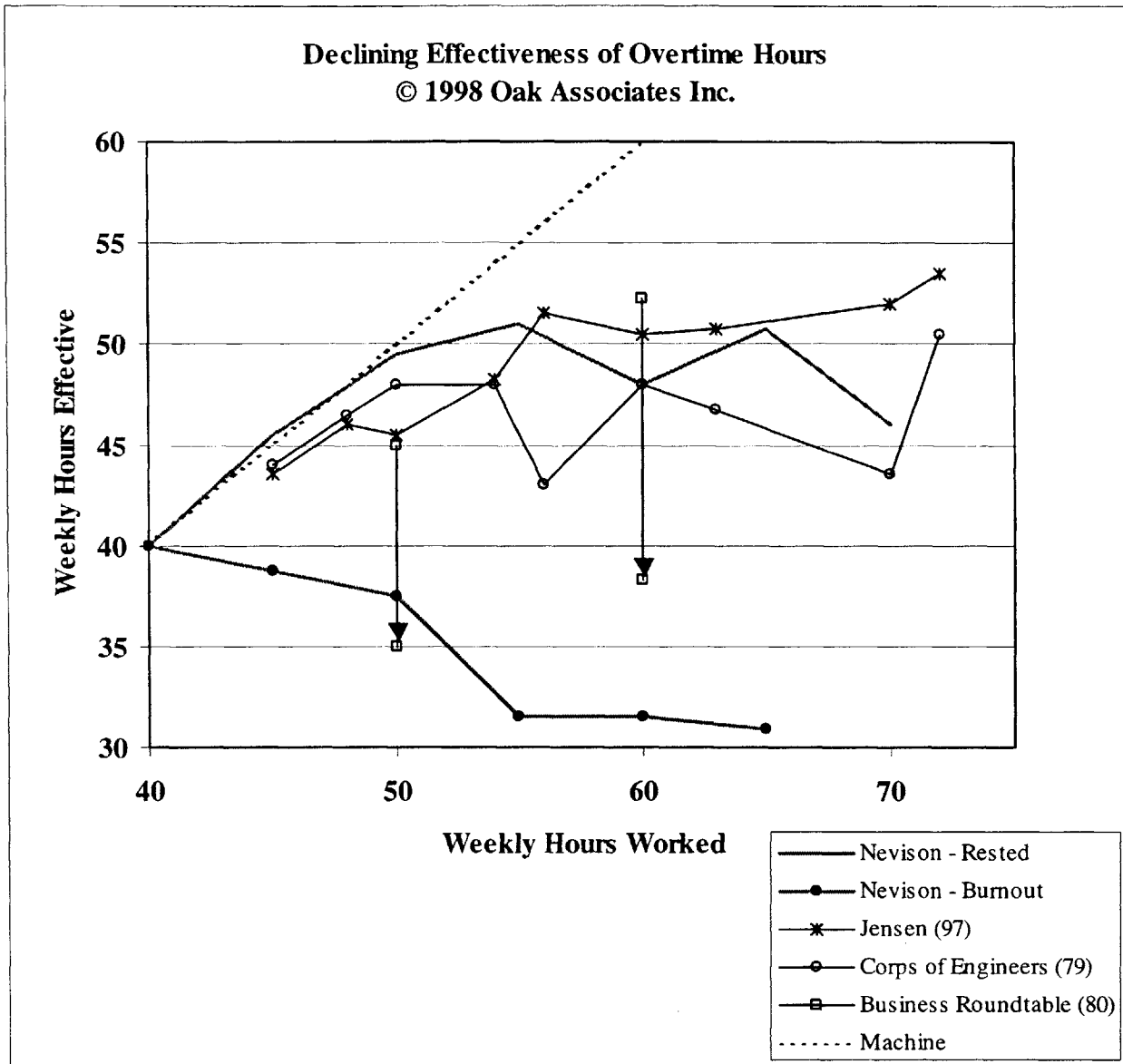


Figure 77: Acquisition Community Organization Chart

## 8.2 Nevison Overtime Effectiveness Chart



**Figure 78: John Nevison Overtime Effectiveness Data Compilation**

References for Figure 78:

Nevison, John M. (1992) *White Collar Project Management Questionnaire Report*, Oak Associates, Concord, MA

Jensen, Don Jr., Murphy, John D., and James, Craig, (1997), *The Seven Legal Elements Necessary For successful Claim For A Constructive Acceleration*, Project Management Journal, March 1997, pp. 34-44

Department of the Army, Office of the Chief of Engineers, (1979) *Modification Impact Evaluation Guide*, Washington, D.C.

The Business Roundtable, (1980) *Scheduled Overtime Effort On Construction Projects – A Construction Industry Cost Effectiveness Task Force Report*. New York.

### 8.3 System Dynamics Essentials

This section presents some of the essential information for reading the system dynamic model diagrams presented throughout this work. Sterman<sup>100</sup> and Richardson and Pugh<sup>101</sup> provide excellent, in-depth discussions of this subject, and were the inspiration for most of the material presented here.

#### 8.3.1 Causal loops

A basic tool for presenting the cause and effect relationships in a system is the causal loop diagram. Figure 79 is a causal loop representation of the rework cycle. The arrows indicate the direction of causality. For example *Un-Discovered Rework* leads to *Discovering Rework*. The + and - signs next to the arrows give the trend of the causal relationship. Table 1 follows Sterman<sup>102</sup> and provides a mathematical interpretation.

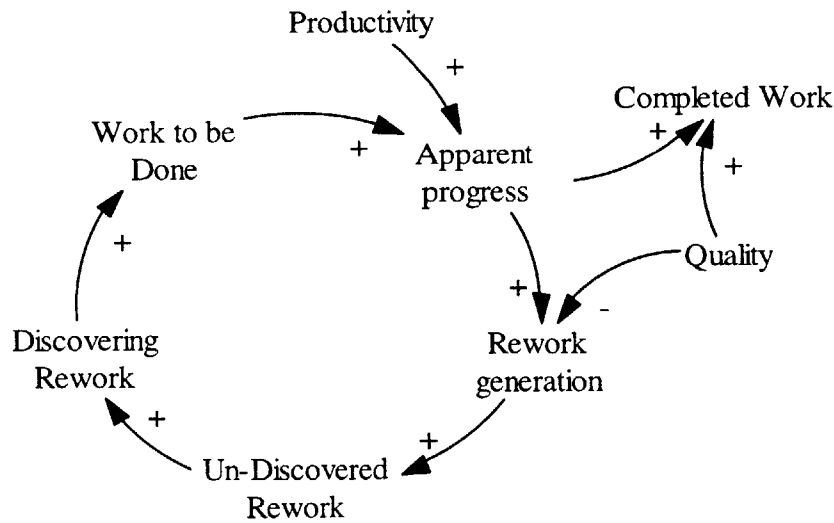


Figure 79: Causal Loop Diagram of Rework Cycle

Table 3: Definitions of Link Polarity

Symbol	Interpretation	Mathematics
$X \xrightarrow{+} Y$	All else equal, if X increases (decreases) then Y increases (decreases) above what it would have been	$\frac{\partial Y}{\partial X} \geq 0$
$X \xrightarrow{-} Y$	All else equal, if X increases (decreases) the Y decreases (increases) above what it would have been	$\frac{\partial Y}{\partial X} \leq 0$

<sup>100</sup> Sterman, John D., *Business Dynamics: Systems Thinking and Modeling for a Complex World* (working title), Partial Draft, Version 1, 1997. Chapters 5 and 6. Contact: jsterman@mit.edu or 617-258-7579

<sup>101</sup> Richardson, George P., Pugh, Alexander L., *Introduction to System Dynamics Modeling with Dynamo*, Productivity Press, Portland, OR, 1981. Pages 25-42

<sup>102</sup> Ibid Footnote 100, page 5-3.

### 8.3.2 Stock and flow diagrams

Almost all the model diagrams in this work are presented as stock and flow diagrams. Similar to causal loop diagrams, they clearly show the causal links between variables. However they also distinguish between various classes of variables and whether the flows are physical substance or information. Figure 80 shows a stock and flow representation of the rework cycle while Figure 81 provides a key to the notation. For example *Work to be Done* is the physical number of tasks or man-hours of effort know to be remaining at any time during the project. *Apparent progress rate* controls the rate at which work is removed from the stock of *Work to be Done*. Notice that *Perceived progress*, the amount of work management believes has been completed, is not a stock, but an information variable which is the sum of *Real Progress* and *Un-Discovered Rework*.

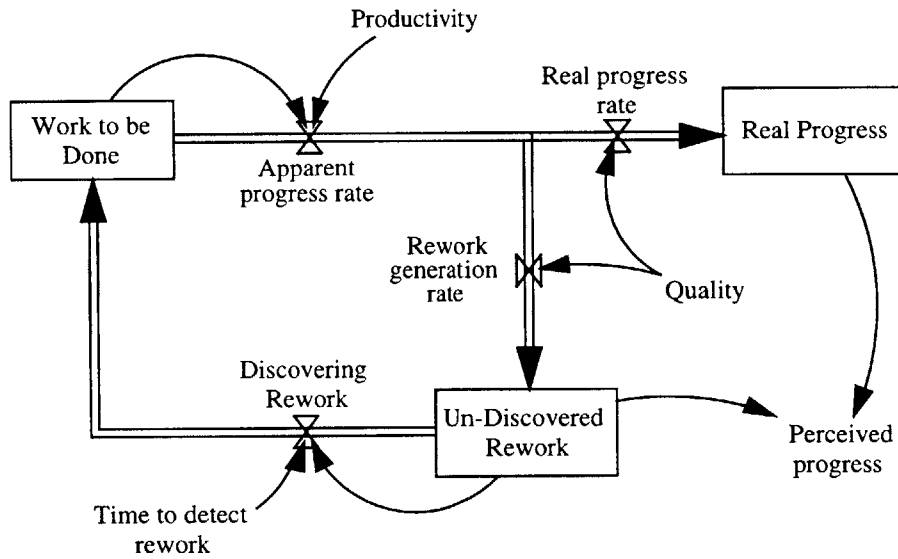


Figure 80: Stock and Flow Diagram of the Rework Cycle

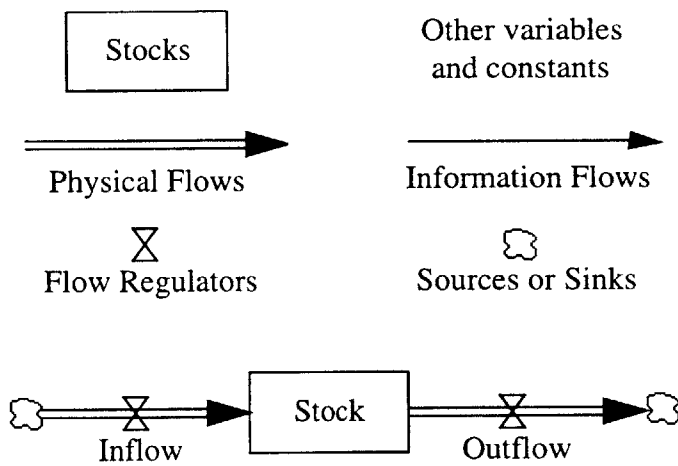


Figure 81: Stock and Flow Diagram Notation with Example

Mathematically the value of a stock is the integration over time of its inflows and outflows. In integral notation its value may be written as:

$$Stock = \int_{t_0}^t (Inflow(s) - Outflow(s)) ds + Stock(t_0)$$

Or in differential notation:

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t)$$

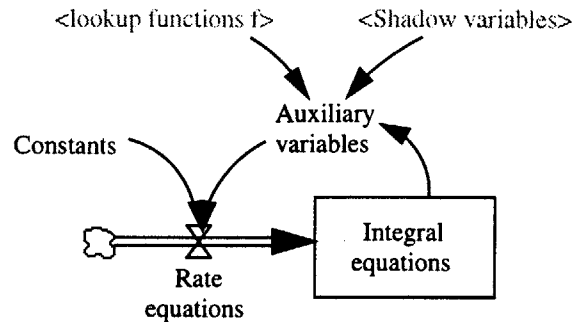
As expected, all inflows and outflows have units of *X/simulation time unit*, where *X* is any combination of units.

Other variables are the instantaneous evaluation of their individual mathematical formula – predominately sums, differences or products. For example the equation for *Rework generation rate* is:

$$Rework\ generation\ rate = Apparent\ progress\ rate \times (1 - Quality)$$

## 8.4 Simple Project Model Documentation

This section documents the equations that comprise the simple project model. For clarity, each section is started with the stock and flow diagram which corresponds to the equations which follow it. Some important notational conventions are:



**Integral equations** are the numerical integration of the given arguments (x).

Rate equations are the arguments for the integral equations, having units of X/time unit.

Constants are variables that remain fixed over the simulation period.

<Shadow variables> are variables defined in a different section of the model.

<lookup functions f> are table functions – translating a given input (x) into an output (y). In equation form they use the format;  $[(x_0, y_0)-(x_1, y_1), (x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)]$ , where the numbers in square brackets are the data's graphical range and the series of number-pairs that follow, in ordinary parenthesis, describe the functional relationship.

The model, as documented, is compatible with the Vensim simulation environment.<sup>103</sup> Some notation specific to the Vensim programming language is:

ACTIVE INITIAL(X,Y)	ACTIVE INITIAL(active equation, initial equation) Returns the value of the active equation during simulation. However, for determining initial conditions the value of the initial equation is returned. Normally this function is used to break a loop of simultaneous initial value equations.
DELAY INFORMATION	DELAY INFORMATION (input, delay time, initial value) This function returns the value of the input delayed by the delay time – a material delay.
IF THEN ELSE	IF THEN ELSE(condition, true value, false value) This function returns first true value if the condition is true and false value if condition is false.
INTEG(X,Y)	INTEG(rate, initial value) This function performs the integral of the given rate, starting from the initial value.
MAX(X,Y)	Function which returns the greater of X or Y.
MIN(X,Y)	Function which returns the lesser of X or Y.
SMOOTH(X,Y)	SMOOTH(input, delay time) This function is equivalent to INTEG((input-SMOOTH)/delay time, input)
SMOOTH_I(X,Y,Z)	SMOOTH(input, delay time, initial value) Essentially the SMOOTH function with a designated initial value. It is equivalent to INTEG((input-SMOOTH_I)/delay time, initial value)

<sup>103</sup> Vensim Simulation Environment, Vensim DSS32 Version 3.0B, © Ventana Systems, Inc.



#### 8.4.1 Simulation Control Parameters

TIME

Initial Value = INITIAL TIME  
Units: Month  
Comment: Time for the simulation

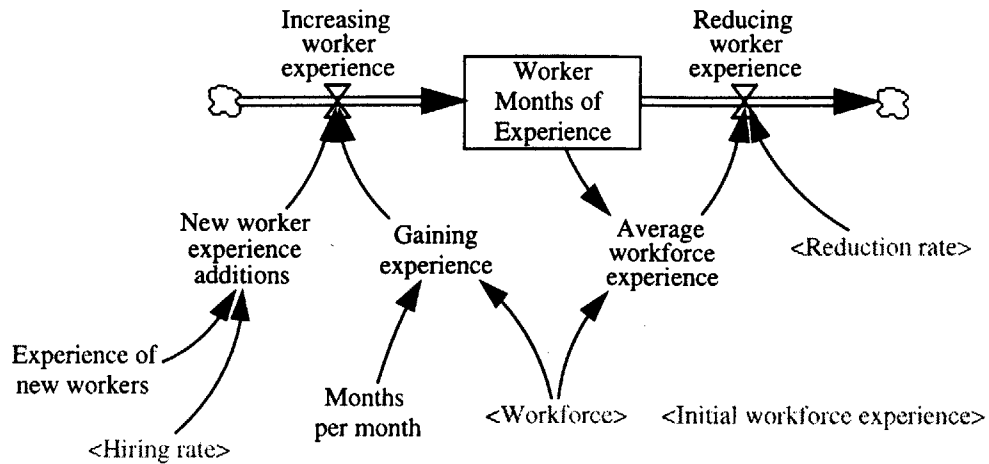
(02) FINAL TIME = IF THEN ELSE(Work Done Correctly>Initial project definition\*0.995,0,100)  
Units: Month  
Comment: The final time for the simulation.

(03) INITIAL TIME = 0  
Units: Month  
Comment: The initial time for the simulation.  
Uses: (01)Time

(04) SAVEPER = 1  
Units: Month  
Comment: The frequency with which output is stored.

(05) TIME STEP = 0.125  
Units: Month  
Comment: The time step for the simulation.  
Uses: (50)Apparent progress rate  
(90)Reduction rate

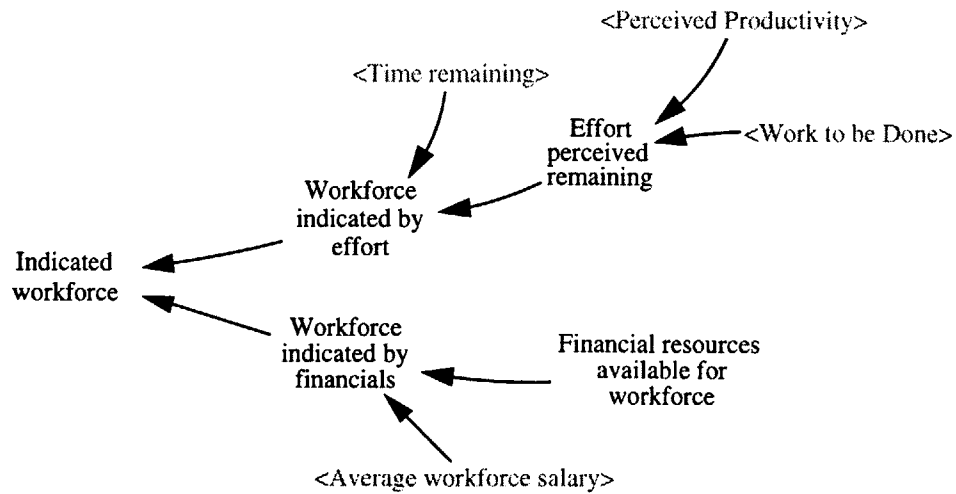
## 8.4.2 Workforce Experience



- (07)  $\text{Average workforce experience} = \text{Worker Months of Experience} / \text{MAX}(1e-005, \text{Workforce})$   
 Units: months  
 Uses: (14) Reducing worker experience  
 (48) Workforce fraction of experience required to attain normal quality  
 (36) Workforce fraction of experience to attain normal productivity
- (08)  $\text{Experience of new workers} = 0$   
 Units: months  
 Uses: (13) New worker experience additions
- (09)  $\text{Gaining experience} = \text{Workforce} * \text{Months per month}$   
 Units: man\*months/Month  
 Uses: (10) Increasing worker experience
- (10)  $\text{Increasing worker experience} = \text{Gaining experience} + \text{New worker experience additions}$   
 Units: man\*months/Month  
 Uses: (15) Worker Months of Experience
- (11)  $\text{Initial workforce experience} = 36$   
 Units: months  
 Uses: (15) Worker Months of Experience
- (12)  $\text{Months per month} = 1$   
 Units: months/Month  
 Uses: (09) Gaining experience
- (13)  $\text{New worker experience additions} = \text{Hiring rate} * \text{Experience of new workers}$   
 Units: man\*Month/Month  
 Uses: (10) Increasing worker experience
- (14)  $\text{Reducing worker experience} = \text{Reduction rate} * \text{Average workforce experience}$   
 Units: man\*months/Month  
 Uses: (15) Worker Months of Experience

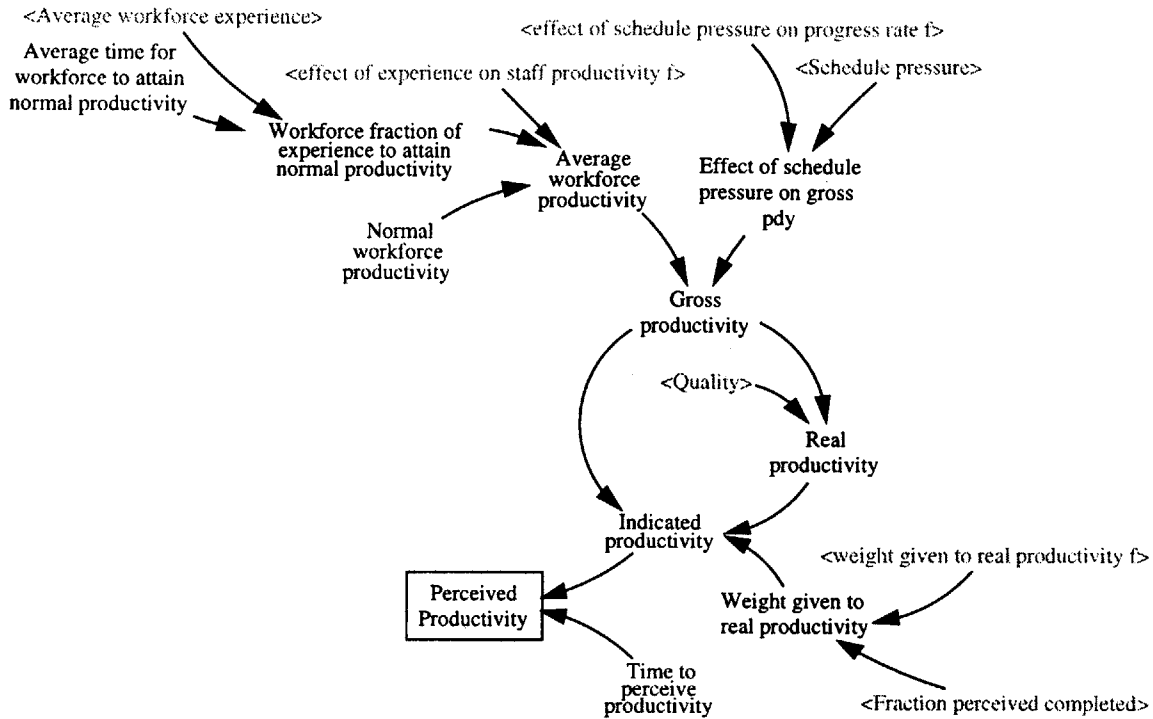
Worker Months of Experience = INTEG (Increasing worker experience - Reducing worker experience)  
Initial value: Initial workforce\*Initial workforce experience  
Units: man\*months  
Comment: Total man - months of experience of workers on the project.  
Uses: (07)Average workforce experience

### 8.4.3 Indicated Workforce



- (17)  $\text{Effort perceived remaining} = \text{Work to be Done} / \text{Perceived Productivity}$   
 Units: man\*months  
 Uses: (75)Time perceived required  
 (20)Workforce indicated by effort
- (18)  $\text{Financial resources available for workforce} = 180000$   
 Units: \$/Month  
 Uses: (21)Workforce indicated by financials
- (19)  $\text{Indicated workforce} = \text{MIN}(\text{Workforce indicated by effort}, \text{Workforce indicated by financials})$   
 Units: man  
 Uses: (86)Excess workforce  
 (94)Workforce deficit
- (20)  $\text{Workforce indicated by effort} = \text{Effort perceived remaining} / \text{Time remaining}$   
 Units: man  
 Uses: (19)Indicated workforce
- (21)  $\text{Workforce indicated by financials} = (\text{Financial resources available for workforce} / \text{Average workforce salary})$   
 Units: man  
 Uses: (19)Indicated workforce

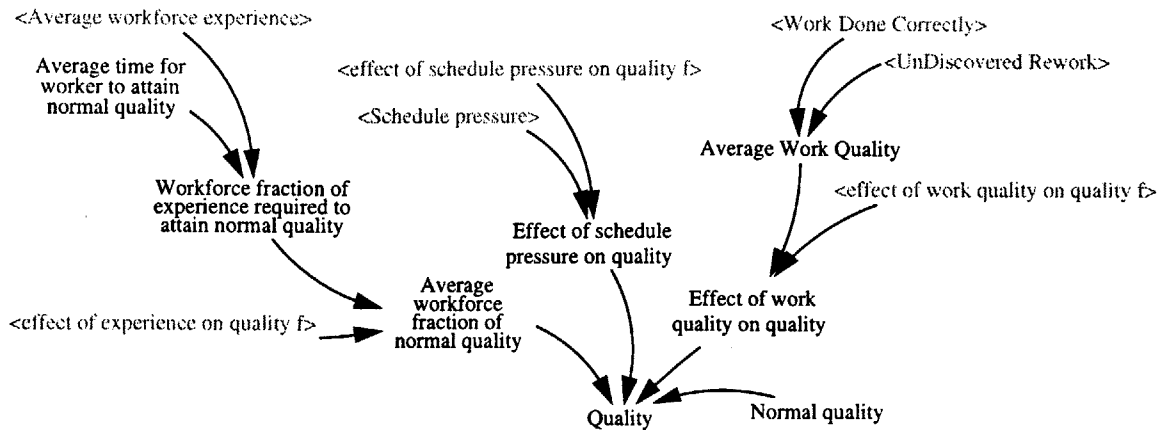
### 8.4.4 Productivity



- (23) Average time for workforce to attain normal productivity = 60  
 Units: Month  
 Comment: The average time required for an individual new to the project to fully learn the project's tools and methods. That is, to attain the expected level of productivity.  
 Uses: (36) Workforce fraction of experience to attain normal productivity
- (24) Average workforce productivity = effect of experience on staff productivity  $f$   
 (Workforce fraction of experience to attain normal productivity) \* Normal workforce productivity  
 Units: tasks/(Month\*man)  
 Uses: (28) Gross productivity
- (25) effect of experience on staff productivity  $f$  [(0,0)-(1,1)], (0,0.3), (0.1,0.5), (0.2,0.625), (0.3,0.73), (0.4,0.8), (0.5,0.86), (0.6,0.9), (0.7,0.94), (0.8,0.965), (0.9,0.99), (1,1)  
 Units: dmnl  
 Comment: From James Lyneis  
 Uses: (24) Average workforce productivity
- (26) Effect of schedule pressure on gross pdy =  
 effect of schedule pressure on progress rate  $f$  (Schedule pressure)  
 Units: dmnl  
 Uses: (28) Gross productivity

- (27) effect of schedule pressure on progress rate  $f([(0,1)-(0.7,1.2)],(0,1),(0.1,1.0125),(0.2,1.0375),$   
 $(0.3,1.075),(0.4,1.125),(0.5,1.1625),(0.6,1.1875),(0.7,1.2))$   
Units: dmn1  
Comment: From James Lyneis  
Uses: (26)Effect of schedule pressure on gross pdy
- (28) Gross productivity = ACTIVE INITIAL (Average workforce productivity\*  
Effect of schedule pressure on gross pdy, Average workforce productivity)  
Units: tasks/(Month\*man)  
Comment: The "Active Initial" construction was used to break a simultaneous initial value  
problem. Initial value is Average workforce productivity.  
Uses: (50)Apparent progress rate  
(29)Indicated productivity  
(31)Perceived Productivity  
(32)Real productivity
- (29) Indicated productivity = Real productivity\*Weight given to real productivity  
+ Gross productivity\*(1-Weight given to real productivity)  
Units: tasks/(Month\*man)  
Uses: (31)Perceived Productivity
- (30) Normal workforce productivity = 0.75  
Units: tasks/(man\*Month)  
Comment: The normal number of tasks per month an individual is assumed capable of completing.  
Uses: (24)Average workforce productivity
- (31) Perceived Productivity =  
SMOOTH(Indicated productivity, Time to perceive productivity, Gross productivity)  
Units: tasks/(Month\*man)  
Uses: (17)Effort perceived remaining
- (32) Real productivity = Gross productivity\*Quality  
Units: tasks/man/Month  
Uses: (29)Indicated productivity
- (33) Time to perceive productivity = 3  
Units: Month  
Uses: (31)Perceived Productivity
- (34) Weight given to real productivity = weight given to real productivity f(Fraction perceived completed)  
Units: dmn1  
Uses: (29)Indicated productivity
- (35) weight given to real productivity  $f([(0,0)-(1,1)],(0,0),(0.1,0.5),(0.2,0.7),(0.4,0.9),(0.6,0.96),$   
 $(0.8,0.98),(1,1))$   
Units: dmn1  
Comment: Weight given to real productivity as a function of fraction perceived completed  
Uses: (34)Weight given to real productivity
- (36) Workforce fraction of experience to attain normal productivity =  
Average workforce experience/Average time for workforce to attain normal productivity  
Units: dmn1  
Uses: (24)Average workforce productivity

### 8.4.5 Quality

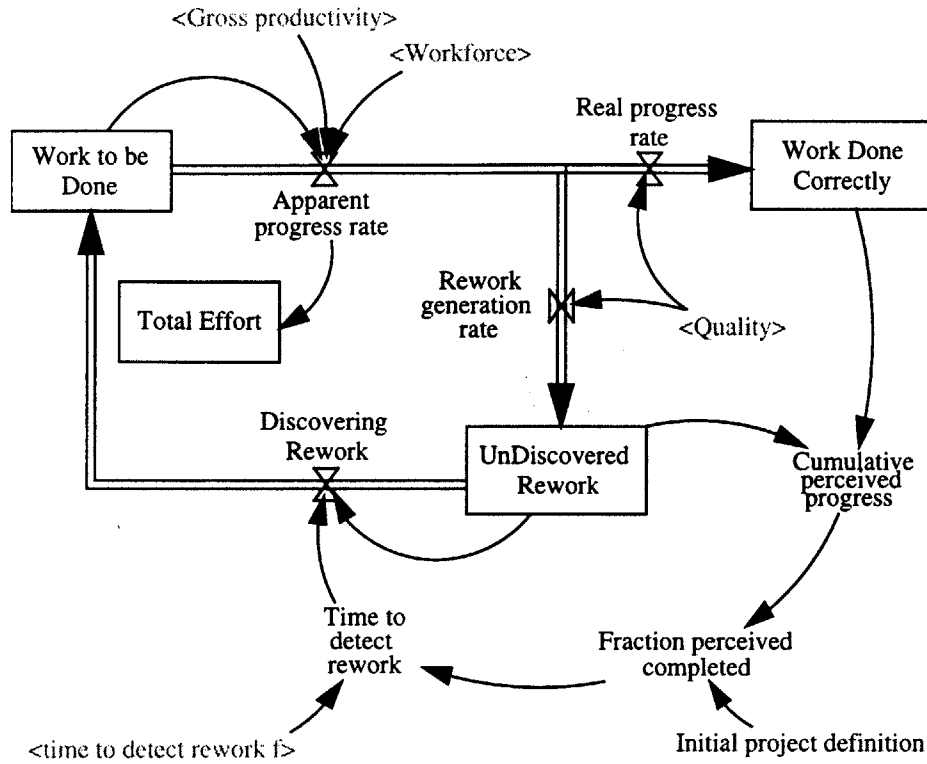


- (38) Average time for worker to attain normal quality = 60  
 Units: Month  
 Comment: The average time required for an individual new to the project to fully learn the project's tools and methods. That is, to attain the expected level of skill.  
 Uses: (48) Workforce fraction of experience required to attain normal quality
- (39) Average Work Quality = IF THEN ELSE(Work Done Correctly = 0,1,  
 Work Done Correctly/MAX(0.0001,UnDiscovered Rework + Work Done Correctly))  
 Units: fraction  
 Uses: (44) Effect of work quality on quality
- (40) Average workforce fraction of normal quality =  
 effect of experience on quality f(Workforce fraction of experience required to attain normal quality)  
 Units: fraction  
 Comment: Normal fraction of work completed correctly  
 Uses: (47) Quality
- (41) effect of experience on quality f([(0,0)-(1,1)],(0,0.3),(0.1,0.5),(0.2,0.625),(0.3,0.73),(0.4,0.8),  
 (0.5,0.86),(0.6,0.9),(0.7,0.94),(0.8,0.965),(0.9,0.99),(1,1))  
 Units: Dimensionless  
 Uses: (40) Average workforce fraction of normal quality
- (42) Effect of schedule pressure on quality = effect of schedule pressure on quality f(Schedule pressure)  
 Units: dmnl  
 Uses: (47) Quality
- (43) effect of schedule pressure on quality f([(0,0.6)-(0.7,1)],(0,1),(0.1,0.975),(0.2,0.925),(0.3,0.85),  
 (0.4,0.75),(0.5,0.675),(0.6,0.625),(0.7,0.6))  
 Units: dmnl  
 Comment: From James Lyneis  
 Uses: (42) Effect of schedule pressure on quality
- (44) Effect of work quality on quality = effect of work quality on quality f(Average Work Quality)  
 Units: dmnl  
 Uses: (47) Quality

- (45) effect of work quality on quality  $f([(0,0)-(1,1)],(0,0.1),(0.1,0.25),(0.2,0.35),(0.3,0.45),(0.4,0.55),$   
 $(0.5,0.65),(0.6,0.74),(0.7,0.83),(0.8,0.9),(0.9,0.95),(1,1))$   
 Units: dmn1  
 Comment: From James Lyneis  
 Uses: (44)Effect of work quality on quality
- (46) Normal quality = 0.75  
 Units: fraction  
 Uses: (47)Quality
- (47) Quality = Normal quality\*Average workforce fraction of normal quality  
 \*Effect of schedule pressure on quality\*Effect of work quality on quality  
 Units: fraction  
 Comment: Fraction of work completed which will never need to be reworked.  
 Uses: (32)Real productivity  
 (55)Real progress rate  
 (56)Rework generation rate
- (48) Workforce fraction of experience required to attain normal quality =  
 Average workforce experience/Average time for worker to attain normal quality  
 Units: dmn1  
 Uses: (40)Average workforce fraction of normal quality



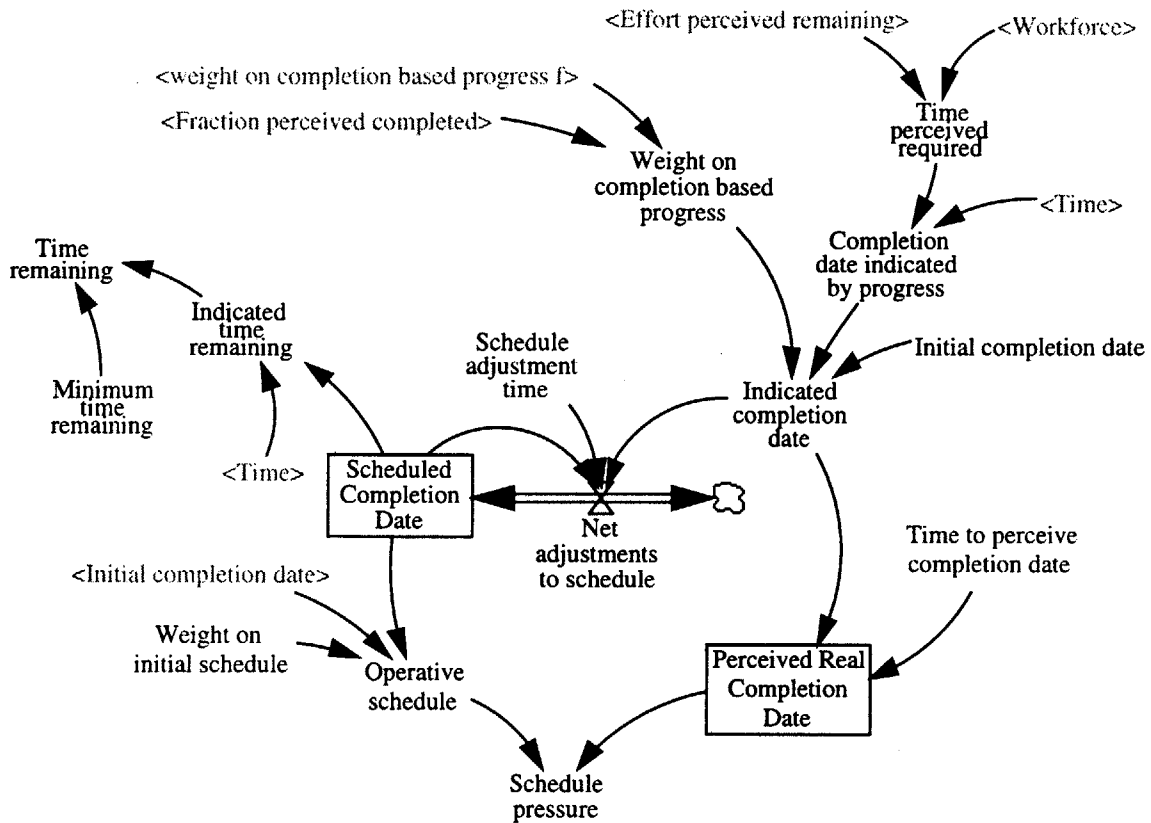
### 8.4.6 Rework



- (50)  $\text{Apparent progress rate} = \text{MIN}(\text{Workforce} * \text{Gross productivity}, \text{Work to be Done} / \text{TIME STEP})$   
 Units: tasks/Month  
 Uses: (59) Total Effort  
 (62) Work to be Done  
 (55) Real progress rate  
 (56) Rework generation rate
- (51)  $\text{Cumulative perceived progress} = \text{Work Done Correctly} + \text{UnDiscovered Rework}$   
 Units: tasks  
 Uses: (53) Fraction perceived completed
- (52)  $\text{Discovering Rework} = \text{UnDiscovered Rework} / \text{Time to detect rework}$   
 Units: tasks/Month  
 Uses: (60) UnDiscovered Rework  
 (62) Work to be Done
- (53)  $\text{Fraction perceived completed} = \text{MIN}(\text{Cumulative perceived progress} / \text{Initial project definition}, 1)$   
 Units: dmnl  
 Uses: (57) Time to detect rework  
 (34) Weight given to real productivity  
 (78) Weight on completion based progress

- (54) Initial project definition = 100  
 Units: tasks  
 Uses: (62)Work to be Done  
 (02)FINAL TIME  
 (53)Fraction perceived completed
- (55) Real progress rate = Apparent progress rate\*Quality  
 Units: tasks/Month  
 Uses: (61)Work Done Correctly
- (56) Rework generation rate = Apparent progress rate\*(1-Quality)  
 Units: tasks/Month  
 Uses: (60)UnDiscovered Rework
- (57) Time to detect rework = time to detect rework f(Fraction perceived completed)  
 Units: Month  
 Uses: (52)Discovering Rework
- (58) time to detect rework f([(0,0)-(1,20)],(0,12),(0.4,12),(0.6,10),(0.8,5),(1,0.5) )  
 Units: Month  
 Comment: Time to detect rework as a function of fraction of project completed  
 Uses: (57)Time to detect rework
- (59) Total Effort = INTEG (Apparent progress rate)  
 Initial Value = 0  
 Units: tasks
- (60) UnDiscovered Rework = INTEG(Rework generation rate - Discovering Rework)  
 Initial Value = 0  
 Units: tasks  
 Uses: (39)Average Work Quality  
 (51)Cumulative perceived progress  
 (52)Discovering Rework
- (61) Work Done Correctly = INTEG(Real progress rate)  
 Initial Value = 0  
 Units: tasks  
 Uses: (39)Average Work Quality  
 (51)Cumulative perceived progress  
 (02)FINAL TIME
- (62) Work to be Done = INTEG (Discovering Rework-Apparent progress rate,Initial project definition)  
 Units: tasks  
 Uses: (50)Apparent progress rate  
 (17)Effort perceived remaining

### 8.4.7 Schedule



- (64)  $\text{Completion date indicated by progress} = \text{Time perceived required} + \text{Time}$   
 Units: Month  
 Uses: (65) Indicated completion date
- (65)  $\text{Indicated completion date} = \text{Initial completion date} * (1 - \text{Weight on completion based progress}) + \text{Completion date indicated by progress} * \text{Weight on completion based progress}$   
 Units: Month  
 Uses: (69) Net adjustments to schedule  
 (71) Perceived Real Completion Date
- (66)  $\text{Indicated time remaining} = \text{Scheduled Completion Date} - \text{Time}$   
 Units: Month  
 Uses: (76) Time remaining
- (67)  $\text{Initial completion date} = 25$   
 Units: Month  
 Comment: Initial desired time to complete the project.  
 Uses: (74) Scheduled Completion Date  
 (65) Indicated completion date  
 (70) Operative schedule  
 (71) Perceived Real Completion Date

- (68) Minimum time remaining = 1  
 Units: Month  
 Comment: A minimum time remaining of 1 month  
 Uses: (76)Time remaining
- (69) Net adjustments to schedule = (Indicated completion date-Scheduled Completion Date)  
 /Schedule adjustment time  
 Units: fraction  
 Uses: (74)Scheduled Completion Date
- (70) Operative schedule = Initial completion date\*Weight on initial schedule  
 + (1-Weight on initial schedule)\*Scheduled Completion Date  
 Units: Month  
 Uses: (73)Schedule pressure
- (71) Perceived Real Completion Date =  
 SMOOTH(Indicated completion date, Time to perceive completion date, Initial completion date)  
 Units: Month  
 Uses: (73)Schedule pressure
- (72) Schedule adjustment time = 6  
 Units: Month  
 Uses: (69)Net adjustments to schedule
- (73) Schedule pressure = MAX(0,(Perceived Real Completion Date-Operative schedule)  
 /Operative schedule)  
 Units: fraction  
 Uses: (26)Effect of schedule pressure on gross pdy  
 (42)Effect of schedule pressure on quality
- (74) Scheduled Completion Date = INTEG(Net adjustments to schedule, Initial completion date)  
 Units: Month  
 Uses: (66)Indicated time remaining  
 (69)Net adjustments to schedule  
 (70)Operative schedule
- (75) Time perceived required = Effort perceived remaining/Workforce  
 Units: Month  
 Uses: (64)Completion date indicated by progress
- (76) Time remaining = MAX(Indicated time remaining, Minimum time remaining)  
 Units: Month  
 Uses: (20)Workforce indicated by effort
- (77) Time to perceive completion date = 1  
 Units: Month  
 Uses: (71)Perceived Real Completion Date
- (78) Weight on completion based progress =  
 weight on completion based progress f(Fraction perceived completed)  
 Units: Dimensionless  
 Uses: (65)Indicated completion date

(79) weight on completion based progress  $f([(0,0)-(1,1)],(0,0),(0.1,0.1),(0.2,0.3),(0.3,0.5),(0.4,0.7),$   
 $(0.5,0.85),(0.6,0.95),(0.7,1),(0.8,1),(0.9,1),(1,1))$

Units: Dimensionless

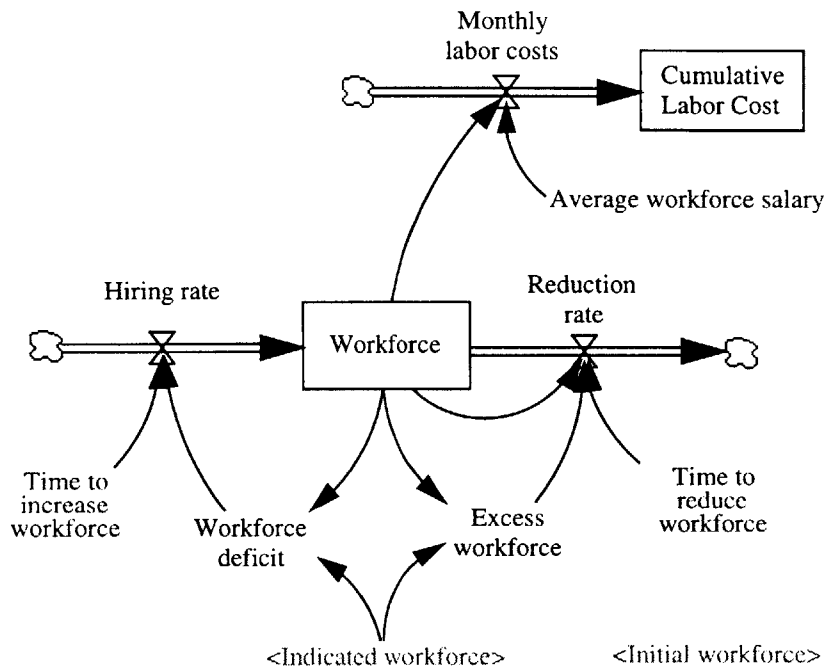
Uses: (78)Weight on completion based progress

(80) Weight on initial schedule = 0.75

Units: dmn1

Uses: (70)Operative schedule

### 8.4.8 Workforce

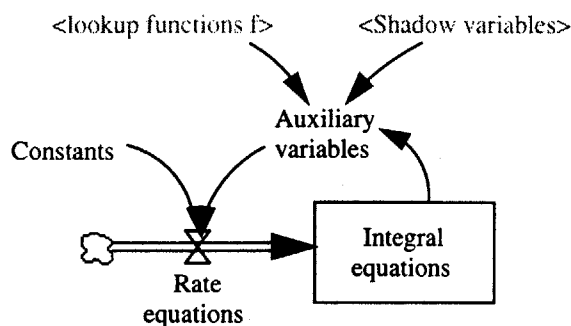


- (84) Average workforce salary = 4300  
 Units: \$/(Month\*man)  
 Comment: Based on McDonnell Douglas 1996 annual report: ((salaries and wages)/personnel)  
 Uses: (89)Monthly labor costs  
 (21)Workforce indicated by financials
- (85) Cumulative Labor Cost = INTEG (Monthly labor costs)  
 Initial Value = 0  
 Units: \$
- (86) Excess workforce = MAX(0,Workforce-Indicated workforce)  
 Units: man  
 Uses: (90)Reduction rate
- (87) Hiring rate = Workforce deficit/Time to increase workforce  
 Units: man/Month  
 Uses: (93)Workforce  
 (13)New worker experience additions
- (88) Initial workforce = 2  
 Units: man  
 Uses: (15)Worker Months of Experience  
 (93)Workforce
- (89) Monthly labor costs = Workforce\*Average workforce salary  
 Units: \$/Month  
 Uses: (85)Cumulative Labor Cost

- (90) Reduction rate =  $\text{MIN}(\text{Excess workforce}/\text{Time to reduce workforce}, \text{Workforce}/\text{TIME STEP})$   
 Units: man/Month  
 Uses: (93)Workforce  
 (14)Reducing worker experience
- (91) Time to increase workforce = 5  
 Units: Month  
 Uses: (87)Hiring rate
- (92) Time to reduce workforce = 5  
 Units: Month  
 Comment: Average time required to reduce the workforce on a project.  
 Uses: (90)Reduction rate
- (93) Workforce =  $\text{INTEG}(\text{Hiring rate}-\text{Reduction rate})$   
 Initial Value = Initial workforce  
 Units: man  
 Comment: Total workforce  
 Uses: (50)Apparent progress rate  
 (07)Average workforce experience  
 (86)Excess workforce  
 (09)Gaining experience  
 (89)Monthly labor costs  
 (90)Reduction rate  
 (75)Time perceived required  
 (94)Workforce deficit
- (94) Workforce deficit =  $\text{MAX}(0, \text{Indicated workforce}-\text{Workforce})$   
 Units: man  
 Uses: (87)Hiring rate

## 8.5 SPO-Contractor Model Documentation

This section documents the equations that comprise the SPO-contractor model. For clarity, each section is started with the stock and flow diagram that corresponds to the equations that follow it. The sections are grouped into those equations that define the contractor, Section 8.5.1, and those which define the SPO, Section 8.5.2. Section 8.5.3 documents the Government funding overlay. Some important notational conventions are:



**Integral equations** are the numerical integration of the given arguments (x).

Rate equations are the arguments for the integral equations, having units of X/time unit.

Constants are variables that remain fixed over the simulation period.

<Shadow variables> are variables defined in a different section of the model.

<lookup functions f> are table functions – translating a given input (x) into an output (y). In equation form they use the format;  $[(x_0, y_0)-(x_1, y_1), (x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)]$ , where the numbers in square brackets are the data's graphical range and the series of number-pairs that follow, in ordinary parenthesis, describe the functional relationship.

The model, as documented, simulates perfect conditions. For constants, which, under normal circumstances would have different values, those values are typically indicated in the notes. The model is compatible with the Vensim simulation environment.<sup>104</sup> Some notation specific to the Vensim programming language is:

ACTIVE INITIAL(X,Y)	ACTIVE INITIAL(active equation, initial equation) Returns the value of the active equation during simulation. However, for determining initial conditions the value of the initial equation is returned. Normally this function is used to break a loop of simultaneous initial value equations.
DELAY INFORMATION	DELAY INFORMATION (input, delay time, initial value) This function returns the value of the input delayed by the delay time – a material delay.
IF THEN ELSE	IF THEN ELSE(condition, true value, false value) This function returns first true value if the condition is true and false value if condition is false.
INTEG(X,Y)	INTEG(rate, initial value) This function performs the integral of the given rate, starting from the initial value.
MAX(X,Y)	Function which returns the greater of X or Y.
MIN(X,Y)	Function which returns the lesser of X or Y.
SMOOTH(X,Y)	SMOOTH(input, delay time) This function is equivalent to INTEG((input-SMOOTH)/delay time, input)
SMOOTH(X,Y,Z)	SMOOTH(input, delay time, initial value) Essentially the SMOOTH function with a designated initial value. It is equivalent to INTEG((input-SMOOTHI)/delay time, initial value)

<sup>104</sup> Vensim Simulation Environment, Vensim DSS32 Version 3.0B, © Ventana Systems, Inc.

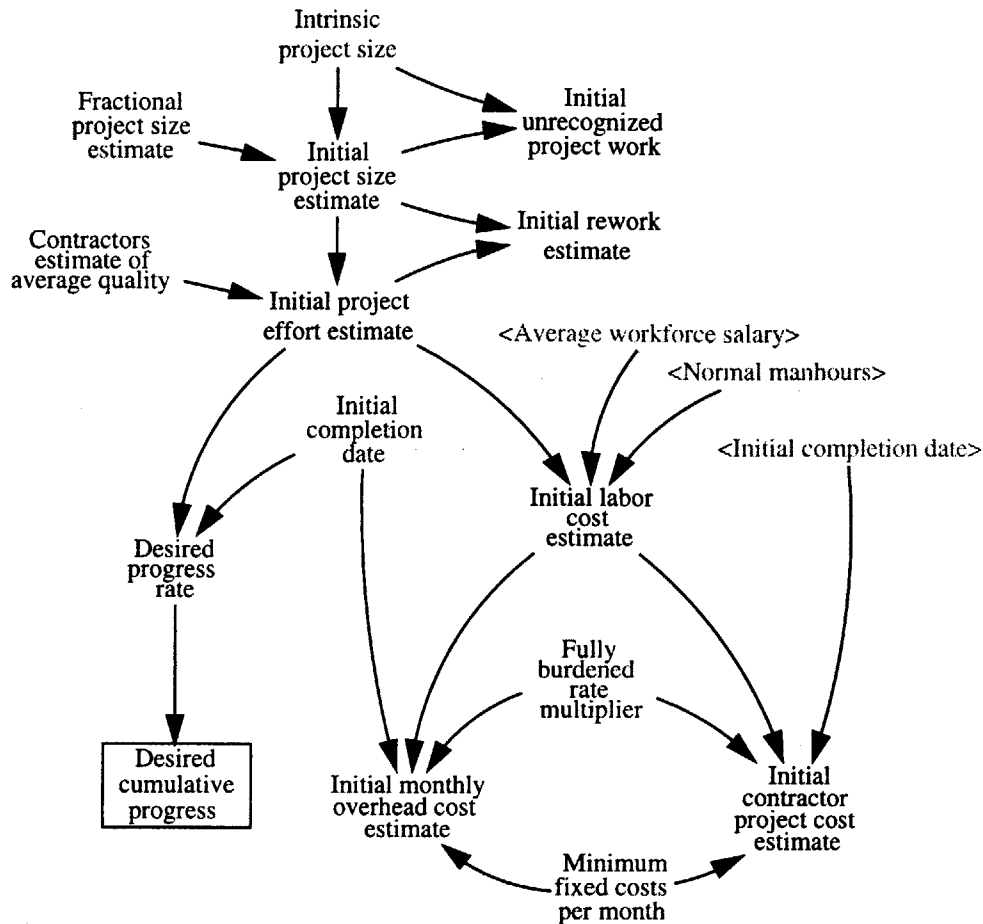


## 8.5.1 Contractor Model Documentation

### 8.5.1.1 Simulation Control Parameters

- (001) TIME  
Initial Value = INITIAL TIME  
Units: Month  
Comment: Time for the simulation
- (002) FINAL TIME = IF THEN ELSE(Project completed = 1,0,200)  
Units: Month  
Comment: The final time for the simulation.
- (003) INITIAL TIME = 0  
Units: Month  
Comment: The initial time for the simulation.  
Uses: (001)Time -
- (004) SAVEPER = 0.25  
Units: Month  
Comment: The frequency with which output is stored.
- (005) TIME STEP = 0.03125  
Units: Month  
Comment: The time step for the simulation.  
Uses: (694)Project Cost Overrun -  
(696)Project Schedule Slip -  
(074)Apparent development progress rate -  
(076)Apparent rework progress rate -  
(494)Experienced civilian firing -  
(109)Experienced workforce firing -  
(498)Expert civilian firing -  
(113)Expert workforce firing -  
(447)Force reductions -  
(721)Government releasing contractor funds -  
(722)Government releasing SPO administered funds -  
(723)Government releasing SPO operating funds -  
(453)Military transfer out rate -  
(507)New civilian firing -  
(124)New workforce firing -  
(026)Releasing unreimbursed funds -  
(412)SPO apparent development progress rate -  
(414)SPO apparent rework progress rate -  
(406)SPO disbursing administered funds -

### 8.5.1.2 Contractor Initial Cost Estimates

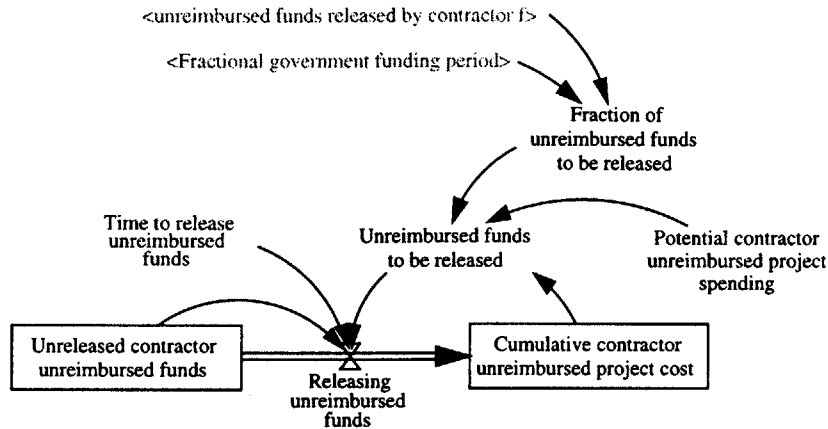


- (007) Contractors estimate of average quality = 1  
 Units: fraction  
 Comment: The contractor's estimate of average quality for the project.  
 Uses: (016)Initial project effort estimate -
- (008) Desired cumulative progress = INTEG(Desired progress rate,0)  
 Units: manhours
- (009) Desired progress rate = Initial project effort estimate/Initial completion date  
 Units: manhours/Month  
 Uses: (008)Desired cumulative progress -
- (010) Fractional project size estimate = 1  
 Units: fraction  
 Comment: Initial project size is this fraction of the intrinsic project size.  
 Uses: (017)Initial project size estimate -

- (011) Fully burdened rate multiplier = 2  
 Units: dnmnl  
 Comment: Method used to account for overhead for engineering work.  
 Uses: (013)Initial contractor project cost estimate -  
 (015)Initial monthly overhead cost estimate -  
 (041)Overhead cost per month -
- (012) Initial completion date = 60  
 Units: Month  
 Uses: (255)Scheduled completion date -  
 (272)Target completion date -  
 (009)Desired progress rate -  
 (309)Initial authorized civilian cost estimate -  
 (312)Initial authorized military cost estimate -  
 (013)Initial contractor project cost estimate -  
 (015)Initial monthly overhead cost estimate -  
 (295)Original schedule slip -  
 (251)Perceived real completion date -  
 (314)SPO initial authorization based operations cost estimate -  
 (323)SPO initial effort based operations cost estimate -  
 (629)SPO perceived real completion date -
- (013) Initial contractor project cost estimate =  $\text{MAX}(\text{Initial labor cost estimate}$   
 $\text{*Fully burdened rate multiplier, Initial labor cost estimate}$   
 $\text{+Minimum fixed costs per month*Initial completion date})$   
 Units: \$  
 Uses: (293)Contractor cost overrun -  
 (708)Indicated initial nonpersonnel project budget -  
 (692)Initial total project cost estimate less administered funds -
- (014) Initial labor cost estimate =  
 $\text{Average workforce salary}*(\text{Initial project effort estimate}/\text{Normal manhours})$   
 Units: \$  
 Uses: (013)Initial contractor project cost estimate -  
 (015)Initial monthly overhead cost estimate -
- (015) Initial monthly overhead cost estimate =  
 $\text{MAX}(\text{Initial labor cost estimate}*(\text{Fully burdened rate multiplier}-1)/\text{Initial completion date,}$   
 $\text{Minimum fixed costs per month})$   
 Units: \$/Month  
 Uses: (033)Average overhead cost per month -
- (016) Initial project effort estimate = Initial project size estimate/Contractors estimate of average quality  
 Units: manhours  
 Comment: The contractor's initial estimate of the total effort required to complete the project including the effect of rework.  
 Uses: (009)Desired progress rate -  
 (014)Initial labor cost estimate -  
 (018)Initial rework estimate -

- (017) Initial project size estimate = Intrinsic project size\*Fractional project size estimate  
 Units: manhours  
 Uses: (080)Current project definition -  
 (091)Work to be done -  
 (016)Initial project effort estimate -  
 (018)Initial rework estimate -  
 (019)Initial unrecognized project work -
- (018) Initial rework estimate = Initial project effort estimate-Initial project size estimate  
 Units: manhours
- (019) Initial unrecognized project work = Intrinsic project size-Initial project size estimate  
 Units: manhours  
 Comment: The number of manhours work unrecognized at the start of the project.  
 Uses: (090)Undiscovered work -  
 (083)Discovering work -
- (020) Intrinsic project size = 2e+007  
 Units: manhours  
 Uses: (017)Initial project size estimate -  
 (019)Initial unrecognized project work -  
 (328)SPO intrinsic project size -
- (021) Minimum fixed costs per month = 134375  
 Units: \$/Month  
 Comment: The floor for fixed costs. (Based on 2e6 manhours and 40 months)  
 Uses: (013)Initial contractor project cost estimate -  
 (015)Initial monthly overhead cost estimate -  
 (041)Overhead cost per month -  
 (305)Project in progress minimum required cash flow -

### 8.5.1.3 Contractor Unreimbursed Funds



(023) Cumulative contractor unreimbursed project cost = INTEG (Releasing unreimbursed funds,0)  
Units: \$

Uses: (045)Total contractor reimbursed project cost -  
(029)Unreimbursed funds to be released -

(024) Fraction of unreimbursed funds to be released =  
unreimbursed funds released by contractor f(Fractional government funding period)

Units: fraction

Comment: The fraction of unreimbursed funds released by the contractor as a function of the Government funding period.

Uses: (029)Unreimbursed funds to be released -

(025) Potential contractor unreimbursed project spending = 0

Units: \$

Comment: Total funds which the contractor will ultimately spend on the project for which it is not compensated by the government.

Uses: (030)Unreleased contractor unreimbursed funds -  
(029)Unreimbursed funds to be released -

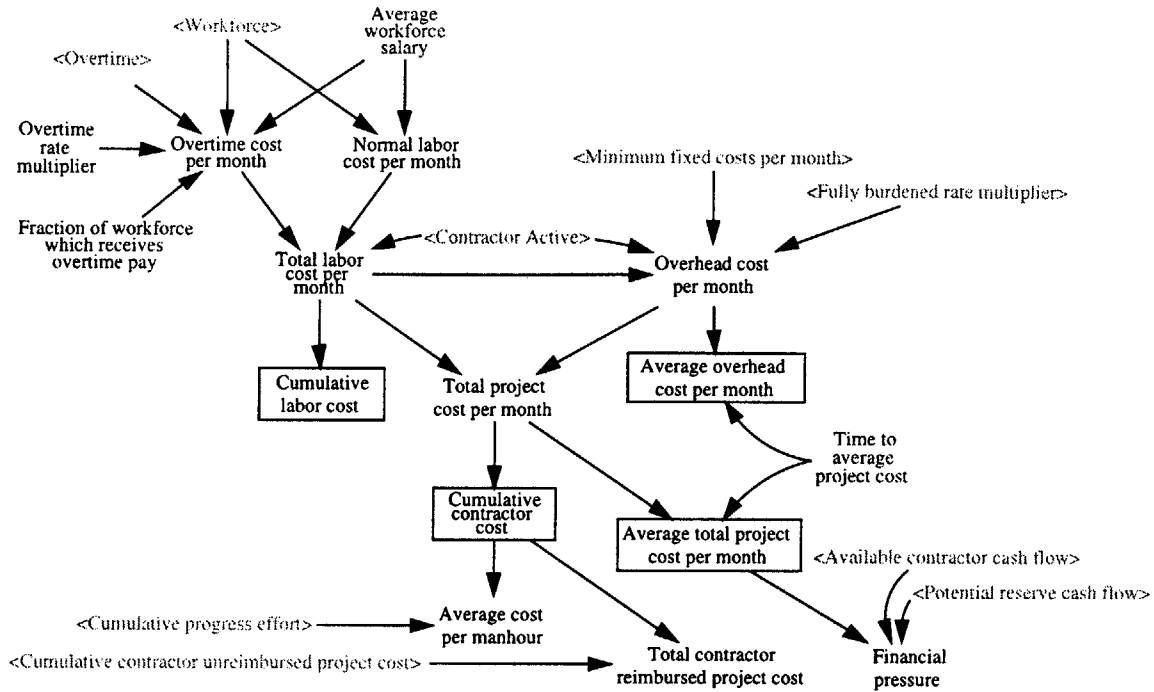
(026) Releasing unreimbursed funds =  
MIN(Unreimbursed funds to be released/Time to release unreimbursed funds,  
Unreleased contractor unreimbursed funds/TIME STEP)

Units: \$/Month

Uses: (023)Cumulative contractor unreimbursed project cost -  
(030)Unreleased contractor unreimbursed funds -  
(051)Aggregating financial resources -

- (027) Time to release unreimbursed funds = 1  
 Units: Month  
 Uses: (026)Releasing unreimbursed funds -
- (028) unreimbursed funds released by contractor  $f([(0,0.4)-(1,1)],(0,0.5),(0.1,0.9),(0.15,0.975),(0.2,1),(1,1))$   
 Units: fraction  
 Comment: function describing the release of the contractor's unreimbursed funds as a function of the government funding period.  
 Uses: (024)Fraction of unreimbursed funds to be released -
- (029) Unreimbursed funds to be released =  $\text{MAX}(\text{Fraction of unreimbursed funds to be released} \times \text{Potential contractor unreimbursed project spending} - \text{Cumulative contractor unreimbursed project cost}, 0)$   
 Units: \$  
 Uses: (026)Releasing unreimbursed funds -
- (030) Unreleased contractor unreimbursed funds =  $\text{INTEG}(-\text{Releasing unreimbursed funds}, \text{Potential contractor unreimbursed project spending})$   
 Units: \$  
 Uses: (026)Releasing unreimbursed funds -

### 8.5.1.4 Contractor Labor and Project Costs



(032) Average cost per manhour = IF THEN ELSE(Cumulative progress effort = 0, 0, Cumulative contractor cost/Cumulative progress effort)

Units: \$/manhours

Uses: (070)MR funds indicated by discovering rework -

(033) Average overhead cost per month = SMOOTHI(Overhead cost per month, Time to average project cost, Initial monthly overhead cost estimate)

Units: \$/Month

Uses: (143)Financial resources available for workforce -

(034) Average total project cost per month = SMOOTHI(Total project cost per month, Time to average project cost, 0)

Units: \$/Month

Uses: (038)Financial pressure -

(035) Average workforce salary = 4300

Units: \$/(Month\*man)

Comment: Based on McDonnell Douglas 1996 annual report: ((salaries and wages)/personnel)

Uses: (014)Initial labor cost estimate -

(040)Normal labor cost per month -

(042)Overtime cost per month -

(305)Project in progress minimum required cash flow -

(147)Workforce indicated by financials -

- (036) Cumulative contractor cost = INTEG(Total project cost per month,0)  
 Units: \$  
 Uses: (032)Average cost per manhour -  
 (045)Total contractor reimbursed project cost -
- (037) Cumulative labor cost = INTEG(Total labor cost per month,0)  
 Units: \$
- (038) Financial pressure = IF THEN ELSE((Available contractor cash flow+Potential reserve cash flow)>0,  
 MIN( Average total project cost per month/(Available contractor cash flow  
 +Potential reserve cash flow),1.8), 0)  
 Units: fraction  
 Comment: Fraction of financial resources utilized by the project  
 Uses: (094)Effect of financial pressure on rework detection -
- (039) Fraction of workforce which receives overtime pay = 0.5  
 Units: dmn1  
 Comment: This is used to account for that part of the workforce which is salaried and would not  
 receive additional pay for overtime work.  
 Uses: (042)Overtime cost per month -  
 (147)Workforce indicated by financials -
- (040) Normal labor cost per month = Average workforce salary\*Workforce  
 Units: \$/Month  
 Uses: (046)Total labor cost per month -
- (041) Overhead cost per month =  
 MAX(Total labor cost per month\*(Fully burdened rate multiplier-1),  
 Minimum fixed costs per month)\*Contractor Active  
 Units: \$/Month  
 Uses: (033)Average overhead cost per month -  
 (047)Total project cost per month -
- (042) Overtime cost per month = IF THEN ELSE(Overtime>= 0,  
 (Workforce\*Fraction of workforce which receives overtime pay\*Overtime  
 \*Overtime rate multiplier\*Average workforce salary),  
 (Workforce\*Fraction of workforce which receives overtime pay  
 \*Overtime\*Average workforce salary))  
 Units: \$/Month  
 Comment: This construction causes overtime to be paid at the overtime rate (e.g. time and a  
 half), while undertime decreases the normal pay by the normal hourly rate.  
 Uses: (046)Total labor cost per month -
- (043) Overtime rate multiplier = 1.5  
 Units: dmn1  
 Comment: The fractional increase in pay rate for overtime hours worked.  
 Uses: (042)Overtime cost per month -  
 (147)Workforce indicated by financials -
- (044) Time to average project cost = 1  
 Units: Month  
 Uses: (033)Average overhead cost per month -  
 (034)Average total project cost per month -



(045) Total contractor reimbursed project cost =  
Cumulative contractor cost-Cumulative contractor unreimbursed project cost

Units: \$

Comment: Total cost to the government of the contractor's portion of the project

Uses: (694)Project Cost Overrun -  
(293)Contractor cost overrun -  
(697)Project Total Cost -

(046) Total labor cost per month =  
( Normal labor cost per month+Overtime cost per month)\*Contractor Active

Units: \$/Month

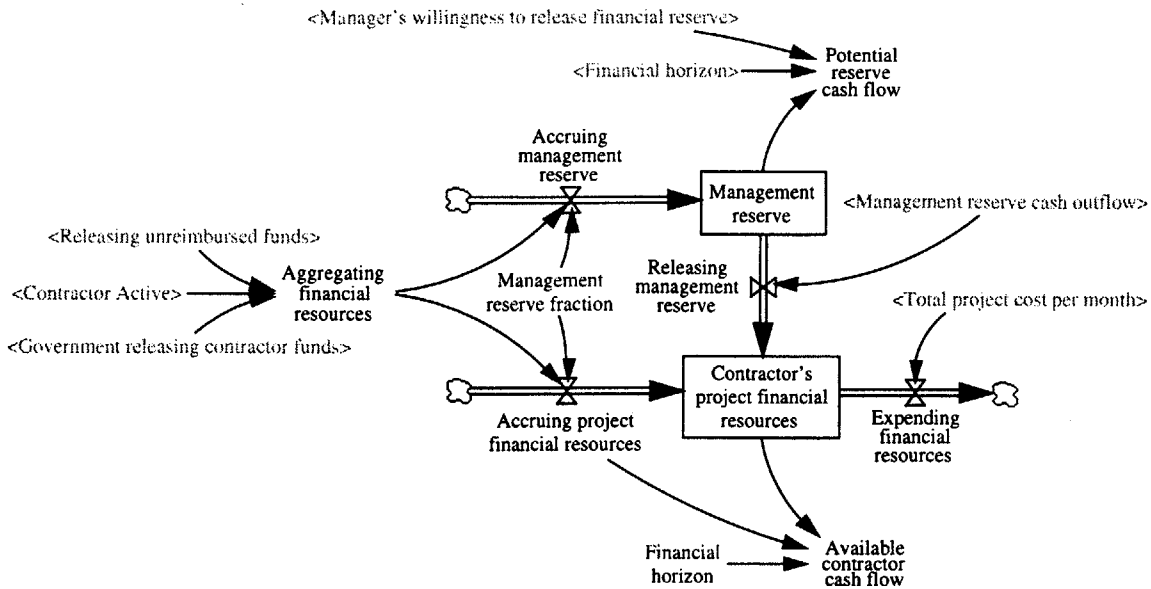
Uses: (037)Cumulative labor cost -  
(041)Overhead cost per month -  
(047)Total project cost per month -

(047) Total project cost per month = Total labor cost per month+Overhead cost per month

Units: \$/Month

Uses: (036)Cumulative contractor cost -  
(034)Average total project cost per month -  
(054)Expending financial resources -  
(069)MR funds indicated by cash flow shortfall -

### 8.5.1.5 Contractor Financial Resources



(049)  $\text{Accruing management reserve} = \text{Aggregating financial resources} * \text{Management reserve fraction}$   
 Units: \$/Month  
 Uses: (056)Management reserve -

(050)  $\text{Accruing project financial resources} = \text{Aggregating financial resources} * (1 - \text{Management reserve fraction})$   
 Units: \$/Month  
 Comment: The net flow of dollars into the project which the manager will initially spend  
 Uses: (053)Contractor's project financial resources -  
 (052)Available contractor cash flow -

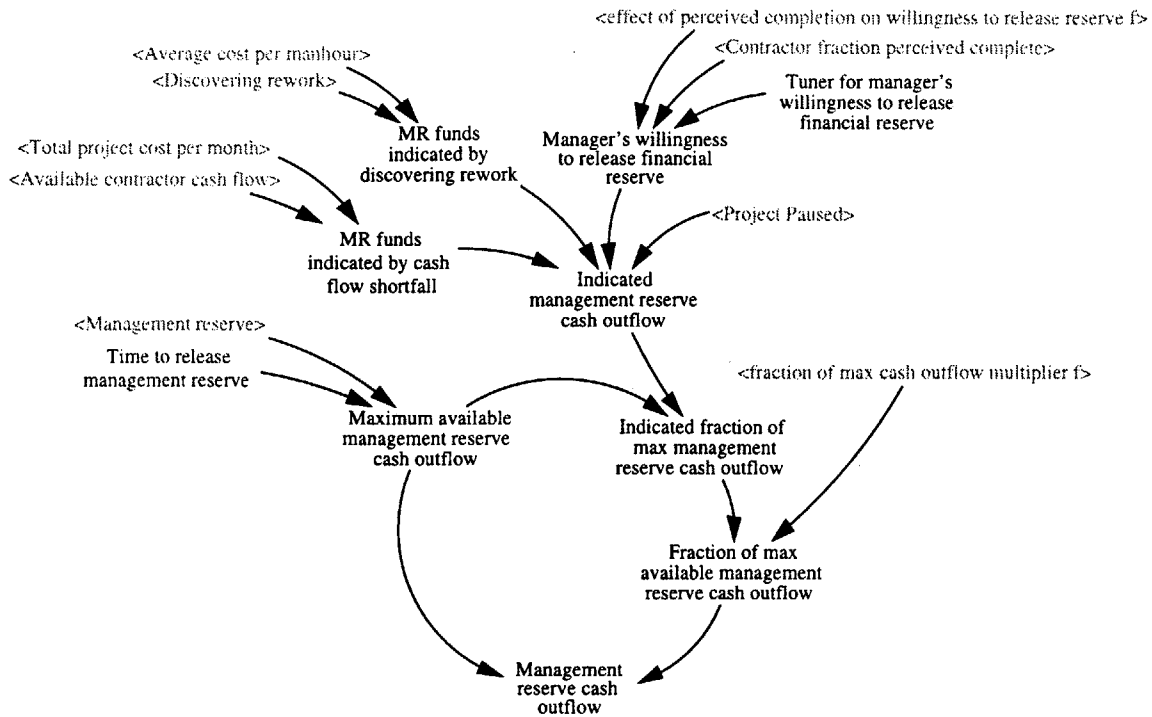
(051)  $\text{Aggregating financial resources} = (\text{Releasing unreimbursed funds} + \text{Government releasing contractor funds}) * \text{Contractor Active}$   
 Units: \$/Month  
 Comment: Net flow of financial resources into the project  
 Uses: (049)Accruing management reserve -  
 (050)Accruing project financial resources -

(052)  $\text{Available contractor cash flow} = \text{Accruing project financial resources} + \text{MAX}(0, \text{Contractor's project financial resources} / \text{Financial horizon})$   
 Units: \$/Month  
 Uses: (038)Financial pressure -  
 (143)Financial resources available for workforce -  
 (069)MR funds indicated by cash flow shortfall -  
 (306)Project Paused -

(053)  $\text{Contractor's project financial resources} = \text{INTEG}(\text{Accruing project financial resources} + \text{Releasing management reserve} - \text{Expending financial resources}, 0)$   
 Units: \$  
 Comment: The accumulated financial resources for the project  
 Uses: (052)Available contractor cash flow -

- (054) Expending financial resources = Total project cost per month  
 Units: \$/Month  
 Comment: The total monthly expenditures of financial resources per month  
 Uses: (053)Contractor's project financial resources -
- (055) Financial horizon = 12  
 Units: Month  
 Uses: (052)Available contractor cash flow -  
 (058)Potential reserve cash flow -
- (056) Management reserve = INTEG (Accruing management reserve-Releasing management reserve,0)  
 Units: \$  
 Uses: (068)Maximum available management reserve cash outflow -  
 (058)Potential reserve cash flow -
- (057) Management reserve fraction = 0  
 Units: fraction  
 Comment: Fraction of potentially available cash flow that management holds in reserve.  
 Uses: (049)Accruing management reserve -  
 (050)Accruing project financial resources -
- (058) Potential reserve cash flow = MAX(0, Management reserve/Financial horizon)  
\*Manager's willingness to release financial reserve  
 Units: \$/Month  
 Comment: The potential cash flow available from the contractor's management reserve.  
 Uses: (038)Financial pressure -  
 (143)Financial resources available for workforce -  
 (306)Project Paused -
- (059) Releasing management reserve = Management reserve cash outflow  
 Units: \$/Month  
 Uses: (053)Contractor's project financial resources -  
 (056)Management reserve -

### 8.5.1.6 Contractor Management Reserve



(061) effect of perceived completion on willingness to release reserve f  
 ((0,0)-(1,1]),(0,0),(0.1,0),(0.2,0.0175),(0.3,0.05),(0.4,0.175),  
 (0.5,0.4),(0.6,0.78),(0.7,0.925),(0.8,0.98),(0.85,1),(1,1))

Units: dmnl

Uses: (067)Manager's willingness to release financial reserve -

(062) Fraction of max available management reserve cash outflow =  
 IF THEN ELSE(Indicated fraction of max management reserve cash outflow>2,  
 fraction of max cash outflow multiplier f(2),  
 fraction of max cash outflow multiplier f(Indicated fraction of max management reserve cash outflow))

Units: fraction

Uses: (066)Management reserve cash outflow -

(063) fraction of max cash outflow multiplier f([(0,0)-(2,1]),(0,0),(0.9,0.9),(1,0.95),(2,1))

Units: dmnl

Uses: (062)Fraction of max available management reserve cash outflow -

(064) Indicated fraction of max management reserve cash outflow =  
 IF THEN ELSE(Maximum available management reserve cash outflow<= 0, 0,  
 Indicated management reserve cash outflow/Maximum available management reserve cash outflow)

Units: fraction

Uses: (062)Fraction of max available management reserve cash outflow -

(065) Indicated management reserve cash outflow = MAX(MR funds indicated by cash flow shortfall, MR funds indicated by discovering rework)\*Manager's willingness to release financial reserve  
 \*(1-Project Paused)

Units: \$/Month

Uses: (064)Indicated fraction of max management reserve cash outflow -

(066) Management reserve cash outflow = Maximum available management reserve cash outflow  
 \*Fraction of max available management reserve cash outflow

Units: \$/Month

Uses: (059)Releasing management reserve -

(067) Manager's willingness to release financial reserve =  
 (effect of perceived completion on willingness to release reserve f  
 (Contractor fraction perceived complete))  
 \*Tuner for manager's willingness to release financial reserve  
 +(1-Tuner for manager's willingness to release financial reserve)

Units: dmnl

Uses: (065)Indicated management reserve cash outflow -  
 (058)Potential reserve cash flow -

(068) Maximum available management reserve cash outflow =  
 Management reserve/Time to release management reserve

Units: \$/Month

Uses: (064)Indicated fraction of max management reserve cash outflow -  
 (066)Management reserve cash outflow -

(069) MR funds indicated by cash flow shortfall =  
 MAX(0,Total project cost per month-Available contractor cash flow)

Units: \$/Month

Comment: When the total project cost per month is more than the available cash flow, there is a  
 shortfall.

Uses: (065)Indicated management reserve cash outflow -

(070) MR funds indicated by discovering rework = Discovering rework\*Average cost per manhour

Units: \$/Month

Uses: (065)Indicated management reserve cash outflow -

(071) Time to release management reserve = 1

Units: Month

Uses: (068)Maximum available management reserve cash outflow -

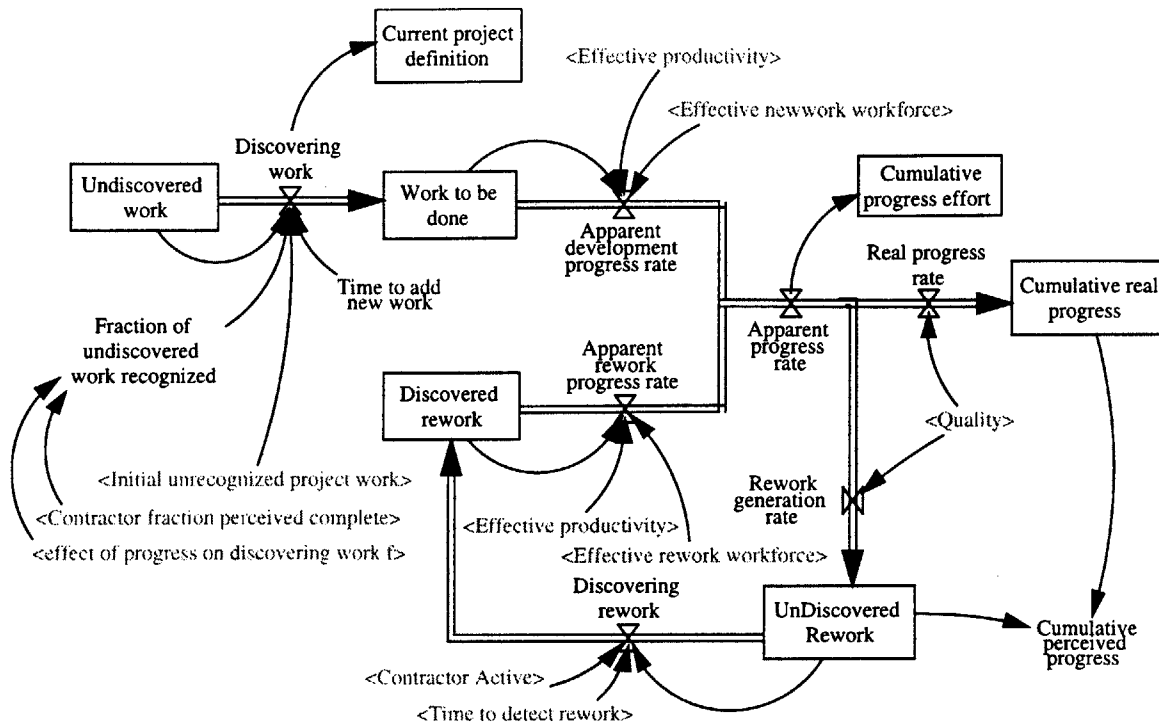
(072) Tuner for manager's willingness to release financial reserve = 1

Units: dmnl

Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the  
 full strength of the function, while a value of 0 results in a complete negation of the  
 function. e.g. Effect = Function(Variable)\*Tuner + (1-Tuner)

Uses: (067)Manager's willingness to release financial reserve -

### 8.5.1.7 Contractor Rework Cycle



(074) Apparent development progress rate =  
 $\text{MIN}(\text{Effective newwork workforce} * \text{Effective productivity}, \text{Work to be done} / \text{TIME STEP})$

Units: manhours/Month

Uses: (091) Work to be done -  
 (075) Apparent progress rate -

(075) Apparent progress rate = Apparent development progress rate + Apparent rework progress rate

Units: manhours/Month

Uses: (078) Cumulative progress effort -  
 (086) Real progress rate -  
 (087) Rework generation rate -

(076) Apparent rework progress rate =  
 $\text{MIN}(\text{Effective rework workforce} * \text{Effective productivity}, \text{Discovered rework} / \text{TIME STEP})$

Units: manhours/Month

Uses: (081) Discovered rework -  
 (075) Apparent progress rate -

(077) Cumulative perceived progress = Cumulative real progress + UnDiscovered Rework

Units: manhours

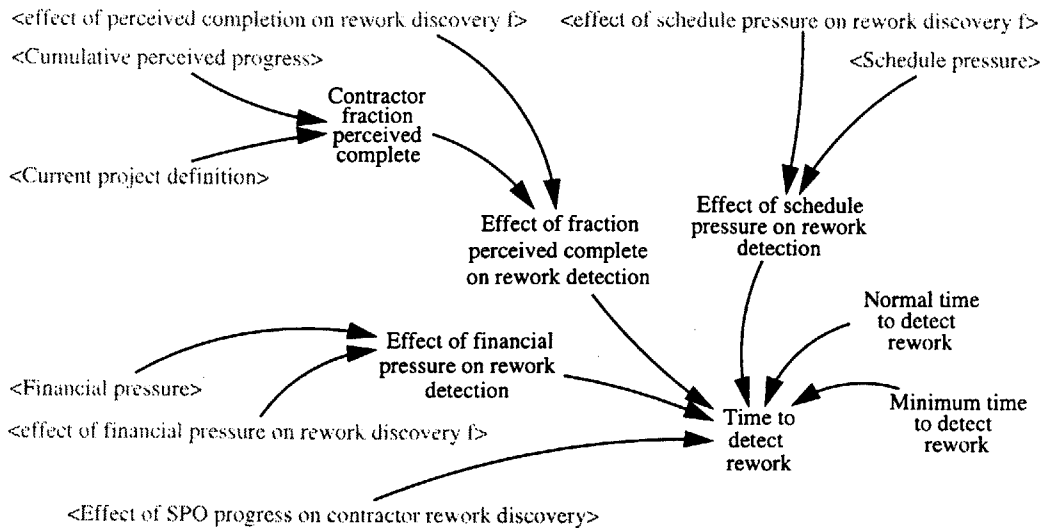
Uses: (301) Contractor Active -  
 (093) Contractor fraction perceived complete -

- (078) Cumulative progress effort = INTEG (Apparent progress rate,0)  
 Units: manhours  
 Uses: (032)Average cost per manhour -
- (079) Cumulative real progress = INTEG(Real progress rate, 0)  
 Units: manhours  
 Uses: (209)Average contractor work quality -  
 (077)Cumulative perceived progress -  
 (296)Product quality -  
 (297)Productivity estimated from contractor labor -
- (080) Current project definition = INTEG (Discovering work,Initial project size estimate)  
 Units: manhours  
 Comment: Current project definition is initialized to the initial project size and then increased as the true size of the project is discovered.  
 Uses: (301)Contractor Active -  
 (093)Contractor fraction perceived complete -
- (081) Discovered rework = INTEG(Discovering rework-Apparent rework progress rate,0)  
 Units: manhours  
 Uses: (076)Apparent rework progress rate -  
 (142)Effort perceived remaining -  
 (135)Indicated fraction of remaining workforce engaged in rework -  
 (296)Product quality -
- (082) Discovering rework = (UnDiscovered Rework / Time to detect rework)\*Contractor Active  
 Units: manhours/Month  
 Uses: (081)Discovered rework -  
 (089)UnDiscovered Rework -  
 (070)MR funds indicated by discovering rework -
- (083) Discovering work = (Undiscovered work-(1-Fraction of undiscovered work recognized)  
 \*Initial unrecognized project work)/Time to add new work  
 Units: manhours/Month  
 Uses: (080)Current project definition -  
 (090)Undiscovered work -  
 (091)Work to be done -
- (084) effect of progress on discovering work f([(0,0)-(1,1)],(0,0),(0.1,0.02),(0.125,0.07),(0.2,0.5),  
 (0.280967,0.864035),(0.323263,0.942982),(0.374622,0.973684),  
 (0.567976,0.982456),(1,1))  
 Units: fraction  
 Comment: fraction of undiscovered work found as a function of perceived progress.  
 Uses: (085)Fraction of undiscovered work recognized -
- (085) Fraction of undiscovered work recognized =  
 effect of progress on discovering work f(Contractor fraction perceived complete)  
 Units: dmnl  
 Comment: This construction is taken from James M. James Lyneis' Project Management lecture notes 15.976 fall 1997.  
 Uses: (083)Discovering work -

- (086) Real progress rate = Apparent progress rate\*Quality  
 Units: manhours/Month  
 Uses: (079)Cumulative real progress -
- (087) Rework generation rate = Apparent progress rate\*(1-Quality)  
 Units: manhours/Month  
 Uses: (089)UnDiscovered Rework -
- (088) Time to add new work = 0.25  
 Units: Month  
 Comment: Suggesting that within 1 month most of the affects are recognized  
 Uses: (083)Discovering work -
- (089) UnDiscovered Rework = INTEG(Rework generation rate - Discovering rework, 0)  
 Units: manhours  
 Uses: (209)Average contractor work quality -  
 (077)Cumulative perceived progress -  
 (082)Discovering rework -  
 (296)Product quality -  
 (297)Productivity estimated from contractor labor -
- (090) Undiscovered work = INTEG (-Discovering work,Initial unrecognized project work)  
 Units: manhours  
 Comment: Current project definition is initialized to the initial project size and then increased as  
 the true size of the project is discovered.  
 Uses: (083)Discovering work -
- (091) Work to be done =  
 INTEG (+Discovering work-Apparent development progress rate, Initial project size estimate)  
 Units: manhours  
 Uses: (074)Apparent development progress rate -  
 (142)Effort perceived remaining -  
 (135)Indicated fraction of remaining workforce engaged in rework -



### 8.5.1.8 Contractor Time to Discover Rework



(093) Contractor fraction perceived complete =  

$$\text{MIN}(\text{Cumulative perceived progress}/\text{Current project definition}, 1)$$

Units: dmn1

- Uses: (662)Contractor progress relative to required progress -  
 (671)Effect of contractor progress on SPO rework discovery -  
 (096)Effect of fraction perceived complete on rework detection -  
 (235)Effect of perceived completion on weight -  
 (237)Effect of progress on willingness to slip -  
 (085)Fraction of undiscovered work recognized -  
 (402)Fractional disbursement of administered funds indicated by contractor progress -  
 (067)Manager's willingness to release financial reserve -  
 (303)Minimum cash flow required for project progress -  
 (283)Required SPO progress -  
 (286)SPO weight on early phase productivity function -  
 (206)Weight given to real productivity -  
 (145)Willingness to change workforce -

(094) Effect of financial pressure on rework detection =  

$$\text{effect of financial pressure on rework discovery } f(\text{Financial pressure})$$

Units: dmn1

- Uses: (102)Time to detect rework -

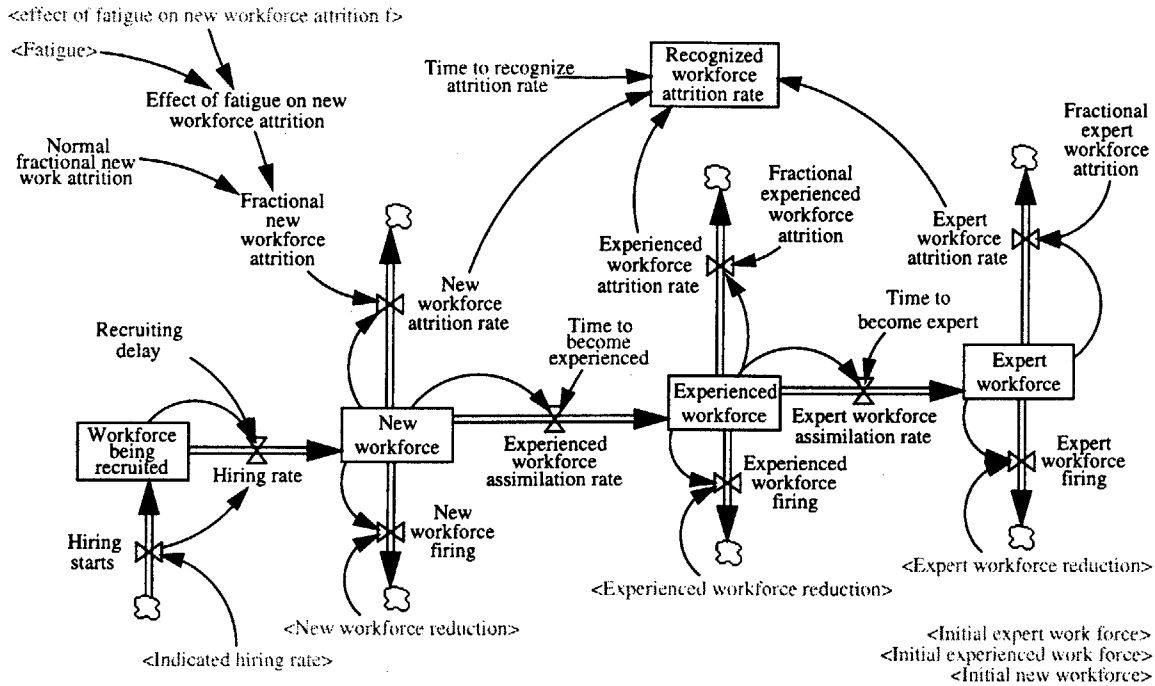
(095) effect of financial pressure on rework discovery  $f([(0,0)-(2,2)],(0,1),(1,1),(1.2,1.05),(1.4,1.1),$   
 $(1.6,1.2),(1.8,1.4))$

Units: dmn1

- Uses: (094)Effect of financial pressure on rework detection -

- (096) Effect of fraction perceived complete on rework detection =  
 effect of perceived completion on rework discovery f(Contractor fraction perceived complete)  
 Units: dmn1  
 Uses: (102)Time to detect rework -
- (097) effect of perceived completion on rework discovery f([(0,0)-(1,1)],(0,1),(0.4,1),(0.5,0.95),  
 (0.6,0.825),(0.7,0.65),(0.8,0.425),(0.9,0.2),(0.95,0.125),(1,0.08))  
 Units: dmn1  
 Comment: Fraction of normal time to detect rework as a function of project completion.  
 Uses: (096)Effect of fraction perceived complete on rework detection -
- (098) Effect of schedule pressure on rework detection =  
 effect of schedule pressure on rework discovery f(Schedule pressure)  
 Units: dmn1  
 Uses: (102)Time to detect rework -
- (099) effect of schedule pressure on rework discovery f([(0,0.8)-(0.8,2)],(0,1),(0.1,1),(0.2,1.02),  
 (0.3,1.06),(0.4,1.12),(0.5,1.2),(0.6,1.3),(0.7,1.4))  
 Units: dmn1  
 Comment: Estimate by author, based upon experience and analytical judgment.  
 Uses: (098)Effect of schedule pressure on rework detection -
- (100) Minimum time to detect rework = 0.25  
 Units: Month  
 Uses: (102)Time to detect rework -
- (101) Normal time to detect rework = 6  
 Units: Month  
 Uses: (102)Time to detect rework -
- (102) Time to detect rework = MAX(Effect of fraction perceived complete on rework detection  
 \*Effect of schedule pressure on rework detection\*Effect of financial pressure on rework detection  
 \*Effect of SPO progress on contractor rework discovery\*Normal time to detect rework,  
 Minimum time to detect rework)  
 Units: Month  
 Uses: (082)Discovering rework -

### 8.5.1.9 Contractor Workforce



- (104) Effect of fatigue on new workforce attrition = effect of fatigue on new workforce attrition f(Fatigue)  
 Units: dmnl  
 Uses: (116)Fractional new workforce attrition -
- (105) effect of fatigue on new workforce attrition f  $[( -0.2, 0 ) - ( 0.5, 2 )]$ ,  
 $( -0.2, 0.99 ) , ( 0, 1 ) , ( 0.1, 1.03 ) , ( 0.2, 1.08 ) , ( 0.3, 1.13 ) , ( 0.5, 1.25 )$   
 Units: dmnl  
 Comment: Fractional attrition increases as fatigue accumulates. Estimate by author, based upon experience and analytical judgment.  
 Uses: (104)Effect of fatigue on new workforce attrition -
- (106) Experienced workforce = INTEG(+Experienced workforce assimilation rate  
 -Expert workforce assimilation rate-Experienced workforce attrition rate  
 -Experienced workforce firing, Initial experienced work force)  
 Units: man  
 Uses: (162)Average experienced workforce experience -  
 (210)Average workforce fraction of normal quality -  
 (194)Average workforce productivity -  
 (108)Experienced workforce attrition rate -  
 (109)Experienced workforce firing -  
 (167)Experienced workforce gaining experience -  
 (154)Experienced workforce reduction -  
 (111)Expert workforce assimilation rate -  
 (155)Expert workforce reduction -  
 (158)New workforce reduction -  
 (159)Workforce -

- (107) Experienced workforce assimilation rate =  $\text{MAX}(0, \text{New workforce} / \text{Time to become experienced})$   
 Units: man/months  
 Uses: (106)Experienced workforce -  
 (122)New workforce -  
 (170)Increasing experienced workforce experience -
- (108) Experienced workforce attrition rate =  $\text{MAX}(0, \text{Experienced workforce} * \text{Fractional experienced workforce attrition})$   
 Units: man/months  
 Uses: (106)Experienced workforce -  
 (126)Recognized workforce attrition rate -  
 (179)Reducing experienced workforce experience -
- (109) Experienced workforce firing =  $\text{MIN}(\text{Experienced workforce reduction}, \text{Experienced workforce} / \text{TIME STEP})$   
 Units: man/Month  
 Comment: This construction is intended keep Experienced workforce positive or zero and ensure that new hires are fired first.  
 Uses: (106)Experienced workforce -  
 (179)Reducing experienced workforce experience -
- (110) Expert workforce =  $\text{INTEG}(+\text{Expert workforce assimilation rate} - \text{Expert workforce attrition rate} - \text{Expert workforce firing}, \text{Initial expert work force})$   
 Units: man  
 Uses: (163)Average expert workforce experience -  
 (210)Average workforce fraction of normal quality -  
 (194)Average workforce productivity -  
 (154)Experienced workforce reduction -  
 (112)Expert workforce attrition rate -  
 (113)Expert workforce firing -  
 (169)Expert workforce gaining experience -  
 (155)Expert workforce reduction -  
 (158)New workforce reduction -  
 (159)Workforce -
- (111) Expert workforce assimilation rate =  $\text{Experienced workforce} / \text{Time to become expert}$   
 Units: man/Month  
 Uses: (106)Experienced workforce -  
 (110)Expert workforce -  
 (171)Increasing expert workforce experience -
- (112) Expert workforce attrition rate =  $\text{MAX}(0, \text{Expert workforce} * \text{Fractional expert workforce attrition})$   
 Units: man/months  
 Uses: (110)Expert workforce -  
 (126)Recognized workforce attrition rate -  
 (180)Reducing expert workforce experience -
- (113) Expert workforce firing =  $\text{MIN}(\text{Expert workforce reduction}, \text{Expert workforce} / \text{TIME STEP})$   
 Units: man/Month  
 Comment: This construction is intended keep Expert workforce positive or zero and ensure that new hires and experienced workers are fired first.  
 Uses: (110)Expert workforce -  
 (180)Reducing expert workforce experience -



(122)  $\text{New workforce} = \text{INTEG}(-\text{Experienced workforce assimilation rate} - \text{New workforce attrition rate} - \text{New workforce firing} + \text{Hiring rate}, \text{Initial new workforce})$

Units: man

Uses: (164)Average new workforce experience -  
(210)Average workforce fraction of normal quality -  
(194)Average workforce productivity -  
(107)Experienced workforce assimilation rate -  
(154)Experienced workforce reduction -  
(155)Expert workforce reduction -  
(123)New workforce attrition rate -  
(124)New workforce firing -  
(178)New workforce gaining experience -  
(158)New workforce reduction -  
(159)Workforce -

(123)  $\text{New workforce attrition rate} = \text{MAX}(0, \text{New workforce} * \text{Fractional new workforce attrition})$

Units: man/months

Uses: (122)New workforce -  
(126)Recognized workforce attrition rate -  
(181)Reducing new workforce experience -

(124)  $\text{New workforce firing} = \text{MIN}(\text{New workforce reduction}, \text{New workforce} / \text{TIME STEP})$

Units: man/Month

Comment: This construction is intended to keep firing from draining New workforce below zero.

Uses: (122)New workforce -  
(181)Reducing new workforce experience -

(125)  $\text{Normal fractional new work attrition} = 0.01$

Units: 1/Month

Comment: Normal fraction of new workforce which chooses to leave each month.

Uses: (116)Fractional new workforce attrition -

(126)  $\text{Recognized workforce attrition rate} = \text{SMOOTH}(\text{Expert workforce attrition rate} + \text{Experienced workforce attrition rate} + \text{New workforce attrition rate}, \text{Time to recognize attrition rate})$

Units: man/Month

Uses: (150)Attritors replacement -  
(153)Base hiring rate -

(127)  $\text{Recruiting delay} = 2$

Units: Month

Comment: Estimate by author, based upon experts anecdotes.

Uses: (150)Attritors replacement -  
(117)Hiring rate -

(128)  $\text{Time to become experienced} = 24$

Units: Month

Uses: (107)Experienced workforce assimilation rate -

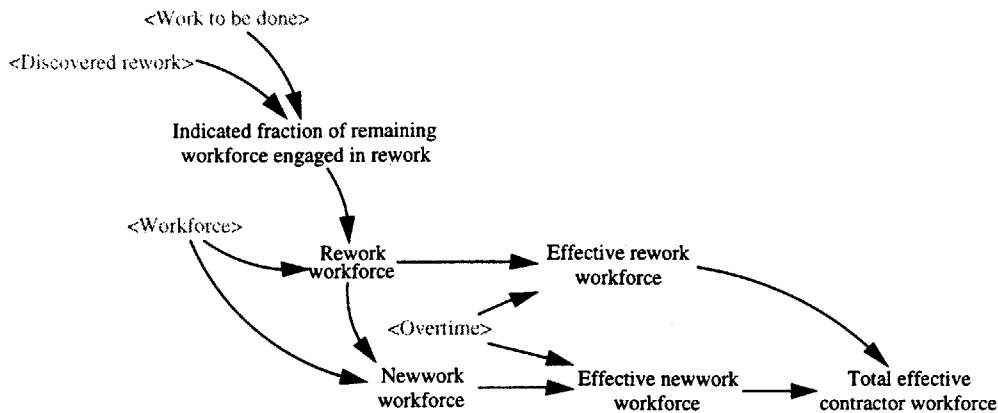
(129)  $\text{Time to become expert} = 24$

Units: Month

Uses: (111)Expert workforce assimilation rate -

- (130) Time to recognize attrition rate = 1  
Units: Month  
Uses: (126)Recognized workforce attrition rate -
- (131) Workforce being recruited = INTEG(+Hiring starts-Hiring rate,Attritors replacement)  
Units: man  
Uses: (149)Attrition correction -  
(117)Hiring rate -

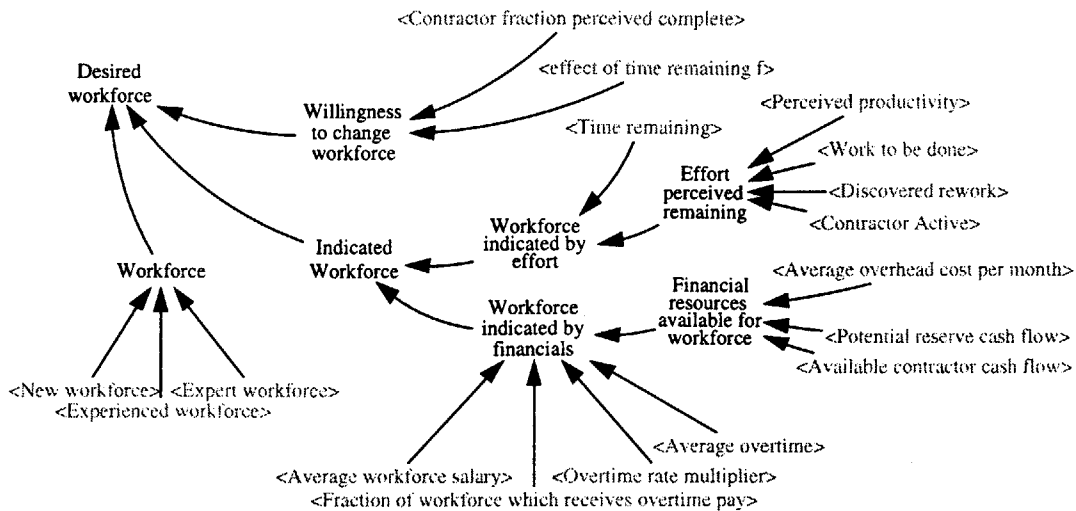
### 8.5.1.10 Contractor Workforce Distribution



- (133)  $\text{Effective newwork workforce} = \text{Newwork workforce} * (1 + \text{Overtime})$   
 Units: man  
 Uses: (074) Apparent development progress rate -  
 (138) Total effective contractor workforce -
- (134)  $\text{Effective rework workforce} = \text{Rework workforce} * (1 + \text{Overtime})$   
 Units: man  
 Uses: (076) Apparent rework progress rate -  
 (138) Total effective contractor workforce -
- (135) Indicated fraction of remaining workforce engaged in rework =  
 $\text{IF THEN ELSE}((\text{Work to be done} + \text{Discovered rework}) = 0, 0, \text{Discovered rework} / (\text{Work to be done} + \text{Discovered rework}))$   
 Units: fraction  
 Uses: (137) Rework workforce -
- (136)  $\text{Newwork workforce} = \text{Workforce} - \text{Rework workforce}$   
 Units: man  
 Uses: (133) Effective newwork workforce -
- (137)  $\text{Rework workforce} = \text{Indicated fraction of remaining workforce engaged in rework} * \text{Workforce}$   
 Units: man  
 Uses: (134) Effective rework workforce -  
 (136) Newwork workforce -
- (138)  $\text{Total effective contractor workforce} = \text{Effective newwork workforce} + \text{Effective rework workforce}$   
 Units: man  
 Comment: The full-time-equivalent personnel workforce is the size of the physical workforce if overtime hours were worked by additional employees.  
 Uses: (294) Cumulative manhours effort -



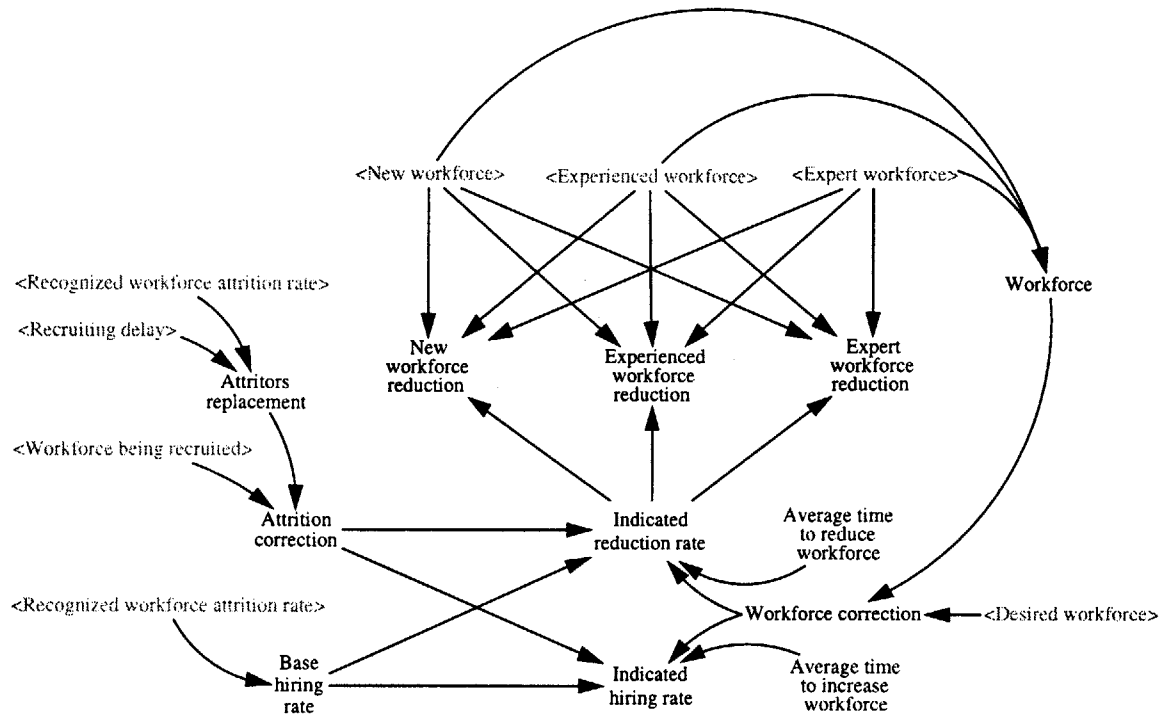
### 8.5.1.11 Contractor Workforce Sizing



- (140)  $\text{Desired workforce} = \text{Indicated Workforce} * \text{Willingness to change workforce} + \text{Workforce} * (1 - \text{Willingness to change workforce})$   
 Units: man  
 Comment: The desired physical workforce...affected by willingness to change workforce policy  
 Uses: (160)Workforce correction -
- (141) effect of time remaining  $f([(0,0)-(1,1)],(0,1),(1,1))$   
 Units: dnm1  
 Comment: Current function values remove the influence of this function.  
 Uses: (145)Willingness to change workforce -
- (142)  $\text{Effort perceived remaining} = ((\text{Work to be done} + \text{Discovered rework}) / \text{Perceived productivity}) * \text{Contractor Active}$   
 Units: man\*months  
 Uses: (252)Perceived time required -  
 (146)Workforce indicated by effort -
- (143)  $\text{Financial resources available for workforce} = \text{MAX}(\text{Available contractor cash flow} + \text{Potential reserve cash flow} - \text{Average overhead cost per month}, 0)$   
 Units: \$/Month  
 Uses: (147)Workforce indicated by financials -
- (144)  $\text{Indicated Workforce} = \text{MIN}(\text{Workforce indicated by effort}, \text{Workforce indicated by financials})$   
 Units: man  
 Uses: (140)Desired workforce -  
 (229)Recognized indicated workforce -

- (145) Willingness to change workforce = effect of time remaining f(Contractor fraction perceived complete)  
 Units: dnm1  
 Comment: willingness to change size of the workforce resulting from time remaining and financial pressure  
 Uses: (140)Desired workforce -
- (146) Workforce indicated by effort = Effort perceived remaining/Time remaining  
 Units: man  
 Uses: (144)Indicated Workforce -
- (147) Workforce indicated by financials =  
 IF THEN ELSE(Average overtime >= 0, Financial resources available for workforce/  
 (Average workforce salary\*(1+Fraction of workforce which receives overtime pay  
 \*Average overtime\*Overtime rate multiplier)),  
 Financial resources available for workforce/(Average workforce salary  
 \*(1+Fraction of workforce which receives overtime pay\*Average overtime)))  
 Units: man  
 Uses: (144)Indicated Workforce -

### 8.5.1.12 Contractor Workforce Management



(149) Attrition correction = Attritors replacement - Workforce being recruited  
 Units: man  
 Uses: (156) Indicated hiring rate -  
 (157) Indicated reduction rate -

(150) Attritors replacement = Recognized workforce attrition rate \* Recruiting delay  
 Units: man  
 Uses: (131) Workforce being recruited -  
 (149) Attrition correction -

(151) Average time to increase workforce = 3  
 Units: Month  
 Uses: (156) Indicated hiring rate -

(152) Average time to reduce workforce = 3  
 Units: Month  
 Uses: (157) Indicated reduction rate -

(153) Base hiring rate = Recognized workforce attrition rate  
 Units: man/Month  
 Comment: The base hiring rate required to maintain the workforce at a constant level.  
 (compensating for attrition)  
 Uses: (156) Indicated hiring rate -  
 (157) Indicated reduction rate -

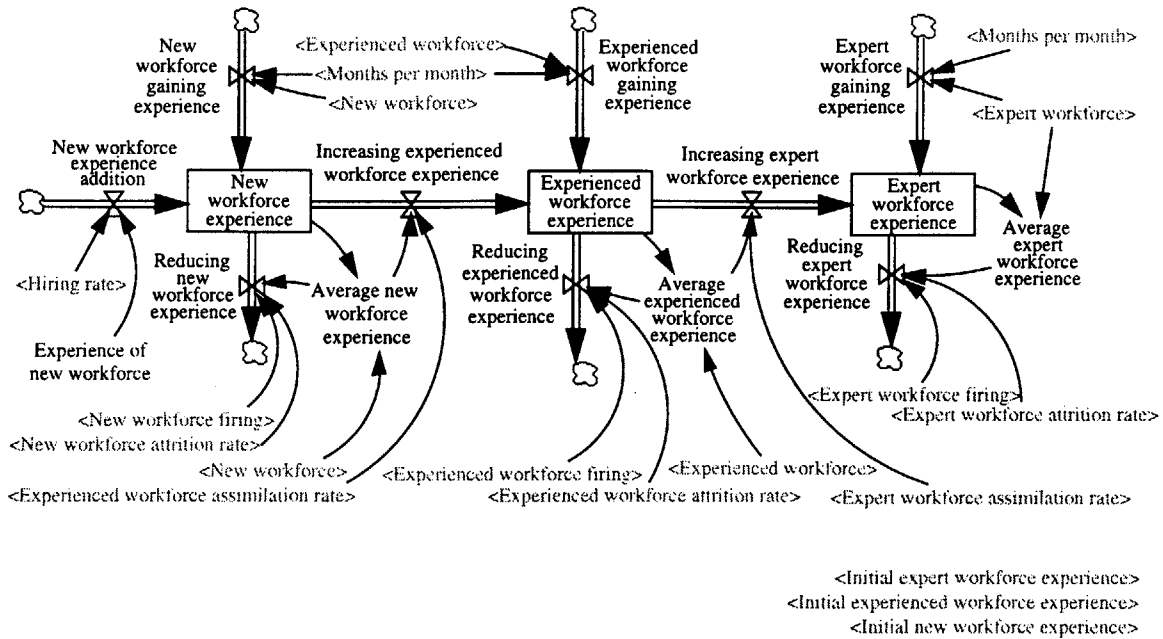
- (154) Experienced workforce reduction = Indicated reduction rate  

$$*(\text{Experienced workforce}/(\text{Expert workforce}+\text{Experienced workforce}+\text{New workforce}))$$
Units: man/Month  
Uses: (109)Experienced workforce firing -
- (155) Expert workforce reduction = Indicated reduction rate  

$$*(\text{Expert workforce}/(\text{Expert workforce}+\text{Experienced workforce}+\text{New workforce}))$$
Units: man/Month  
Uses: (113)Expert workforce firing -
- (156) Indicated hiring rate = MAX(0, Base hiring rate+(Workforce correction+Attrition correction)  
/Average time to increase workforce)  
Units: man/Month  
Uses: (118)Hiring starts -
- (157) Indicated reduction rate = (-1)\*MIN(0, Base hiring rate+(Workforce correction+Attrition correction)  
/Average time to reduce workforce)  
Units: man/Month  
Uses: (154)Experienced workforce reduction -  
(155)Expert workforce reduction -  
(158)New workforce reduction -
- (158) New workforce reduction = Indicated reduction rate  

$$*(\text{New workforce}/(\text{Expert workforce}+\text{Experienced workforce}+\text{New workforce}))$$
Units: man/Month  
Uses: (124)New workforce firing -
- (159) Workforce = Expert workforce+Experienced workforce+New workforce  
Units: man  
Comment: The physical sum of individuals working on the project.  
Uses: (140)Desired workforce -  
(226)Indicated overtime -  
(136)Newwork workforce -  
(040)Normal labor cost per month -  
(042)Overtime cost per month -  
(252)Perceived time required -  
(137)Rework workforce -  
(160)Workforce correction -
- (160) Workforce correction = Desired workforce-Workforce  
Units: man  
Comment: Difference between the actual workforce size and the desired workforce size.  
Uses: (156)Indicated hiring rate -  
(157)Indicated reduction rate -

### 8.5.1.13 Contractor Experience



(162) Average experienced workforce experience =  

$$\text{Experienced workforce experience} / \text{MAX}(1e-005, \text{Experienced workforce})$$

Units: months

- Uses: (187)Experienced worker fraction of normal productivity -  
 (188)Experienced worker quality -  
 (171)Increasing expert workforce experience -  
 (179)Reducing experienced workforce experience -

(163) Average expert workforce experience =  

$$\text{Expert workforce experience} / \text{MAX}(1e-005, \text{Expert workforce})$$

Units: months

- Uses: (189)Expert worker fraction of normal productivity -  
 (190)Expert worker quality -  
 (180)Reducing expert workforce experience -

(164) Average new workforce experience = 
$$\text{New workforce experience} / \text{MAX}(1e-005, \text{New workforce})$$

Units: months

- Uses: (170)Increasing experienced workforce experience -  
 (191)New worker fraction of normal productivity -  
 (192)New worker quality -  
 (181)Reducing new workforce experience -

(165) Experience of new workforce = 0.1

Units: months

- Uses: (177)New workforce experience addition -

- (166) Experienced workforce experience =  

$$\text{INTEG} (+\text{Increasing experienced workforce experience} - \text{Increasing expert workforce experience} - \text{Reducing experienced workforce experience} + \text{Experienced workforce gaining experience}, \text{Initial experienced work force} * \text{Initial experienced workforce experience})$$
Units: man\*months  
Comment: Total man-months of experience of experienced civilian.  
Uses: (162)Average experienced workforce experience -
- (167) Experienced workforce gaining experience = Experienced workforce\*Months per month  
Units: man\*months/Month  
Uses: (166)Experienced workforce experience -
- (168) Expert workforce experience =  

$$\text{INTEG} (+\text{Increasing expert workforce experience} - \text{Reducing expert workforce experience} + \text{Expert workforce gaining experience}, \text{Initial expert work force} * \text{Initial expert workforce experience})$$
Units: man\*months  
Comment: Total man-months of experience of expert civilian.  
Uses: (163)Average expert workforce experience -
- (169) Expert workforce gaining experience = Expert workforce\*Months per month  
Units: man\*months/Month  
Uses: (168)Expert workforce experience -
- (170) Increasing experienced workforce experience =  

$$\text{Average new workforce experience} * \text{Experienced workforce assimilation rate}$$
Units: man\*months/Month  
Uses: (166)Experienced workforce experience -  
(176)New workforce experience -
- (171) Increasing expert workforce experience =  

$$\text{Average experienced workforce experience} * \text{Expert workforce assimilation rate}$$
Units: man\*months/Month  
Uses: (166)Experienced workforce experience -  
(168)Expert workforce experience -
- (172) Initial experienced workforce experience = 30  
Units: Month  
Uses: (166)Experienced workforce experience -
- (173) Initial expert workforce experience = 60  
Units: Month  
Uses: (168)Expert workforce experience -
- (174) Initial new workforce experience = 0  
Units: Month  
Uses: (176)New workforce experience -

- (175) Months per month = 1  
 Units: months/Month  
 Uses: (523)Experienced civilians gaining experience -  
 (167)Experienced workforce gaining experience -  
 (525)Expert civilians gaining experience -  
 (169)Expert workforce gaining experience -  
 (460)Gaining experience -  
 (533)New civilians gaining experience -  
 (178)New workforce gaining experience -  
 (271)Sliding target date -
- (176) New workforce experience =  

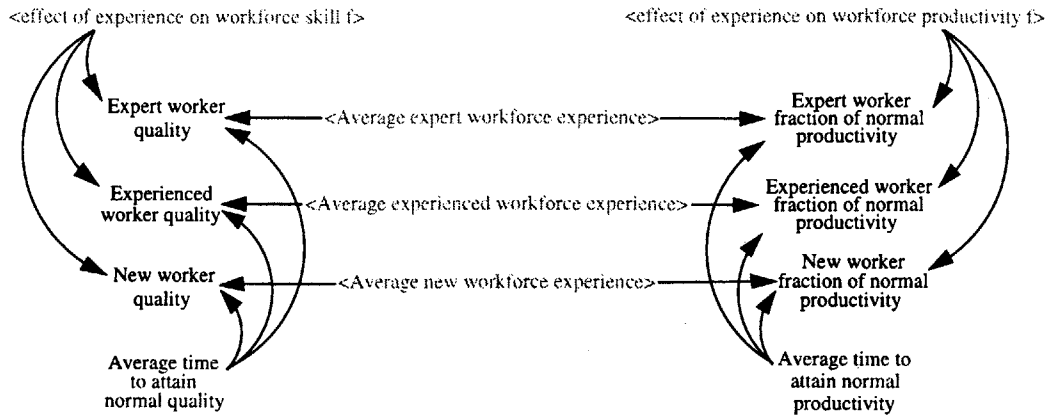
$$\text{INTEG} ( \quad +\text{New workforce gaining experience} + \text{New workforce experience addition} \\ - \text{Reducing new workforce experience} - \text{Increasing experienced workforce experience,} \\ \text{Initial new workforce} * \text{Initial new workforce experience} )$$
  
 Units: man\*months  
 Comment: Total man months of experience of new civilian.  
 Uses: (164)Average new workforce experience -
- (177) New workforce experience addition = Hiring rate\*Experience of new workforce  
 Units: man\*Month/Month  
 Uses: (176)New workforce experience -
- (178) New workforce gaining experience = New workforce\*Months per month  
 Units: man\*months/Month  
 Uses: (176)New workforce experience -
- (179) Reducing experienced workforce experience =  

$$(\text{Experienced workforce attrition rate} + \text{Experienced workforce firing}) \\ * \text{Average experienced workforce experience}$$
  
 Units: man\*months/Month  
 Uses: (166)Experienced workforce experience -
- (180) Reducing expert workforce experience =  

$$(\text{Expert workforce attrition rate} + \text{Expert workforce firing}) * \text{Average expert workforce experience}$$
  
 Units: man\*months/Month  
 Uses: (168)Expert workforce experience -
- (181) Reducing new workforce experience =  

$$(\text{New workforce attrition rate} + \text{New workforce firing}) * \text{Average new workforce experience}$$
  
 Units: man\*months/Month  
 Uses: (176)New workforce experience -

### 8.5.1.14 Effect of Workforce Experience on Contractor Quality and Productivity



- (183) Average time to attain normal productivity = 0.1

Units: Month

Comment: The average time required for an individual new to the project to fully learn the project's tools and methods. That is, to attain the expected level of productivity, typically 5 years.

Uses: (187)Experienced worker fraction of normal productivity -  
 (189)Expert worker fraction of normal productivity -  
 (191)New worker fraction of normal productivity -

- (184) Average time to attain normal quality = 0.1

Units: Month

Comment: The average time required for an individual new to the project to fully learn the project's tools and methods. That is, to attain the expected level of skill, typically 5 years.

Uses: (188)Experienced worker quality -  
 (190)Expert worker quality -  
 (192)New worker quality -

- (185) effect of experience on workforce productivity  $f([(0,0)-(1.5,1)],(0,0.3),(0.1,0.5),(0.2,0.625),$   
 $(0.3,0.73),(0.4,0.8),(0.5,0.86),(0.6,0.9),(0.7,0.94),$   
 $(0.8,0.965),(0.9,0.99),(1,1),(1.5,1))$

Units: dmn1

Comment: After James Lyneis

Uses: (187)Experienced worker fraction of normal productivity -  
 (189)Expert worker fraction of normal productivity -  
 (191)New worker fraction of normal productivity -

- (186) effect of experience on workforce skill  $f([(0,0)-(1.5,1)],(0,0.3),(0.1,0.5),(0.2,0.625),(0.3,0.73),$   
 $(0.4,0.8),(0.5,0.86),(0.6,0.9),(0.7,0.94),(0.8,0.965),(0.9,0.99),(1,1),(1.5,1))$

Units: dmn1

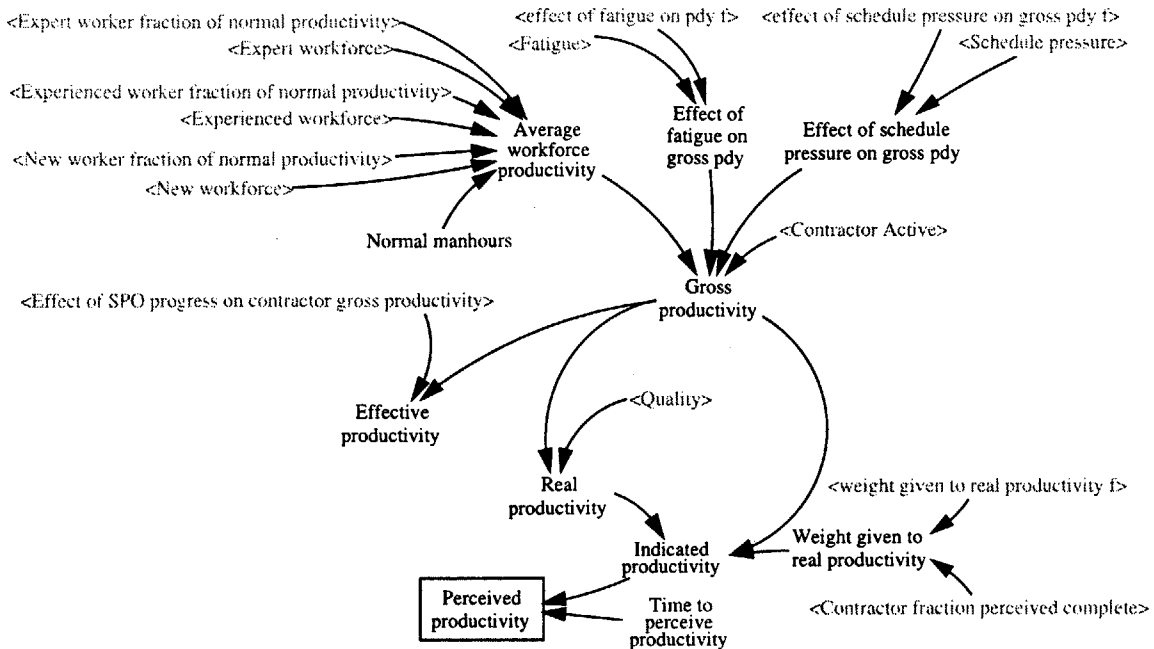
Comment: After James Lyneis

Uses: (188)Experienced worker quality -  
 (190)Expert worker quality -  
 (192)New worker quality -



- (187) Experienced worker fraction of normal productivity = effect of experience on workforce productivity f  
 (Average experienced workforce experience/Average time to attain normal productivity)  
 Units: dmnl  
 Uses: (194)Average workforce productivity -
- (188) Experienced worker quality = effect of experience on workforce skill f  
 (Average experienced workforce experience/Average time to attain normal quality)  
 Units: fraction  
 Comment: Fraction of normal-work-quality of work completed by the average experienced worker.  
 Uses: (210)Average workforce fraction of normal quality -
- (189) Expert worker fraction of normal productivity = effect of experience on workforce productivity f  
 (Average expert workforce experience/Average time to attain normal productivity)  
 Units: dmnl  
 Uses: (194)Average workforce productivity -
- (190) Expert worker quality = effect of experience on workforce skill f  
 (Average expert workforce experience/Average time to attain normal quality)  
 Units: fraction  
 Comment: Fraction of normal-work-quality of work completed by the average expert worker.  
 Uses: (210)Average workforce fraction of normal quality -
- (191) New worker fraction of normal productivity = effect of experience on workforce productivity f  
 (Average new workforce experience/Average time to attain normal productivity)  
 Units: dmnl  
 Uses: (194)Average workforce productivity -
- (192) New worker quality = effect of experience on workforce skill f  
 (Average new workforce experience/Average time to attain normal quality)  
 Units: fraction  
 Comment: Fraction of normal-work-quality of work completed by the average new worker.  
 Uses: (210)Average workforce fraction of normal quality -

### 8.5.1.15 Contractor Productivity



(194) 
$$\text{Average workforce productivity} = \frac{(\text{Expert workforce} * \text{Expert worker fraction of normal productivity} + \text{Experienced workforce} * \text{Experienced worker fraction of normal productivity} + \text{New workforce} * \text{New worker fraction of normal productivity}) * \text{Normal manhours}}{(\text{Expert workforce} + \text{Experienced workforce} + \text{New workforce})}$$

Units: manhours/(Month\*man)  
 Uses: (200)Gross productivity -

(195) 
$$\text{Effect of fatigue on gross pdy} = \text{effect of fatigue on pdy f}(\text{Fatigue})$$
  
 Units: fraction  
 Comment: Represents the slow down in worker productivity when fatigued...they just can't work as fast.  
 Uses: (200)Gross productivity -

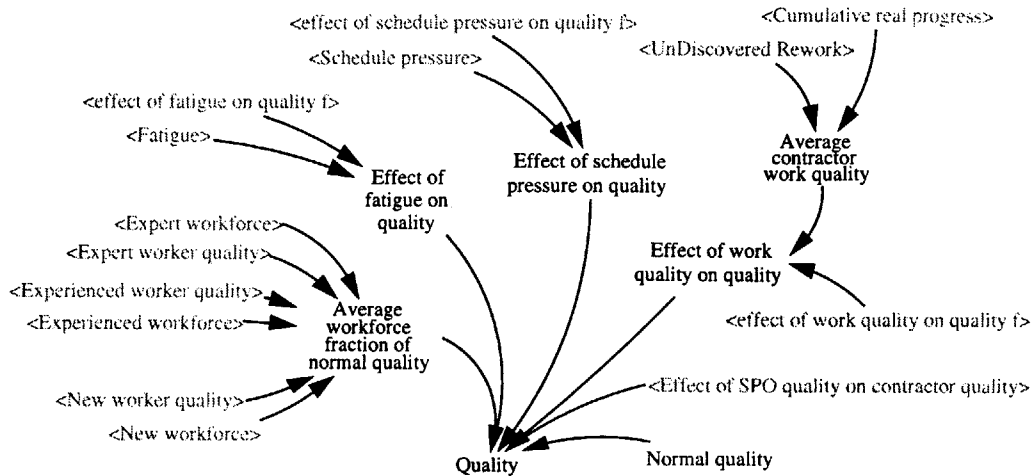
(196) 
$$\text{effect of fatigue on pdy f} \left( [(-0.5,0)- (1,2)], (-0.488402,0.921348), (-0.4,0.9545), (-0.2,1.04869), (-0.1,1.01), (0,1), (0.1,0.9545), (0.2,0.8698), (0.3,0.774), (0.512887,0.47191) \right)$$
  
 Units: fraction  
 Comment: The fraction of normal productivity possible as a function of fatigue. Numbers for positive part of curve Nevison's data Negative end is author's estimate.  
 Uses: (195)Effect of fatigue on gross pdy -

(197) 
$$\text{Effect of schedule pressure on gross pdy} = \text{effect of schedule pressure on gross pdy f}(\text{Schedule pressure})$$
  
 Units: dmn1  
 Comment: Simulates an overtime effect  
 Uses: (200)Gross productivity -

- (198) effect of schedule pressure on gross pdy  $f([(0,1)-(0.7,1.2)],(0,1),(0.1,1.0125),(0.2,1.0375),$   
 $(0.3,1.075),(0.4,1.125),(0.5,1.1625),(0.6,1.1875),(0.7,1.2))$   
Units: dmn1  
Comment: Taken from Jim James Lyneis' project model presented in 15.965 fall of 1997.  
Uses: (197)Effect of schedule pressure on gross pdy -
- (199) Effective productivity = Gross productivity\*Effect of SPO progress on contractor gross productivity  
Units: manhours/(Month\*man)  
Uses: (074)Apparent development progress rate -  
(076)Apparent rework progress rate -
- (200) Gross productivity =  
ACTIVE INITIAL ((Average workforce productivity\*Effect of fatigue on gross pdy  
\*Effect of schedule pressure on gross pdy)\*Contractor Active,  
Average workforce productivity)  
Units: manhours/(Month\*man)  
Uses: (199)Effective productivity -  
(201)Indicated productivity -  
(203)Perceived productivity -  
(204)Real productivity -
- (201) Indicated productivity = Real productivity\*Weight given to real productivity+Gross productivity  
\*(1-Weight given to real productivity)  
Units: manhours/(Month\*man)  
Uses: (203)Perceived productivity -
- (202) Normal manhours = 160  
Units: manhours/(Month\*man)  
Comment: The normal number of productive hours per month an individual is assumed capable  
of working.  
Uses: (294)Cumulative manhours effort -  
(194)Average workforce productivity -  
(014)Initial labor cost estimate -
- (203) Perceived productivity =  
SMOOTH(Indicated productivity,Time to perceive productivity,Gross productivity)  
Units: manhours/(Month\*man)  
Uses: (142)Effort perceived remaining -
- (204) Real productivity = Gross productivity\*Quality  
Units: manhours/man/Month  
Uses: (201)Indicated productivity -
- (205) Time to perceive productivity = 6  
Units: Month  
Uses: (203)Perceived productivity -
- (206) Weight given to real productivity =  
weight given to real productivity f(Contractor fraction perceived complete)  
Units: dmn1  
Uses: (201)Indicated productivity -

(207) weight given to real productivity  $f$   $([(0,0)-(1,1)],(0,0),(0.2,0.1) ,(0.4,0.25),(0.6,0.5),(0.8,0.9),(1,1))$   
Units: dmn1  
Comment: Weight given to real productivity as a function of fraction perceived completed (Pugh & Richardson)  
Uses: (206)Weight given to real productivity -

### 8.5.1.16 Contractor Quality



- (209) Average contractor work quality = IF THEN ELSE(Cumulative real progress = 0,1,  
Cumulative real progress/(UnDiscovered Rework+Cumulative real progress))

Units: dmn1

Uses: (673)Effect of contractor quality on SPO quality -  
(215)Effect of work quality on quality -

- (210) Average workforce fraction of normal quality = (Expert workforce\*Expert worker quality  
+Experienced workforce\*Experienced worker quality  
+New workforce\*New worker quality)  
/(Expert workforce+Experienced workforce+New workforce)

Units: fraction

Comment: Normal fraction of work completed correctly

Uses: (218)Quality -

- (211) Effect of fatigue on quality = effect of fatigue on quality f(Fatigue)

Units: fraction

Uses: (218)Quality -

- (212) effect of fatigue on quality f (((-0.4,0)-(1,2)],(-0.21,1.01),(0,1),(0.219072,0.970787),  
(0.469072,0.894382),(1,0.5))

Units: fraction

Uses: (211)Effect of fatigue on quality -

- (213) Effect of schedule pressure on quality = effect of schedule pressure on quality f(Schedule pressure)

Units: dmn1

Uses: (218)Quality -

- (214) effect of schedule pressure on quality f([(0,0.6)-(0.7,1)],(0,1),(0.1,0.975),(0.2,0.925),(0.3,0.85),  
(0.4,0.75),(0.5,0.675),(0.6,0.625),(0.7,0.6))

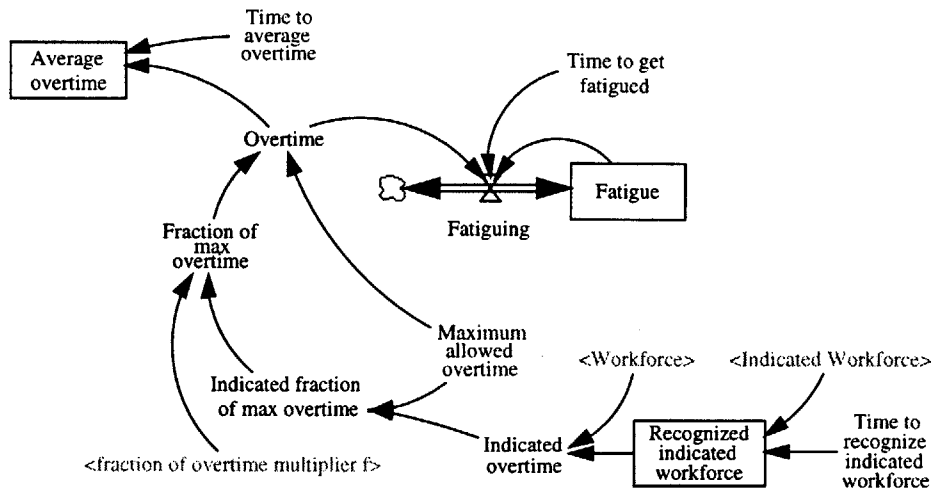
Units: dmn1

Comment: Taken from Jim James Lyneis' project model presented in 15.976 fall 1997

Uses: (213)Effect of schedule pressure on quality -

- (215) Effect of work quality on quality =  
 effect of work quality on quality f(Average contractor work quality)  
 Units: dmn1  
 Uses: (218)Quality -
- (216) effect of work quality on quality f([(0,0)-(1,1)],(0,0.1),(0.1,0.25),(0.2,0.35),(0.3,0.45),  
 (0.4,0.55),(0.5,0.65),(0.6,0.74),(0.7,0.83),(0.8,0.9),(0.9,0.95),(1,1))  
 Units: dmn1  
 Comment: Taken from James Lyneis' project model from 15.962 fall 1997  
 Uses: (215)Effect of work quality on quality -
- (217) Normal quality = 1  
 Units: fraction  
 Comment: The normal fraction of work done correctly by the average very experienced individual. This is the highest quality that can be achieved given the processes utilized.  
 Uses: (218)Quality -
- (218) Quality = Average workforce fraction of normal quality  
 \*Effect of fatigue on quality\*Effect of schedule pressure on quality  
 \*Effect of work quality on quality\*Effect of SPO quality on contractor quality  
 \*Normal quality  
 Units: fraction  
 Comment: Fraction of work completed with acceptable quality.  
 Uses: (204)Real productivity -  
 (086)Real progress rate -  
 (087)Rework generation rate -

### 8.5.1.17 Contractor Overtime and Fatigue

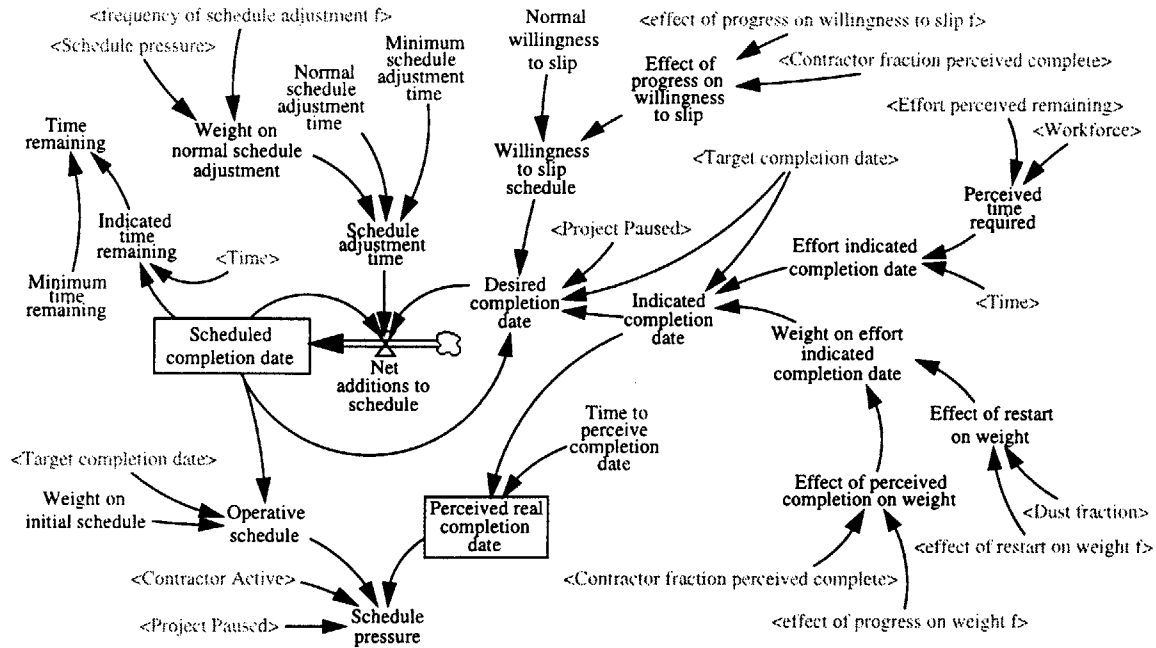


- (220)  $Average\ overtime = SMOOTHI(Overtime, Time\ to\ average\ overtime, 0)$   
 Units: fraction  
 Uses: (147)Workforce indicated by financials -
- (221)  $Fatigue = INTEG(Fatiguing, 0)$   
 Units: fraction  
 Comment: The fraction of the normal work period for which normal rest has been denied.  
 Uses: (195)Effect of fatigue on gross pdy -  
 (104)Effect of fatigue on new workforce attrition -  
 (211)Effect of fatigue on quality -  
 (222)Fatiguing -
- (222)  $Fatiguing = (Overtime - Fatigue) / Time\ to\ get\ fatigued$   
 Units: fraction/Month  
 Uses: (221)Fatigue -
- (223)  $Fraction\ of\ max\ overtime = IF\ THEN\ ELSE(Indicated\ fraction\ of\ max\ overtime < 2,$   
 $fraction\ of\ overtime\ multiplier\ f(Indicated\ fraction\ of\ max\ overtime),$   
 $fraction\ of\ overtime\ multiplier\ f(2))$   
 Units: fraction  
 Uses: (228)Overtime -
- (224)  $fraction\ of\ overtime\ multiplier\ f([(-2, -1) - (2, 1)], (-2, 0), (-0.1, 0), (0, 0), (0.1, 0), (1, 0.9),$   
 $(1.12887, 0.962547), (1.38144, 0.973783), (2, 1))$   
 Units: dmn1  
 Comment: Ceiling function for overtime function  
 Uses: (223)Fraction of max overtime -

- (225) Indicated fraction of max overtime = IF THEN ELSE(Maximum allowed overtime = 0, 0, Indicated overtime/Maximum allowed overtime)  
 Units: fraction  
 Comment: Maximum allowed OT is the ceiling above which OT is not allowed to pass.  
 Uses: (223)Fraction of max overtime -
- (226) Indicated overtime =  
 IF THEN ELSE(Workforce = 0,0,((Recognized indicated workforce-Workforce)/Workforce))  
 Units: fraction  
 Comment: Fraction of workforce needed to fulfill the overtime requirements suggested by indicated workforce.  
 Uses: (225)Indicated fraction of max overtime -
- (227) Maximum allowed overtime = 0.5  
 Units: fraction  
 Comment: Maximum fraction of regular work week which can be worked as overtime (hr/hr or man/man).  
 Uses: (225)Indicated fraction of max overtime -  
 (228)Overtime -
- (228) Overtime = Maximum allowed overtime\*Fraction of max overtime  
 Units: fraction  
 Comment: Fraction of the normal work week which is worked in addition to the normal work week.  
 Uses: (220)Average overtime -  
 (133)Effective newwork workforce -  
 (134)Effective rework workforce -  
 (222)Fatiguing -  
 (042)Overtime cost per month -
- (229) Recognized indicated workforce =  
 SMOOTH(Indicated Workforce, Time to recognize indicated workforce)  
 Units: man  
 Uses: (226)Indicated overtime -
- (230) Time to average overtime = 0.5  
 Units: Month  
 Uses: (220)Average overtime -
- (231) Time to get fatigued = 3  
 Units: months  
 Comment: Estimate by author, based upon experience and anecdotal evidence.  
 Uses: (222)Fatiguing -
- (232) Time to recognize indicated workforce = 0.5  
 Units: Month  
 Uses: (229)Recognized indicated workforce -



### 8.5.1.18 Contractor Schedule



(234) 
$$\text{Desired completion date} = (\text{Willingness to slip schedule} * \text{MAX}(0, (\text{Indicated completion date} - \text{Scheduled completion date})) + \text{Scheduled completion date}) * (1 - \text{Project Paused}) + (\text{Willingness to slip schedule} * (\text{Target completion date} - \text{Scheduled completion date}) + \text{Scheduled completion date}) * \text{Project Paused}$$

Units: Month

Uses: (247) Net additions to schedule -

(235) 
$$\text{Effect of perceived completion on weight} = \text{effect of progress on weight } f(\text{Contractor fraction perceived complete})$$

Units: dmnl

Uses: (258) Weight on effort indicated completion date -

(236) 
$$\text{effect of progress on weight } f([(0,0)-(1,1)],(0,0),(0.1,0.1),(0.2,0.3),(0.3,0.5),(0.4,0.7),(0.5,0.85),(0.6,0.95),(0.7,1),(0.8,1),(0.9,1),(1,1))$$

Units: dmnl

Comment: Taken from James Lyneis' project model for 15.962 fall 1997

Uses: (235) Effect of perceived completion on weight -

(237) 
$$\text{Effect of progress on willingness to slip} = \text{effect of progress on willingness to slip } f(\text{Contractor fraction perceived complete})$$

Units: dmnl

Uses: (261) Willingness to slip schedule -

(238) 
$$\text{effect of progress on willingness to slip } f([(0,0)-(1,1)],(0,0),(0.1,0.3),(0.2,0.6),(0.3,0.9),(0.4,1),(0.5,1),(0.6,1),(0.7,1),(0.8,0.9),(0.9,0.6),(1,0))$$

Units: dmnl

Comment: Taken from James Lyneis' project model from 15.962 fall 1997

Uses: (237) Effect of progress on willingness to slip -

- (239) Effect of restart on weight = effect of restart on weight f(Dust fraction)  
 Units: dmn1  
 Uses: (258)Weight on effort indicated completion date -
- (240) effect of restart on weight f([(0,0)-(1,1)],(0,1),(0.1,0.4),(0.2,0.15),(0.3,0.05),(0.4,0.01),(1,0))  
 Units: dmn1  
 Comment: As the length of a program pause increases the function causes the system to weight the target completion date rather than that indicated by effort required.  
 Uses: (239)Effect of restart on weight -
- (241) Effort indicated completion date = Perceived time required+Time  
 Units: Month  
 Uses: (243)Indicated completion date -
- (242) frequency of schedule adjustment f([(0,0)-(1,1)],(0,1),(0.05,0.87),(0.1,0.75),(0.2,0.55),(0.3,0.4),(0.4,0.275),(0.5,0.175),(0.6,0.1),(0.7,0.05),(0.8,0.02),(0.9,0))  
 Units: dmn1  
 Uses: (260)Weight on normal schedule adjustment -
- (243) Indicated completion date =  

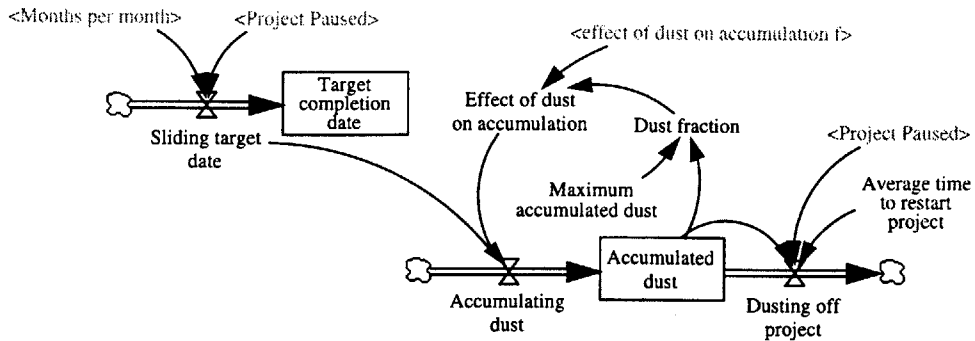
$$\text{Effort indicated completion date} * \text{Weight on effort indicated completion date} + \text{Target completion date} * (1 - \text{Weight on effort indicated completion date})$$
 Units: Month  
 Uses: (234)Desired completion date -  
 (251)Perceived real completion date -
- (244) Indicated time remaining = Scheduled completion date-Time  
 Units: Month  
 Uses: (256)Time remaining -
- (245) Minimum schedule adjustment time = 0.25  
 Units: Month  
 Uses: (253)Schedule adjustment time -
- (246) Minimum time remaining = 1  
 Units: Month  
 Comment: a minimum time remaining of 1 week = 0.25  
 Uses: (256)Time remaining -
- (247) Net additions to schedule =  

$$(\text{Desired completion date} - \text{Scheduled completion date}) / \text{Schedule adjustment time}$$
 Units: fraction  
 Uses: (255)Scheduled completion date -
- (248) Normal schedule adjustment time = 6  
 Units: Month  
 Uses: (253)Schedule adjustment time -
- (249) Normal willingness to slip = 0.5  
 Units: dmn1  
 Uses: (261)Willingness to slip schedule -

- (250) Operative schedule = Target completion date\*Weight on initial schedule  
+ (1-Weight on initial schedule)\*Scheduled completion date  
Units: Month  
Uses: (254)Schedule pressure -
- (251) Perceived real completion date =  
SMOOTH(Indicated completion date, Time to perceive completion date, Initial completion date)  
Units: Month  
Uses: (295)Original schedule slip -  
(254)Schedule pressure -  
(298)Schedule slip -
- (252) Perceived time required = Effort perceived remaining/Workforce  
Units: Month  
Uses: (241)Effort indicated completion date -
- (253) Schedule adjustment time = Normal schedule adjustment time\*Weight on normal schedule adjustment  
+ Minimum schedule adjustment time\*(1-Weight on normal schedule adjustment)  
Units: Month  
Comment: The intent here is to allow the adjustment time to be reduced as the time remaining  
becomes short, but not so small as to cause simulation problems.  
Uses: (247)Net additions to schedule -
- (254) Schedule pressure = MAX(0,(Perceived real completion date-Operative schedule)  
/Operative schedule)\*Contractor Active\*(1-Project Paused)  
Units: dmn1  
Uses: (197)Effect of schedule pressure on gross pdy -  
(213)Effect of schedule pressure on quality -  
(098)Effect of schedule pressure on rework detection -  
(260)Weight on normal schedule adjustment -
- (255) Scheduled completion date = INTEG(Net additions to schedule, Initial completion date)  
Units: Month  
Uses: (234)Desired completion date -  
(244)Indicated time remaining -  
(247)Net additions to schedule -  
(250)Operative schedule -  
(626)SPO indicated time remaining -  
(628)SPO operative schedule -
- (256) Time remaining = MAX(Indicated time remaining, Minimum time remaining)  
Units: Month  
Uses: (146)Workforce indicated by effort -
- (257) Time to perceive completion date = 1  
Units: Month  
Uses: (251)Perceived real completion date -
- (258) Weight on effort indicated completion date =  
MIN(Effect of perceived completion on weight, Effect of restart on weight)  
Units: dmn1  
Uses: (243)Indicated completion date -

- (259) Weight on initial schedule = 0.75  
Units: dmn1  
Uses: (250)Operative schedule -
- (260) Weight on normal schedule adjustment = frequency of schedule adjustment f (Schedule pressure)  
Units: dmn1  
Uses: (253)Schedule adjustment time -
- (261) Willingness to slip schedule = Normal willingness to slip\*Effect of progress on willingness to slip  
Units: dmn1  
Uses: (234)Desired completion date -

### 8.5.1.19 Target Completion Date



- (263)  $\text{Accumulated dust} = \text{INTEG}(\text{Accumulating dust} - \text{Dusting off project}, 0)$   
 Units: Month  
 Uses: (266)Dust fraction -  
 (267)Dusting off project -
- (264)  $\text{Accumulating dust} = \text{Sliding target date} * \text{Effect of dust on accumulation}$   
 Units: months/Month  
 Uses: (263)Accumulated dust -
- (265)  $\text{Average time to restart project} = 4$   
 Units: Month  
 Comment: Estimated average time to restart a project after halting due to lack of funds  
 Uses: (267)Dusting off project -
- (266)  $\text{Dust fraction} = \text{Accumulated dust} / \text{Maximum accumulated dust}$   
 Units: fraction  
 Uses: (268)Effect of dust on accumulation -  
 (239)Effect of restart on weight -
- (267)  $\text{Dusting off project} = (\text{Accumulated dust} / \text{Average time to restart project}) * (1 - \text{Project Paused})$   
 Units: months/Month  
 Uses: (263)Accumulated dust -
- (268)  $\text{Effect of dust on accumulation} = \text{effect of dust on accumulation } f(\text{Dust fraction})$   
 Units: dmnl  
 Uses: (264)Accumulating dust -
- (269)  $\text{effect of dust on accumulation } f([(0,0)-(1,1)],(0,1),(0.95,1),(0.97,0.95),(0.98,0.9),(0.985,0.75),(1,0))$   
 Units: dmnl  
 Comment: Limits the total amount of dust that can accumulate  
 Uses: (268)Effect of dust on accumulation -
- (270)  $\text{Maximum accumulated dust} = 12$   
 Units: Month  
 Uses: (266)Dust fraction -

(271) Sliding target date = Months per month\*Project Paused

Units: months/Month

Uses: (272)Target completion date -

(264)Accumulating dust -

(272) Target completion date = INTEG (Sliding target date, Initial completion date)

Units: Month

Uses: (696)Project Schedule Slip -

(234)Desired completion date -

(243)Indicated completion date -

(250)Operative schedule -

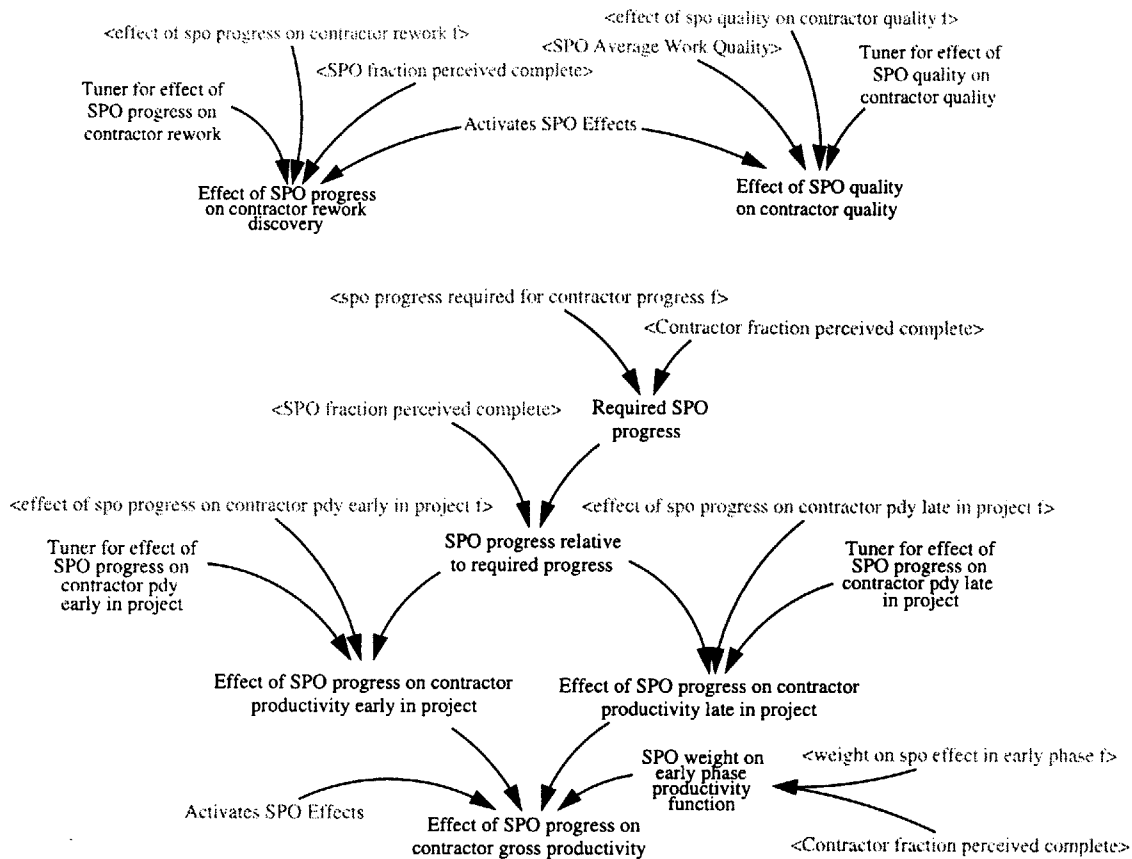
(298)Schedule slip -

(625)SPO Indicated completion date -

(628)SPO operative schedule -

(686)SPO schedule slip -

### 8.5.1.20 SPO Effects on Contractor Quality, Productivity, and Rework Discovery Time



(274) Effect of SPO progress on contractor gross productivity =  
 (Effect of SPO progress on contractor productivity early in project  
 \*SPO weight on early phase productivity function  
 +Effect of SPO progress on contractor productivity late in project  
 \*(1-SPO weight on early phase productivity function ))  
 \*Activates SPO Effects+(1-Activates SPO Effects)

Units: dmn1

Comment: Reduction in contractor gross productivity as determined by the contractor's current progress, resulting from the SPO's real progress relative to its scheduled progress.

Uses: (199)Effective productivity -

(275) effect of spo progress on contractor pdy early in project  $f([(0,0)-(1,1)],(0,0),(0.1,0.3),(0.2,0.55),$   
 $(0.3,0.7),(0.4,0.8),(0.5,0.875),(0.6,0.92),(0.7,0.95),(0.8,0.975),(0.9,0.99),(1,1))$

Units: dmn1

Comment: Relationship determining the reduction in contractor gross productivity as determined by the contractor's current progress, resulting from the SPO's real progress relative to its scheduled progress early in the project.

Uses: (277)Effect of SPO progress on contractor productivity early in project -

(276) effect of spo progress on contractor pdy late in project  $f([(0,0)-(1,1)],(0,0),(0.5,0.0055),$   
 $(0.75,0.015),(0.8,0.0175),(0.85,0.025),(0.9,0.05),(0.92,0.07),$   
 $(0.94,0.1),(0.96,0.15),(0.98,0.25),(0.99,0.5),(1,1))$

Units: dmn1

Comment: Relationship determining the reduction in contractor gross productivity as determined by the contractor's current progress, resulting from the SPO's real progress relative to its scheduled progress late in the project.

Uses: (278)Effect of SPO progress on contractor productivity late in project -

(277) Effect of SPO progress on contractor productivity early in project =  
 effect of spo progress on contractor pdy early in project f  
 (SPO progress relative to required progress)  
 \*Tuner for effect of SPO progress on contractor pdy early in project  
 +(1-Tuner for effect of SPO progress on contractor pdy early in project)

Units: dmn1

Uses: (274)Effect of SPO progress on contractor gross productivity -

(278) Effect of SPO progress on contractor productivity late in project =  
 effect of spo progress on contractor pdy late in project f  
 (SPO progress relative to required progress)  
 \*Tuner for effect of SPO progress on contractor pdy late in project  
 +(1-Tuner for effect of SPO progress on contractor pdy late in project)

Units: dmn1

Uses: (274)Effect of SPO progress on contractor gross productivity -

(279) Effect of SPO progress on contractor rework discovery =  
 (effect of spo progress on contractor rework  $f(\text{SPO fraction perceived complete})$ )  
 \*Tuner for effect of SPO progress on contractor rework  
 +(1-Tuner for effect of SPO progress on contractor rework))  
 \*Activates SPO Effects+(1-Activates SPO Effects)

Units: dmn1

Comment: The increase in rework discovery caused by SPO progress

Uses: (102)Time to detect rework -

(280) effect of spo progress on contractor rework  $f([(0,0)-(1,1)],(0,1),(0.1,1),(0.2,1),(0.3,1),(0.4,0.96),$   
 $(0.5,0.88),(0.6,0.8),(0.7,0.75),(0.8,0.725),(0.9,0.7),(1,0.68))$

Units: dmn1

Uses: (279)Effect of SPO progress on contractor rework discovery -

(281) Effect of SPO quality on contractor quality =  
 (effect of spo quality on contractor quality  $f(\text{SPO Average Work Quality})$ )  
 \*Tuner for effect of SPO quality on contractor quality  
 +(1-Tuner for effect of SPO quality on contractor quality))  
 \*Activates SPO Effects+(1-Activates SPO Effects)

Units: dmn1

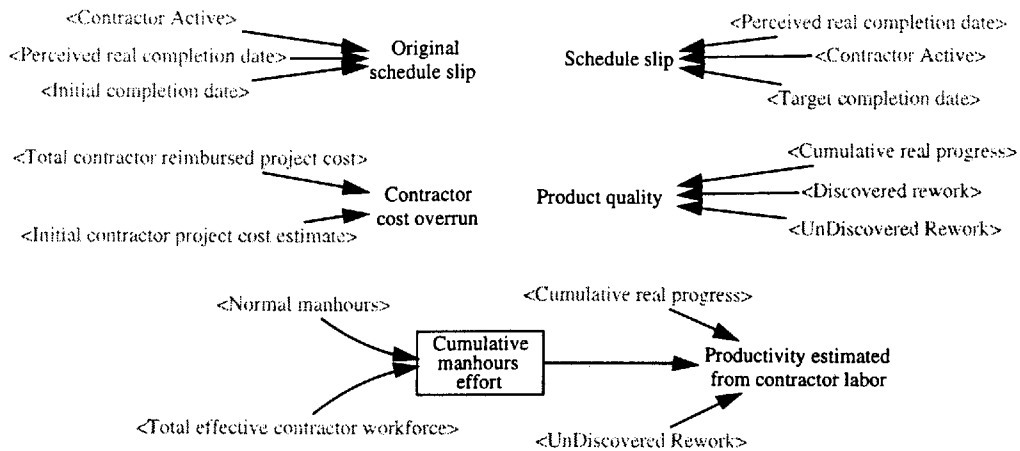
Uses: (218)Quality -



- (282) effect of spo quality on contractor quality  $f([(0,0)-(1,1)],(0,0.5),(0.1,0.65),(0.2,0.76),(0.3,0.85),(0.4,0.9),(0.5,0.93),(0.6,0.95),(0.7,0.96),(0.8,0.97),(1,1))$
- Units: dmn1  
 Comment: Functional relationship between the quality of work done at the SPO and the quality of work done by the contractor.  
 Uses: (281)Effect of SPO quality on contractor quality -
- (283) Required SPO progress =  
 spo progress required for contractor progress  $f(\text{Contractor fraction perceived complete})$
- Units: fraction  
 Comment: Determines the progress which the spo must have achieved to all the contractor to continue at its current rate of productivity  
 Uses: (284)SPO progress relative to required progress -
- (284) SPO progress relative to required progress =  
 $\text{MIN}(1, \text{IF THEN ELSE}(\text{Required SPO progress} = 0 : \text{OR} : \text{SPO fraction perceived complete} = 0, 1, \text{SPO fraction perceived complete} / \text{Required SPO progress}))$
- Units: fraction  
 Uses: (277)Effect of SPO progress on contractor productivity early in project -  
 (278)Effect of SPO progress on contractor productivity late in project -  
 (401)Effect of SPO relative progress on indicated disbursement -
- (285) spo progress required for contractor progress  $f([(0,0)-(1,1)],(0,0),(1,1))$
- Units: fraction  
 Comment: Functional relationship for the required SPO progress for a given level of contractor progress  
 Uses: (283)Required SPO progress -
- (286) SPO weight on early phase productivity function =  
 weight on spo effect in early phase  $f(\text{Contractor fraction perceived complete})$
- Units: dmn1  
 Comment: Relative importance of the SPO's work as the contractor progresses through the project.  
 Uses: (274)Effect of SPO progress on contractor gross productivity -
- (287) Tuner for effect of SPO progress on contractor pdy early in project = 1
- Units: dmn1  
 Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the full strength of the function, while a value of 0 results in a complete negation of the function. e.g.  $\text{Effect} = \text{Function}(\text{Variable}) * \text{Tuner} + (1 - \text{Tuner})$   
 Uses: (277)Effect of SPO progress on contractor productivity early in project -
- (288) Tuner for effect of SPO progress on contractor pdy late in project = 1
- Units: dmn1  
 Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the full strength of the function, while a value of 0 results in a complete negation of the function.  
 Uses: (278)Effect of SPO progress on contractor productivity late in project -

- (289) Tuner for effect of SPO progress on contractor rework = 1  
 Units: dmnl  
 Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the full strength of the function, while a value of 0 results in a complete negation of the function.  
 Uses: (279)Effect of SPO progress on contractor rework discovery -
- (290) Tuner for effect of SPO quality on contractor quality = 1  
 Units: dmnl  
 Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the full strength of the function, while a value of 0 results in a complete negation of the function.  
 Uses: (281)Effect of SPO quality on contractor quality -
- (291) weight on spo effect in early phase  $f([(0,0)-(1,1)],(0,1),(1,0))$   
 Units: dmnl  
 Comment: Function giving the relative importance of the SPO work to the contractor, as the contractor progresses through the project.  
 Uses: (286)SPO weight on early phase productivity function -

### 8.5.1.21 Contractor Slips

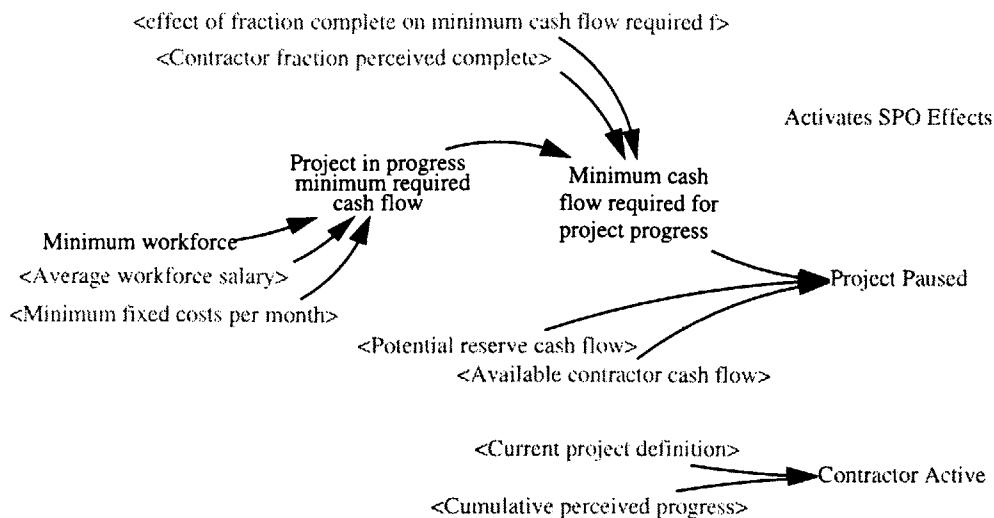


- (293) Contractor cost overrun =  

$$\frac{\text{Total contractor reimbursed project cost} - \text{Initial contractor project cost estimate}}{\text{Initial contractor project cost estimate}}$$
  
 Units: fraction  
 Comment: Fraction of initial cost estimate by which reimbursed project cost exceeds the original estimate.
- (294) Cumulative manhours effort = INTEG (Normal manhours\*Total effective contractor workforce, 0)  
 Units: manhours  
 Uses: (297)Productivity estimated from contractor labor -
- (295) Original schedule slip =  $\frac{(\text{Perceived real completion date} - \text{Initial completion date})}{\text{Initial completion date}} * \text{Contractor Active}$   
 Units: fraction  
 Comment: The fraction of the initial completion date by which the schedule has slipped.
- (296) Product quality =  $\frac{\text{Cumulative real progress}}{\text{MAX}(0.0001, \text{UnDiscovered Rework} + \text{Discovered rework} + \text{Cumulative real progress})}$   
 Units: dmnl
- (297) Productivity estimated from contractor labor =  

$$\text{IF THEN ELSE}(\text{Cumulative manhours effort} > 0, (\text{UnDiscovered Rework} + \text{Cumulative real progress}) / \text{Cumulative manhours effort}, 1)$$
  
 Units: fraction  
 Comment: Not a good measure of the workforce's current productivity because it is a running average of productivity since project inception.
- (298) Schedule slip =  $\frac{(\text{Perceived real completion date} - \text{Target completion date})}{\text{Target completion date}} * \text{Contractor Active}$   
 Units: fraction  
 Comment: The fraction of the initial completion date by which the schedule has slipped.

### 8.5.1.22 Simulation Control Switches for Contractor Section

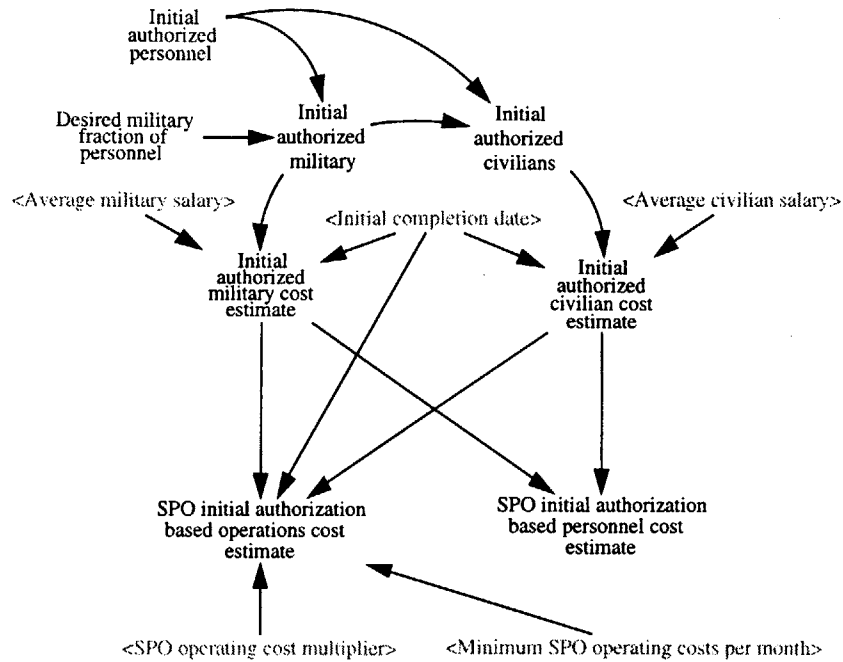


- (300) Activates SPO Effects = 1  
 Units: dmnl  
 Comment: Setting "Activates SPO effects" switch to 1 activates SPO effects on the contractor  
 Uses: (274)Effect of SPO progress on contractor gross productivity -  
 (279)Effect of SPO progress on contractor rework discovery -  
 (281)Effect of SPO quality on contractor quality -
- (301) Contractor Active =  
 IF THEN ELSE(Cumulative perceived progress>0.995\*Current project definition,0,1)  
 Units: dmnl  
 Comment: Logical variable to signal project termination in the event of perceived completion of work or loss of financial resources.  
 Uses: (051)Aggregating financial resources -  
 (082)Discovering rework -  
 (142)Effort perceived remaining -  
 (200)Gross productivity -  
 (295)Original schedule slip -  
 (041)Overhead cost per month -  
 (693)Project completed -  
 (254)Schedule pressure -  
 (298)Schedule slip -  
 (046)Total labor cost per month -
- (302) effect of fraction complete on minimum cash flow required  $f([(0,0)-(1,1)],(0,0),(0.01,0),$   
 $(0.05,0.5),(0.1,0.95),(0.2,1),(0.8,1),(0.9,0.95),(0.985,0),(1,0))$   
 Units: dmnl  
 Comment: During startup and shut down phases minimum cash flow requirements are reduced.  
 Uses: (303)Minimum cash flow required for project progress -

- (303) Minimum cash flow required for project progress = Project in progress minimum required cash flow  
 \*effect of fraction complete on minimum cash flow required f  
 (Contractor fraction perceived complete)  
 Units: \$/Month  
 Uses: (306)Project Paused -
- (304) Minimum workforce = 1  
 Units: man  
 Uses: (305)Project in progress minimum required cash flow -
- (305) Project in progress minimum required cash flow =  
 Minimum fixed costs per month+Minimum workforce\*Average workforce salary  
 Units: \$/Month  
 Uses: (303)Minimum cash flow required for project progress -
- (306) Project Paused = IF THEN ELSE ((Available contractor cash flow+Potential reserve cash flow)  
 <Minimum cash flow required for project progress,1,0)  
 Units: dmn1  
 Uses: (234)Desired completion date -  
 (267)Dusting off project -  
 (065)Indicated management reserve cash outflow -  
 (254)Schedule pressure -  
 (271)Sliding target date -  
 (631)SPO schedule pressure -

## 8.5.2 Program Office Model Documentation

### 8.5.2.1 SPO Initial Authorization Based Cost Estimates



(308) Desired military fraction of personnel = 0.3

Units: fraction

Comment: Fraction of SPO personnel which are military. Source: Jerry Sutton interview 97/03/04

Uses: (481) Civilians indicated by effort -  
 (311) Initial authorized military -  
 (317) Initial effort based civilian labor cost estimate -  
 (318) Initial effort based military labor cost estimate -  
 (441) Military indicated by effort -

(309) Initial authorized civilian cost estimate =

$$\text{Initial authorized civilians} * \text{Average civilian salary} * \text{Initial completion date}$$

Units: \$

Uses: (314) SPO initial authorization based operations cost estimate -  
 (315) SPO initial authorization based personnel cost estimate -

(310) Initial authorized civilians = Initial authorized personnel - Initial authorized military

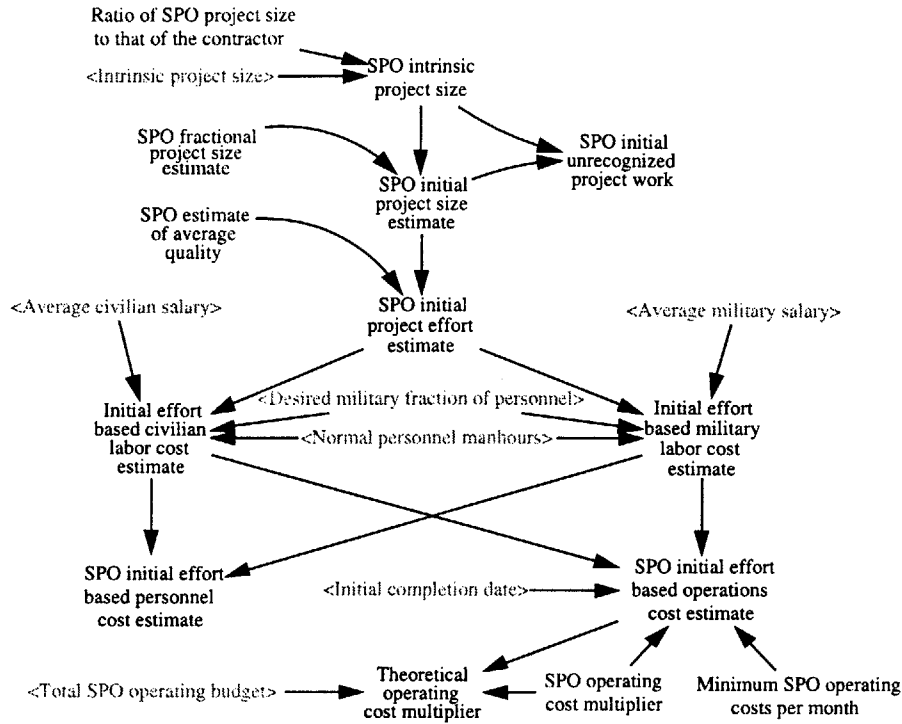
Units: man

Comment: Number of civilian authorized for the program at the SPO level.

Uses: (539) Authorized civilians -  
 (739) Government funds for civilian salary -  
 (309) Initial authorized civilian cost estimate -  
 (547) Maximum allowed authorization -

- (311) Initial authorized military = Initial authorized personnel\*Desired military fraction of personnel  
 Units: man  
 Comment: Number of Military traditionally assigned to a program based upon the civilian authorization.  
 Uses: (468)Authorized military -  
 (740)Government funds for military salary -  
 (310)Initial authorized civilians -  
 (312)Initial authorized military cost estimate -  
 (475)Maximum allowed military authorization -
- (312) Initial authorized military cost estimate =  
 Initial completion date\*Initial authorized military\*Average military salary  
 Units: \$  
 Uses: (314)SPO initial authorization based operations cost estimate -  
 (315)SPO initial authorization based personnel cost estimate -
- (313) Initial authorized personnel = 100  
 Units: man  
 Comment: Initial number of authorized personnel slots for the SPO.  
 Uses: (310)Initial authorized civilians -  
 (311)Initial authorized military -
- (314) SPO initial authorization based operations cost estimate =  
 MAX((Initial authorized military cost estimate+ Initial authorized civilian cost estimate)  
 \*SPO operating cost multiplier,  
 Minimum SPO operating costs per month\*Initial completion date)  
 Units: \$  
 Uses: (332)Initial SPO operating cost estimate -
- (315) SPO initial authorization based personnel cost estimate =  
 Initial authorized civilian cost estimate+Initial authorized military cost estimate  
 Units: \$  
 Uses: (333)Initial SPO personnel cost estimate -

**8.5.2.2 SPO Initial Effort Based Cost Estimates**



(317) Initial effort based civilian labor cost estimate =  

$$\text{Average civilian salary} * (\text{SPO initial project effort estimate} * (1 - \text{Desired military fraction of personnel}) / \text{Normal personnel manhours})$$

Units: \$

Uses: (323) SPO initial effort based operations cost estimate -  
 (324) SPO initial effort based personnel cost estimate -

(318) Initial effort based military labor cost estimate =  

$$\text{Average military salary} * \text{Desired military fraction of personnel} * (\text{SPO initial project effort estimate} / \text{Normal personnel manhours})$$

Units: \$

Uses: (323) SPO initial effort based operations cost estimate -  
 (324) SPO initial effort based personnel cost estimate -

(319) Minimum SPO operating costs per month = 0

Units: \$/Month

Comment: The floor for fixed costs.

Uses: (355) Indicated SPO monthly operating spending -  
 (314) SPO initial authorization based operations cost estimate -  
 (323) SPO initial effort based operations cost estimate -

(320) Ratio of SPO project size to that of the contractor = 0.048

Units: fraction

Comment: The ratio of true SPO project size to that of the contractor's true project size. e.g.  

$$(\text{SPO intrinsic project size} / \text{Contractor's intrinsic project size})$$

Uses: (328) SPO intrinsic project size -



- (321) SPO estimate of average quality = 1  
 Units: fraction  
 Comment: The SPO manager's estimate of the SPO's average quality over the life of the project  
 Uses: (325)SPO initial project effort estimate -
- (322) SPO fractional project size estimate = 1  
 Units: fraction  
 Comment: Initial project size is this fraction of the intrinsic project size.  
 Uses: (326)SPO initial project size estimate -
- (323) SPO initial effort based operations cost estimate =  

$$\text{MAX}((\text{Initial effort based military labor cost estimate} \\ + \text{Initial effort based civilian labor cost estimate}) * \text{SPO operating cost multiplier}, \\ \text{Minimum SPO operating costs per month} * \text{Initial completion date} )$$
  
 Units: \$  
 Uses: (332)Initial SPO operating cost estimate -  
 (330)Theoretical operating cost multiplier -
- (324) SPO initial effort based personnel cost estimate =  

$$\text{Initial effort based civilian labor cost estimate} + \text{Initial effort based military labor cost estimate}$$
  
 Units: \$  
 Uses: (333)Initial SPO personnel cost estimate -
- (325) SPO initial project effort estimate = SPO initial project size estimate/SPO estimate of average quality  
 Units: manhours  
 Uses: (317)Initial effort based civilian labor cost estimate -  
 (318)Initial effort based military labor cost estimate -
- (326) SPO initial project size estimate = SPO intrinsic project size\*SPO fractional project size estimate  
 Units: manhours  
 Uses: (417)SPO current project definition -  
 (428)SPO work to be done -  
 (325)SPO initial project effort estimate -  
 (327)SPO initial unrecognized project work -
- (327) SPO initial unrecognized project work = SPO intrinsic project size - SPO initial project size estimate  
 Units: manhours  
 Comment: The number of manhours work unrecognized at the start of the project.  
 Uses: (427)SPO undiscovered work -  
 (420)SPO discovering work -
- (328) SPO intrinsic project size = Intrinsic project size\*Ratio of SPO project size to that of the contractor  
 Units: manhours  
 Comment: This construction does not necessarily imply a causal link between the two values,  
 but rather is provided to simplify the analysis.  
 Uses: (326)SPO initial project size estimate -  
 (327)SPO initial unrecognized project work -

(329) SPO operating cost multiplier = 0.279

Units: dmn1

Comment: SPO operating costs as a fraction of personnel costs.

Uses: (355)Indicated SPO monthly operating spending -

(314)SPO initial authorization based operations cost estimate -

(323)SPO initial effort based operations cost estimate -

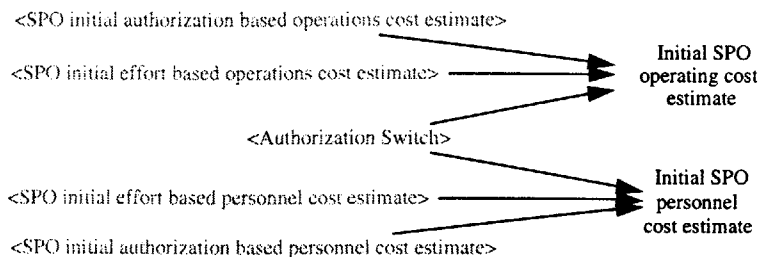
(330)Theoretical operating cost multiplier -

(330) Theoretical operating cost multiplier = Total SPO operating budget

/(SPO initial effort based operations cost estimate/SPO operating cost multiplier)

Units: dmn1

**8.5.2.3 SPO Initial Cost Estimates**



(332) Initial SPO operating cost estimate = SPO initial authorization based operations cost estimate  
 \*Authorization Switch+SPO initial effort based operations cost estimate  
 \*(1-Authorization Switch)

Units: \$

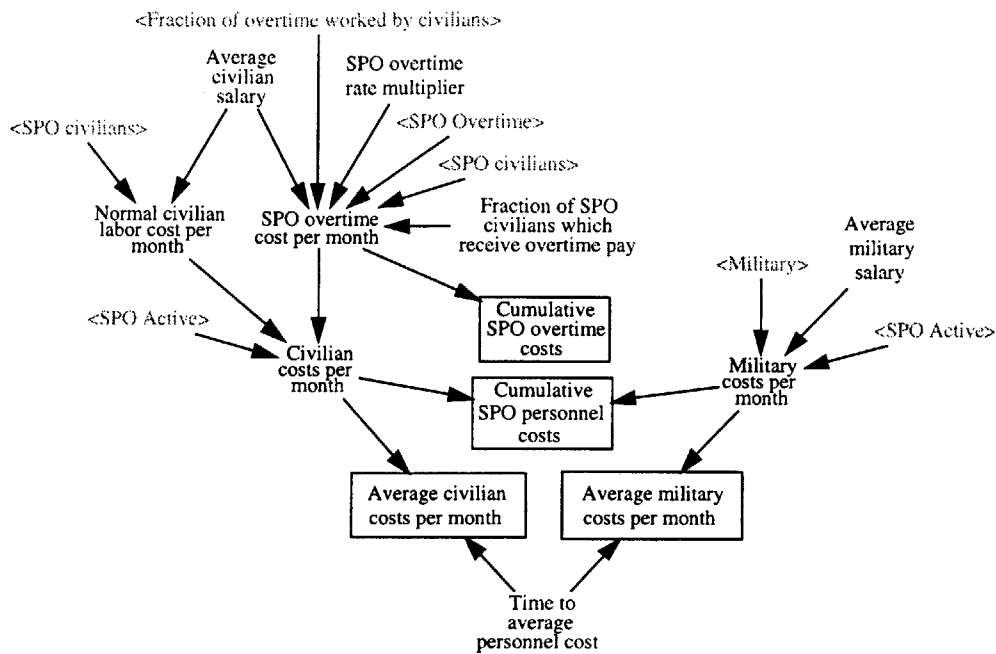
Uses: (681)Initial SPO personnel and operating cost estimate -  
 (692)Initial total project cost estimate less administered funds -

(333) Initial SPO personnel cost estimate = SPO initial authorization based personnel cost estimate  
 \*Authorization Switch+SPO initial effort based personnel cost estimate  
 \*(1-Authorization Switch)

Units: \$

Uses: (681)Initial SPO personnel and operating cost estimate -  
 (692)Initial total project cost estimate less administered funds -

### 8.5.2.4 SPO Personnel Costs



(335) Average civilian costs per month =  

$$\text{SMOOTH}(\text{Civilian costs per month}, \text{Time to average personnel cost})$$
  
 Units: \$/Month

(336) Average civilian salary = 6400  
 Units: \$/(Month\*man)  
 Comment: Sources: Kathy Watern ASC, & Capt Ross McNutt USAF Average civilian salary = \$66,939 (ASC ACQUISITION WORKFORCE AVERAGE FOR FY98) Average contract labor salary = \$100,000 per year Figure based upon 30% contract labor and 70% organic civilian workforce.

- Uses:
- (387) Civilian funding shortfall -
  - (482) Civilians indicated by financials -
  - (658) Financially indicated civilians paid for overtime -
  - (738) Funding available for civilian overtime -
  - (739) Government funds for civilian salary -
  - (309) Initial authorized civilian cost estimate -
  - (317) Initial effort based civilian labor cost estimate -
  - (344) Normal civilian labor cost per month -
  - (345) SPO overtime cost per month -

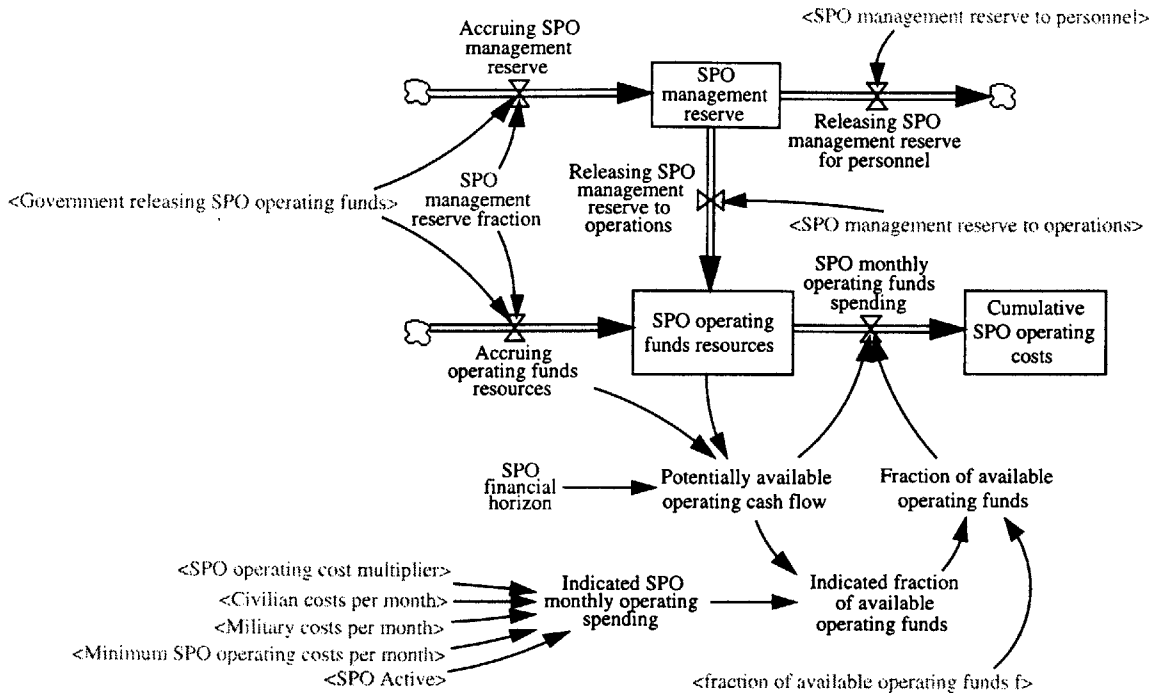
(337) Average military costs per month =  

$$\text{SMOOTH}(\text{Military costs per month}, \text{Time to average personnel cost})$$
  
 Units: \$/Month

- (338) Average military salary = 4758  
 Units: \$(man\*Month)  
 Comment: Source: Kathey Watern ASC, OFFICER - \$79,284 AND ENLISTED \$34,906 (ASC ACQUISITION WORKFORCE AVERAGE FOR FY98). Note the average of the two has been used in the model.  
 Uses: (740)Government funds for military salary -  
 (312)Initial authorized military cost estimate -  
 (318)Initial effort based military labor cost estimate -  
 (343)Military costs per month -  
 (390)Military funding shortfall -  
 (442)Military indicated by financials -
- (339) Civilian costs per month =  
 (Normal civilian labor cost per month+SPO overtime cost per month)\*SPO Active  
 Units: \$/Month  
 Uses: (341)Cumulative SPO personnel costs -  
 (335)Average civilian costs per month -  
 (355)Indicated SPO monthly operating spending -
- (340) Cumulative SPO overtime costs = INTEG (SPO overtime cost per month, 0)  
 Units: \$
- (341) Cumulative SPO personnel costs = INTEG (Civilian costs per month+Military costs per month, 0)  
 Units: \$  
 Uses: (698)Total cost of SPO personnel and operations -
- (342) Fraction of SPO civilians which receive overtime pay = 0.75  
 Units: dmnl  
 Comment: This is used to account for that the fraction of civilian personnel which is salaried and would not receive additional pay for overtime work.  
 Uses: (656)Civilians not paid for overtime -  
 (657)Civilians paid for overtime -  
 (345)SPO overtime cost per month -
- (343) Military costs per month = Military\*Average military salary\*SPO Active  
 Units: \$/Month  
 Uses: (341)Cumulative SPO personnel costs -  
 (337)Average military costs per month -  
 (355)Indicated SPO monthly operating spending -
- (344) Normal civilian labor cost per month = Average civilian salary\*SPO civilians  
 Units: \$/Month  
 Uses: (339)Civilian costs per month -
- (345) SPO overtime cost per month = IF THEN ELSE (SPO Overtime>0,SPO civilians  
 \*Fraction of SPO civilians which receive overtime pay  
 \*SPO Overtime\*Fraction of overtime worked by civilians  
 \*SPO overtime rate multiplier\*Average civilian salary, 0)  
 Units: \$/Month  
 Comment: This construction causes overtime to be paid at the overtime rate, while undertime does not decrease the normal pay.  
 Uses: (340)Cumulative SPO overtime costs -  
 (339)Civilian costs per month -

- (346) SPO overtime rate multiplier = 0.78  
Units: dmn1  
Comment: Source: Kathey Watern, ASC Based upon an overtime hourly salary of \$25.43 per hour and an Average civilian salary = \$66,939 (ASC ACQUISITION WORKFORCE AVERAGE FOR FY98)  
Uses: (658)Financially indicated civilians paid for overtime -  
(738)Funding available for civilian overtime -  
(345)SPO overtime cost per month -
- (347) Time to average personnel cost = 1  
Units: Month  
Uses: (335)Average civilian costs per month -  
(337)Average military costs per month -

### 8.5.2.5 SPO Operating Funds



(349) Accruing operating funds resources =  

$$\text{Government releasing SPO operating funds} * (1 - \text{SPO management reserve fraction})$$
 Units: \$/Month  
 Comment: The net flow of dollars into the project which the SPO manager will initially spend  
 Uses: (363)SPO operating funds resources -  
 (356)Potentially available operating cash flow -

(350) Accruing SPO management reserve =  

$$\text{Government releasing SPO operating funds} * \text{SPO management reserve fraction}$$
 Units: \$/Month  
 Uses: (360)SPO management reserve -  
 (370)Maximum available SPO management reserve cash outflow -

(351) Cumulative SPO operating costs = INTEG (SPO monthly operating funds spending, 0)  
 Units: \$  
 Uses: (698)Total cost of SPO personnel and operations -

(352) Fraction of available operating funds =  
 IF THEN ELSE(Indicated fraction of available operating funds > 2,  
 fraction of available operating funds f(2),  
 fraction of available operating funds f(Indicated fraction of available operating funds))  
 Units: fraction  
 Uses: (362)SPO monthly operating funds spending -

- (353) fraction of available operating funds  $f([(0,0)-(2,1)],(0,0),(0.9,0.9),(1,0.96),(1.15,0.98),(1.3,0.99),(2,1))$   
 Units: fraction  
 Comment: fraction of operating funds released as a function of fraction desired -- of funds available.  
 Uses: (352)Fraction of available operating funds -
- (354) Indicated fraction of available operating funds =  

$$\text{IF THEN ELSE}(\text{Potentially available operating cash flow} < = 1, 0, \text{Indicated SPO monthly operating spending}/\text{Potentially available operating cash flow})$$
  
 Units: fraction  
 Comment: (Cutting the function off at \$1 rather than \$0 prevents division by small number overflow.)  
 Uses: (352)Fraction of available operating funds -
- (355) Indicated SPO monthly operating spending =  

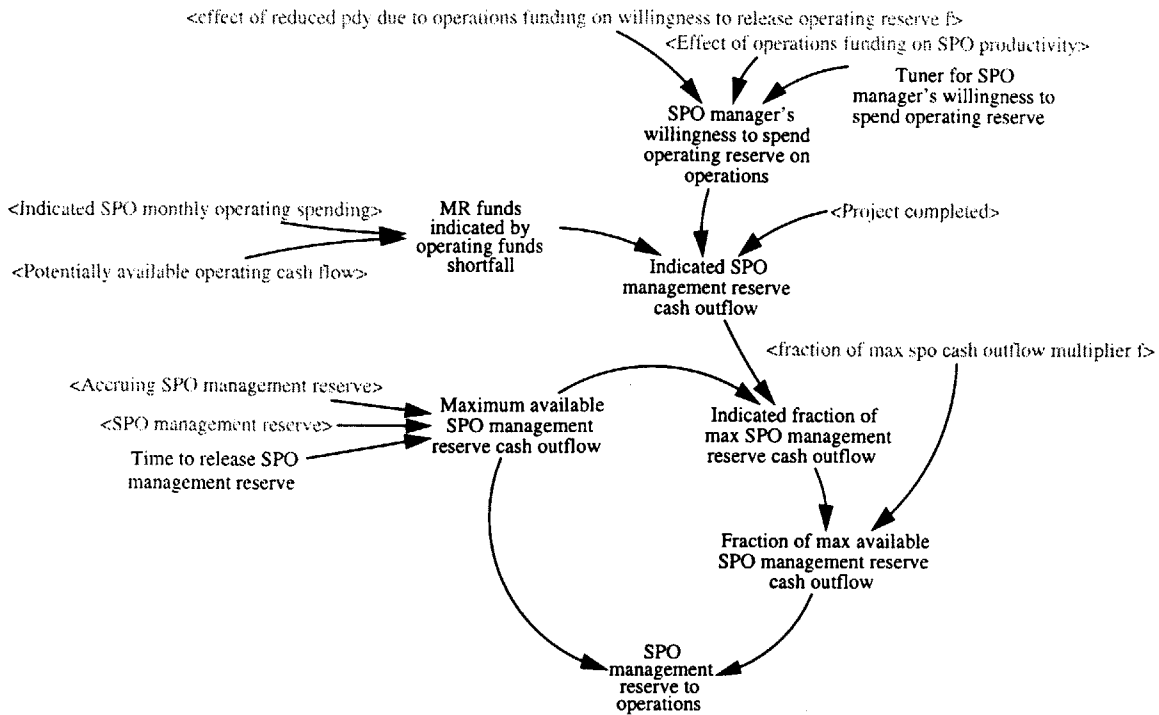
$$\text{MAX}((\text{Civilian costs per month} + \text{Military costs per month}) * \text{SPO operating cost multiplier}, \text{Minimum SPO operating costs per month}) * \text{SPO Active}$$
  
 Units: \$/Month  
 Uses: (592)Fraction of desired operating funds spent -  
 (354)Indicated fraction of available operating funds -  
 (371)MR funds indicated by operating funds shortfall -
- (356) Potentially available operating cash flow =  $\text{Accruing operating funds resources} + \text{MAX}(0, \text{SPO operating funds resources}/\text{SPO financial horizon})$   
 Units: \$/Month  
 Uses: (354)Indicated fraction of available operating funds -  
 (371)MR funds indicated by operating funds shortfall -  
 (362)SPO monthly operating funds spending -
- (357) Releasing SPO management reserve for personnel =  $\text{SPO management reserve to personnel}$   
 Units: \$/Month  
 Uses: (360)SPO management reserve -  
 (485)Operating funds for civilians -  
 (443)Operating funds for military personnel -
- (358) Releasing SPO management reserve to operations =  $\text{SPO management reserve to operations}$   
 Units: \$/Month  
 Uses: (360)SPO management reserve -  
 (363)SPO operating funds resources -
- (359) SPO financial horizon = 12  
 Units: Month  
 Uses: (356)Potentially available operating cash flow -
- (360) SPO management reserve =  

$$\text{INTEG}(\text{Accruing SPO management reserve} - \text{Releasing SPO management reserve to operations} - \text{Releasing SPO management reserve for personnel}, 0)$$
  
 Units: \$  
 Uses: (370)Maximum available SPO management reserve cash outflow -



- (361) SPO management reserve fraction = 0  
 Units: fraction  
 Comment: Fraction of potentially available cash flow that SPO management holds in reserve.  
 Uses: (349)Accruing operating funds resources -  
 (350)Accruing SPO management reserve -
- (362) SPO monthly operating funds spending =  
 Potentially available operating cash flow\*Fraction of available operating funds  
 Units: \$/Month  
 Comment: The total monthly expenditure of operating funds per month  
 Uses: (351)Cumulative SPO operating costs -  
 (363)SPO operating funds resources -  
 (592)Fraction of desired operating funds spent -
- (363) SPO operating funds resources = INTEG (Accruing operating funds resources  
 +Releasing SPO management reserve to operations-SPO monthly operating funds spending, 0)  
 Units: \$  
 Comment: The accumulated financial resources for the project  
 Uses: (356)Potentially available operating cash flow -

### 8.5.2.6 SPO Operating Funds Reserve



(365) effect of reduced pdy due to operations funding on willingness to release operating reserve f  
 ((0,0)-(1,1)],(0,1),(0.1,1),(0.25,0.99),(0.3,0.98),(0.4,0.925),(0.5,0.725),  
 (0.6,0.375),(0.7,0.1),(0.8,0.02),(0.9,0.005),(1,0))

Units: dmnl

Uses: (373)SPO manager's willingness to spend operating reserve on operations -

(366) Fraction of max available SPO management reserve cash outflow =  
 IF THEN ELSE(Indicated fraction of max SPO management reserve cash outflow>2,  
 fraction of max spo cash outflow multiplier f(2),  
 fraction of max spo cash outflow multiplier f  
 (Indicated fraction of max SPO management reserve cash outflow))

Units: fraction

Uses: (372)SPO management reserve to operations -

(367) fraction of max spo cash outflow multiplier f([(0,0)-(2,1)],(0,0),(0.9,0.9),(1,0.95),(2,1))

Units: dmnl

Uses: (366)Fraction of max available SPO management reserve cash outflow -

(368) Indicated fraction of max SPO management reserve cash outflow =  
 IF THEN ELSE(Maximum available SPO management reserve cash outflow<= 1, 0,  
 Indicated SPO management reserve cash outflow  
 /Maximum available SPO management reserve cash outflow)

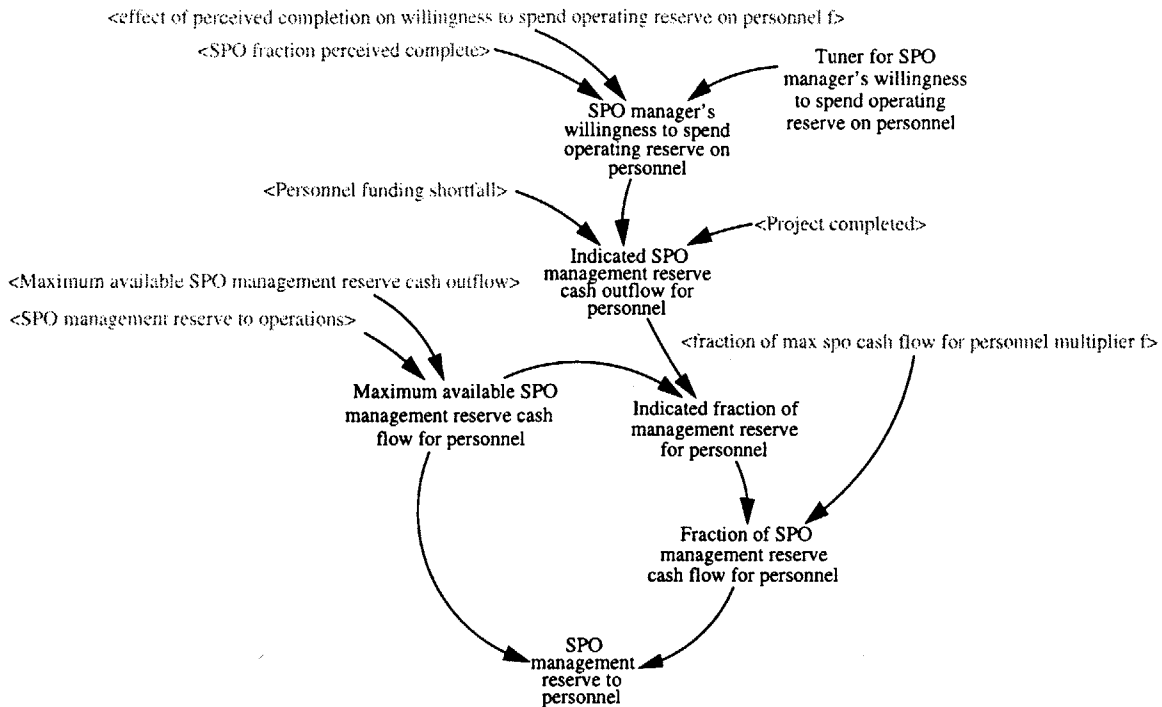
Units: fraction

Comment: (Cutting the function off at \$1 rather than \$0 prevents division by small number overflow.)

Uses: (366)Fraction of max available SPO management reserve cash outflow -

- (369) Indicated SPO management reserve cash outflow =  
SPO manager's willingness to spend operating reserve on operations  
\*MR funds indicated by operating funds shortfall  
\*(1-Project completed)  
Units: \$/Month  
Uses: (368)Indicated fraction of max SPO management reserve cash outflow -
- (370) Maximum available SPO management reserve cash outflow = Accruing SPO management reserve  
+SPO management reserve/Time to release SPO management reserve  
Units: \$/Month  
Uses: (368)Indicated fraction of max SPO management reserve cash outflow -  
(382)Maximum available SPO management reserve cash flow for personnel -  
(372)SPO management reserve to operations -
- (371) MR funds indicated by operating funds shortfall =  
MAX(0,Indicated SPO monthly operating spending-Potentially available operating cash flow)  
Units: \$/Month  
Comment: When the indicated monthly operating spending is more than the available operating  
cash flow, there is a shortfall  
Uses: (369)Indicated SPO management reserve cash outflow -
- (372) SPO management reserve to operations = Maximum available SPO management reserve cash outflow  
\*Fraction of max available SPO management reserve cash outflow  
Units: \$/Month  
Uses: (382)Maximum available SPO management reserve cash flow for personnel -  
(358)Releasing SPO management reserve to operations -
- (373) SPO manager's willingness to spend operating reserve on operations =  
effect of reduced pdy due to operations funding on willingness to release operating reserve f  
(Effect of operations funding on SPO productivity)  
\*Tuner for SPO manager's willingness to spend operating reserve  
+(1-Tuner for SPO manager's willingness to spend operating reserve)  
Units: dmn1  
Uses: (369)Indicated SPO management reserve cash outflow -
- (374) Time to release SPO management reserve = 1  
Units: Month  
Uses: (370)Maximum available SPO management reserve cash outflow -
- (375) Tuner for SPO manager's willingness to spend operating reserve = 1  
Units: dmn1  
Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the  
full strength of the function, while a value of 0 results in a complete negation of the  
function. e.g. Effect = Function(Variable)\*Tuner + (1-Tuner)  
Uses: (373)SPO manager's willingness to spend operating reserve on operations -

### 8.5.2.7 SPO Operating Funds to Personnel



(377) effect of perceived completion on willingness to spend operating reserve on personnel f  
 ((0,0)-(1,1)],(0,0),(0.05,0.01),(0.1,0.1),(0.2,0.6),(0.3,0.9),(0.4,0.98),(1,1))

Units: dnm1

Comment: Estimate by author, based upon judgment and anecdotal evidence.

Uses: (384)SPO manager's willingness to spend operating reserve on personnel -

(378) fraction of max spo cash flow for personnel multiplier f((0,0)-(2,1)],(0,0),(0.9,0.9),(1,0.95),(2,1))

Units: fraction

Uses: (379)Fraction of SPO management reserve cash flow for personnel -

(379) Fraction of SPO management reserve cash flow for personnel =  
 IF THEN ELSE(Indicated fraction of management reserve for personnel>2,  
 fraction of max spo cash flow for personnel multiplier f(2),  
 fraction of max spo cash flow for personnel multiplier f  
 (Indicated fraction of management reserve for personnel))

Units: fraction

Uses: (383)SPO management reserve to personnel -

(380) Indicated fraction of management reserve for personnel =  
 IF THEN ELSE(Maximum available SPO management reserve cash flow for personnel<= 1, 0,  
 Indicated SPO management reserve cash outflow for personnel  
 /Maximum available SPO management reserve cash flow for personnel)

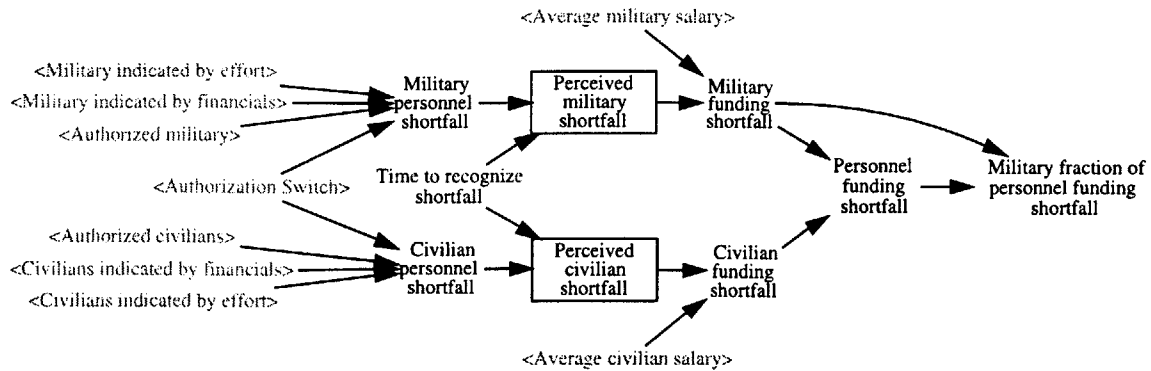
Units: fraction

Comment: Cutting the function off at \$1 rather than \$0 prevents division by small number overflow.

Uses: (379)Fraction of SPO management reserve cash flow for personnel -

- (381) Indicated SPO management reserve cash outflow for personnel = Personnel funding shortfall  
\* SPO manager's willingness to spend operating reserve on personnel \* (1 - Project completed)  
Units: \$/Month  
Uses: (380) Indicated fraction of management reserve for personnel -
- (382) Maximum available SPO management reserve cash flow for personnel =  
Maximum available SPO management reserve cash outflow  
- SPO management reserve to operations  
Units: \$/Month  
Uses: (380) Indicated fraction of management reserve for personnel -  
(383) SPO management reserve to personnel -
- (383) SPO management reserve to personnel =  
Maximum available SPO management reserve cash flow for personnel  
\* Fraction of SPO management reserve cash flow for personnel  
Units: \$/Month  
Uses: (357) Releasing SPO management reserve for personnel -
- (384) SPO manager's willingness to spend operating reserve on personnel =  
effect of perceived completion on willingness to spend operating reserve on personnel f  
(SPO fraction perceived complete)  
\* Tuner for SPO manager's willingness to spend operating reserve on personnel  
+ (1 - Tuner for SPO manager's willingness to spend operating reserve on personnel)  
Units: dmnl  
Uses: (381) Indicated SPO management reserve cash outflow for personnel -
- (385) Tuner for SPO manager's willingness to spend operating reserve on personnel = 1  
Units: dmnl  
Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the full strength of the function, while a value of 0 results in a complete negation of the function. e.g. Effect = Function(Variable) \* Tuner + (1 - Tuner)  
Uses: (384) SPO manager's willingness to spend operating reserve on personnel -

### 8.5.2.8 SPO Operating Funds Shortfall

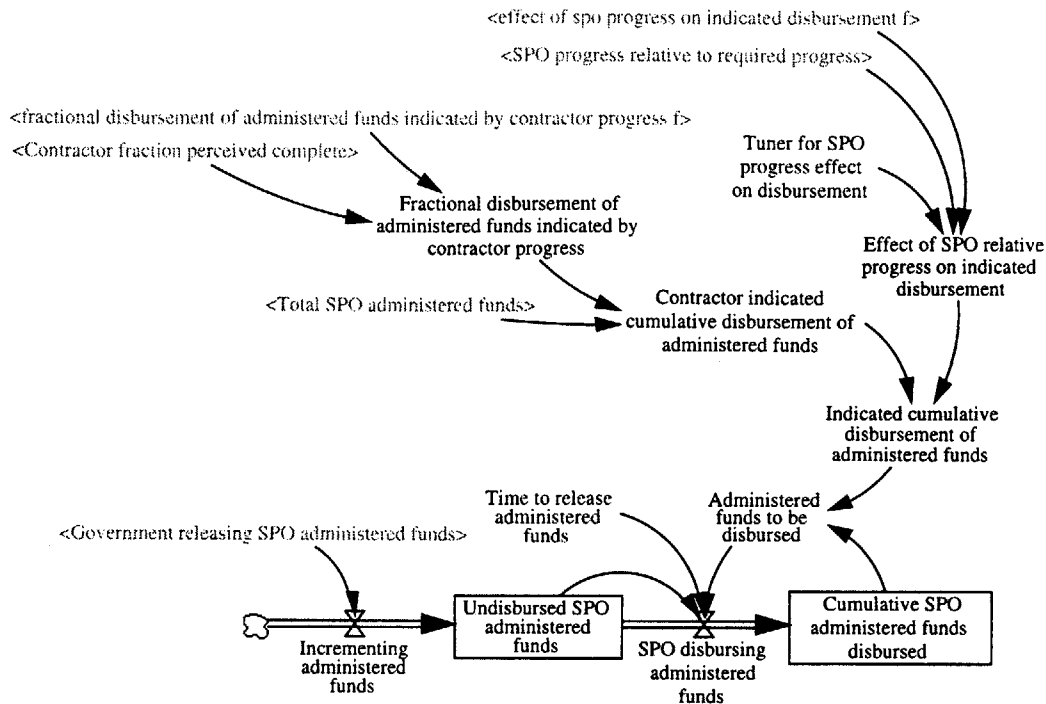


- (387) **Civilian funding shortfall = Perceived civilian shortfall\*Average civilian salary**  
 Units: \$/Month  
 Uses: (394)Personnel funding shortfall -
- (388) **Civilian personnel shortfall =**  

$$\text{MAX}(0, (\text{Authorized civilians} * \text{Authorization Switch} + \text{Civilians indicated by effort} * (1 - \text{Authorization Switch}) - \text{Civilians indicated by financials}))$$
  
 Units: man  
 Uses: (392)Perceived civilian shortfall -
- (389) **Military fraction of personnel funding shortfall = IF THEN ELSE(Personnel funding shortfall > 0, Military funding shortfall/Personnel funding shortfall, 0)**  
 Units: fraction  
 Uses: (443)Operating funds for military personnel -
- (390) **Military funding shortfall = Perceived military shortfall\*Average military salary**  
 Units: \$/Month  
 Uses: (389)Military fraction of personnel funding shortfall -  
 (394)Personnel funding shortfall -
- (391) **Military personnel shortfall = MAX(0, (Authorized military\*Authorization Switch + Military indicated by effort\*(1-Authorization Switch)-Military indicated by financials))**  
 Units: man  
 Uses: (393)Perceived military shortfall -
- (392) **Perceived civilian shortfall = SMOOTHI(Civilian personnel shortfall, Time to recognize shortfall, 0)**  
 Units: man  
 Uses: (387)Civilian funding shortfall -
- (393) **Perceived military shortfall = SMOOTHI(Military personnel shortfall, Time to recognize shortfall, 0)**  
 Units: man  
 Uses: (390)Military funding shortfall -
- (394) **Personnel funding shortfall = Civilian funding shortfall+Military funding shortfall**  
 Units: \$/Month  
 Uses: (381)Indicated SPO management reserve cash outflow for personnel -  
 (389)Military fraction of personnel funding shortfall -

(395) Time to recognize shortfall = 2  
Units: Month  
Uses: (392) Perceived civilian shortfall -  
(393) Perceived military shortfall -

### 8.5.2.9 SPO Administered Funds



(397) Administered funds to be disbursed = MAX(Indicated cumulative disbursement of administered funds - Cumulative SPO administered funds disbursed, 0)

Units: \$

Comment: The difference can not be negative -- you can not un-spend the administered funds.

Uses: (406)SPO disbursing administered funds -

(398) Contractor indicated cumulative disbursement of administered funds = Total SPO administered funds \* Fractional disbursement of administered funds indicated by contractor progress

Units: \$

Uses: (405)Indicated cumulative disbursement of administered funds -

(399) Cumulative SPO administered funds disbursed = INTEG (SPO disbursing administered funds, 0)

Units: \$

Uses: (397)Administered funds to be disbursed -  
(699)Total SPO cost -

(400) effect of spo progress on indicated disbursement  $f([(0,0)-(1,1)],(0,0),(1,1))$

Units: dmn1

Uses: (401)Effect of SPO relative progress on indicated disbursement -

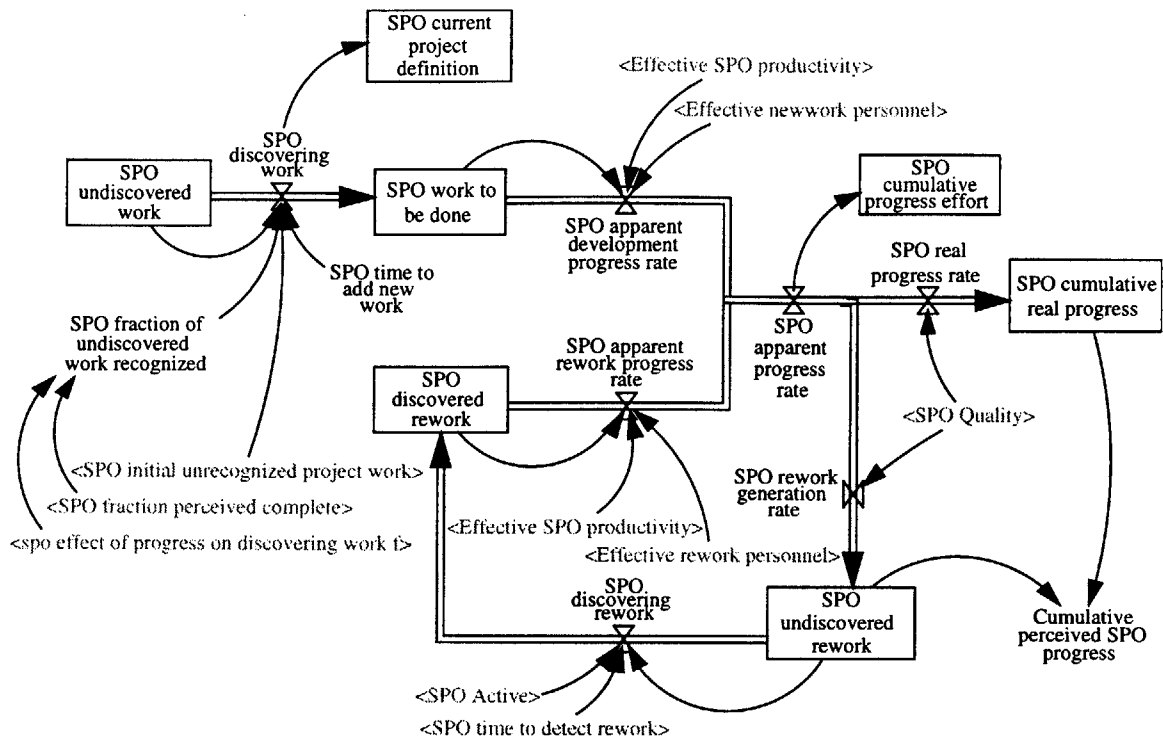
(401) Effect of SPO relative progress on indicated disbursement =  
effect of spo progress on indicated disbursement  $f(\text{SPO progress relative to required progress})$   
\*Tuner for SPO progress effect on disbursement  
+(1-Tuner for SPO progress effect on disbursement)

Units: dmn1

Uses: (405)Indicated cumulative disbursement of administered funds -



- (402) Fractional disbursement of administered funds indicated by contractor progress =  
fractional disbursement of administered funds indicated by contractor progress f  
(Contractor fraction perceived complete)  
Units: fraction  
Comment: Administered funds spending rate indicated by fraction of work completed by the contractor.  
Uses: (398)Contractor indicated cumulative disbursement of administered funds -
- (403) fractional disbursement of administered funds indicated by contractor progress  $f([(0,0)-(1,1)], (0,0),(0.98,1),(1,1))$   
Units: dmn1  
Comment: This function should be adjusted to fit the scenario being investigated.  
Uses: (402)Fractional disbursement of administered funds indicated by contractor progress -
- (404) Incrementing administered funds = Government releasing SPO administered funds  
Units: \$/Month  
Uses: (409)Undisbursed SPO administered funds -
- (405) Indicated cumulative disbursement of administered funds =  
Contractor indicated cumulative disbursement of administered funds  
\*Effect of SPO relative progress on indicated disbursement  
Units: \$  
Uses: (397)Administered funds to be disbursed -
- (406) SPO disbursing administered funds =  $\text{MIN}(\text{Administered funds to be disbursed} / \text{Time to release administered funds}, \text{Undisbursed SPO administered funds} / \text{TIME STEP})$   
Units: \$/Month  
Uses: (399)Cumulative SPO administered funds disbursed -  
(409)Undisbursed SPO administered funds -
- (407) Time to release administered funds = 1  
Units: Month  
Uses: (406)SPO disbursing administered funds -
- (408) Tuner for SPO progress effect on disbursement = 1  
Units: dmn1  
Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the full strength of the function, while a value of 0 results in a complete negation of the function. e.g.  $\text{Effect} = \text{Function}(\text{Variable}) * \text{Tuner} + (1 - \text{Tuner})$   
Uses: (401)Effect of SPO relative progress on indicated disbursement -
- (409) Undisbursed SPO administered funds =  
INTEG (Incrementing administered funds-SPO disbursing administered funds, 0)  
Units: \$  
Uses: (406)SPO disbursing administered funds -

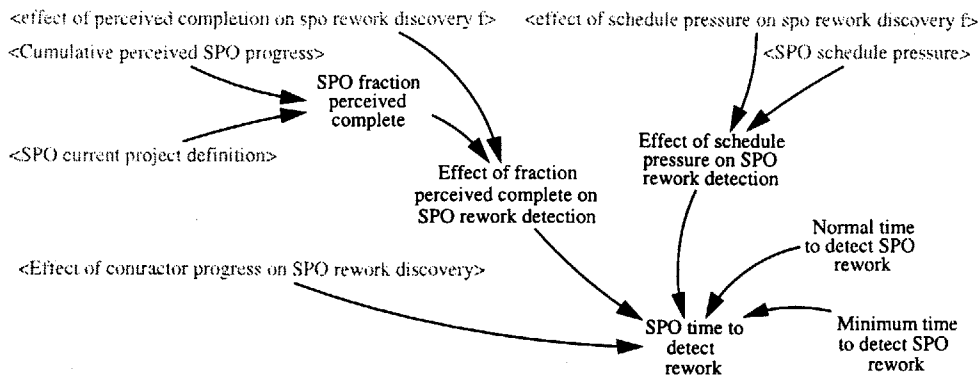


- (411) Cumulative perceived SPO progress = SPO cumulative real progress+SPO undiscovered rework  
 Units: manhours  
 Uses: (690)SPO Active -  
 (436)SPO fraction perceived complete -
- (412) SPO apparent development progress rate =  
 $\text{MIN}(\text{Effective newwork personnel} * \text{Effective SPO productivity}, \text{SPO work to be done} / \text{TIME STEP})$   
 Units: manhours/Month  
 Uses: (428)SPO work to be done -  
 (413)SPO apparent progress rate -
- (413) SPO apparent progress rate =  
 $\text{SPO apparent development progress rate} + \text{SPO apparent rework progress rate}$   
 Units: manhours/Month  
 Uses: (415)SPO cumulative progress effort -  
 (423)SPO real progress rate -  
 (424)SPO rework generation rate -
- (414) SPO apparent rework progress rate =  $\text{MIN}(\text{Effective rework personnel} * \text{Effective SPO productivity}, \text{SPO discovered rework} / \text{TIME STEP})$   
 Units: manhours/Month  
 Uses: (418)SPO discovered rework -  
 (413)SPO apparent progress rate -

- (415) SPO cumulative progress effort = INTEG (SPO apparent progress rate, 0)  
Units: manhours
- (416) SPO cumulative real progress = INTEG(SPO real progress rate, 0)  
Units: manhours  
Uses: (411)Cumulative perceived SPO progress -  
(682)Productivity estimated from SPO labor -  
(621)SPO Average Work Quality -  
(685)SPO product quality -
- (417) SPO current project definition = INTEG (SPO discovering work, SPO initial project size estimate)  
Units: manhours  
Comment: Current project definition is initialized to the initial project size (for the SPO) and then increased as the true size of the project is discovered.  
Uses: (690)SPO Active -  
(436)SPO fraction perceived complete -
- (418) SPO discovered rework = INTEG(SPO discovering rework-SPO apparent rework progress rate, 0)  
Units: manhours  
Uses: (567)Indicated fraction of remaining personnel engaged in rework -  
(414)SPO apparent rework progress rate -  
(486)SPO effort perceived remaining -  
(685)SPO product quality -
- (419) SPO discovering rework = (SPO undiscovered rework / SPO time to detect rework)\*SPO Active  
Units: manhours/Month  
Uses: (418)SPO discovered rework -  
(426)SPO undiscovered rework -
- (420) SPO discovering work = (SPO undiscovered work-(1-SPO fraction of undiscovered work recognized)  
\*SPO initial unrecognized project work)/SPO time to add new work  
Units: manhours/Month  
Uses: (417)SPO current project definition -  
(427)SPO undiscovered work -  
(428)SPO work to be done -
- (421) spo effect of progress on discovering work f([(0,0)-  
(1,1)],(0,0),(0.25,0.1),(0.5,0.5),(0.75,0.9),(1,1))  
Units: fraction  
Comment: fraction of UnDiscovered work found as a function of perceived progress  
Uses: (422)SPO fraction of undiscovered work recognized -
- (422) SPO fraction of undiscovered work recognized =  
spo effect of progress on discovering work f(SPO fraction perceived complete)  
Units: dnmnl  
Comment: This construction is taken from James M. James Lyneis' Project Management lecture notes 15.976 fall 1997.  
Uses: (420)SPO discovering work -
- (423) SPO real progress rate = SPO apparent progress rate\*SPO Quality  
Units: manhours/Month  
Uses: (416)SPO cumulative real progress -

- (424) SPO rework generation rate = SPO apparent progress rate\*(1-SPO Quality)  
 Units: manhours/Month  
 Uses: (426)SPO undiscovered rework -
- (425) SPO time to add new work = 0.75  
 Units: Month  
 Comment: Suggesting that within 1 month most of the affects are recognized  
 Uses: (420)SPO discovering work -
- (426) SPO undiscovered rework = INTEG(SPO rework generation rate - SPO discovering rework, 0)  
 Units: manhours  
 Uses: (411)Cumulative perceived SPO progress -  
 (682)Productivity estimated from SPO labor -  
 (621)SPO Average Work Quality -  
 (419)SPO discovering rework -  
 (685)SPO product quality -
- (427) SPO undiscovered work = INTEG (-SPO discovering work, SPO initial unrecognized project work)  
 Units: manhours  
 Comment: Current project definition is initialized to the initial project size and then increased as  
 the true size of the project is discovered.  
 Uses: (420)SPO discovering work -
- (428) SPO work to be done = INTEG (+SPO discovering work-SPO apparent development progress rate,  
 SPO initial project size estimate)  
 Units: manhours  
 Uses: (567)Indicated fraction of remaining personnel engaged in rework -  
 (412)SPO apparent development progress rate -  
 (486)SPO effort perceived remaining -

### 8.5.2.10 SPO Time to Detect Rework



- (430) Effect of fraction perceived complete on SPO rework detection =  
 effect of perceived completion on spo rework discovery  $f(\text{SPO fraction perceived complete})$   
 Units: dmn1  
 Uses: (437)SPO time to detect rework -
- (431) effect of perceived completion on spo rework discovery  $f([(0,0)(1,1)],(0,1),(0.4,1),(0.5,0.95),$   
 $(0.6,0.825),(0.7,0.65),(0.8,0.425),(0.9,0.2),(0.95,0.125),(1,0.1))$   
 Units: dmn1  
 Comment: Fraction of normal time to detect rework as a function of project completion.  
 Uses: (430)Effect of fraction perceived complete on SPO rework detection -
- (432) Effect of schedule pressure on SPO rework detection =  
 effect of schedule pressure on spo rework discovery  $f(\text{SPO schedule pressure})$   
 Units: dmn1  
 Uses: (437)SPO time to detect rework -
- (433) effect of schedule pressure on spo rework discovery  $f([(0,0)-(0.4,10)],(0,1),(0.1,1),(0.15,1.05),$   
 $(0.2,1.25),(0.25,2),(0.3,5))$   
 Units: dmn1  
 Comment: Estimate by author, based upon experience and anecdotal evidence.  
 Uses: (432)Effect of schedule pressure on SPO rework detection -
- (434) Minimum time to detect SPO rework = 0.25  
 Units: Month  
 Uses: (437)SPO time to detect rework -
- (435) Normal time to detect SPO rework = 12  
 Units: Month  
 Comment: Normal or initial time to detect rework.  
 Uses: (437)SPO time to detect rework -

(436) SPO fraction perceived complete =  
MIN(Cumulative perceived SPO progress/SPO current project definition,1)

Units: dnm1

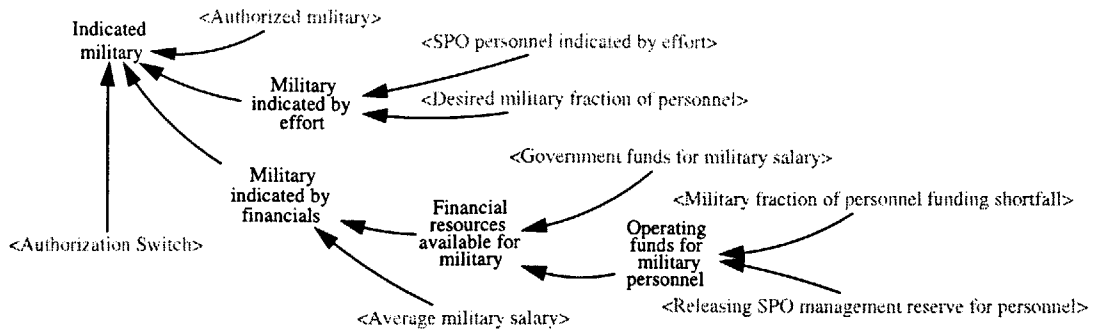
Uses: (665)Contractor weight on early phase productivity function -  
(430)Effect of fraction perceived complete on SPO rework detection -  
(279)Effect of SPO progress on contractor rework discovery -  
(675)Required contractor progress -  
(422)SPO fraction of undiscovered work recognized -  
(384)SPO manager's willingness to spend operating reserve on personnel -  
(284)SPO progress relative to required progress -  
(634)SPO Weight on completion based progress -  
(611)Weight given to real SPO productivity -

(437) SPO time to detect rework = MAX(Effect of fraction perceived complete on SPO rework detection  
\*Effect of schedule pressure on SPO rework detection  
\*Effect of contractor progress on SPO rework discovery  
\*Normal time to detect SPO rework,  
Minimum time to detect SPO rework)

Units: Month

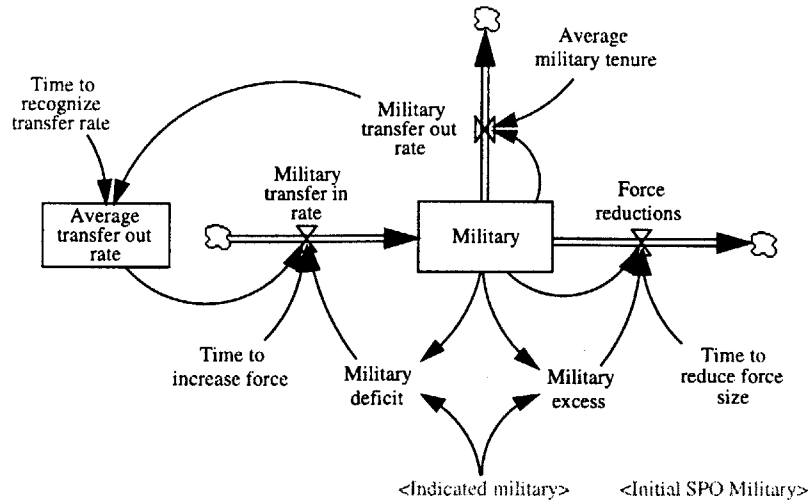
Uses: (419)SPO discovering rework -

### 8.5.2.11 SPO Military Workforce Sizing



- (439) Financial resources available for military =  
 $\text{MAX}(\text{Government funds for military salary} + \text{Operating funds for military personnel}, 0)$   
 Units: \$/Month  
 Uses: (442) Military indicated by financials -
- (440) Indicated military =  $\text{MIN}(\text{Authorized military} * \text{Authorization Switch} + \text{Military indicated by effort} * (1 - \text{Authorization Switch}), \text{Military indicated by financials})$   
 Units: man  
 Comment: "Civilian is set to minimum of authorization or financial limits" - Jerry Sutton  
 Uses: (450) Military deficit -  
 (451) Military excess -
- (441) Military indicated by effort =  $\text{SPO personnel indicated by effort} * \text{Desired military fraction of personnel}$   
 Units: man  
 Uses: (471) Desired military authorization -  
 (440) Indicated military -  
 (391) Military personnel shortfall -
- (442) Military indicated by financials =  $\text{Financial resources available for military} / \text{Average military salary}$   
 Units: man  
 Uses: (440) Indicated military -  
 (391) Military personnel shortfall -
- (443) Operating funds for military personnel =  
 $\text{Military fraction of personnel funding shortfall} * \text{Releasing SPO management reserve for personnel}$   
 Units: \$/Month  
 Uses: (439) Financial resources available for military -  
 (485) Operating funds for civilians -

### 8.5.2.12 SPO Military Workforce

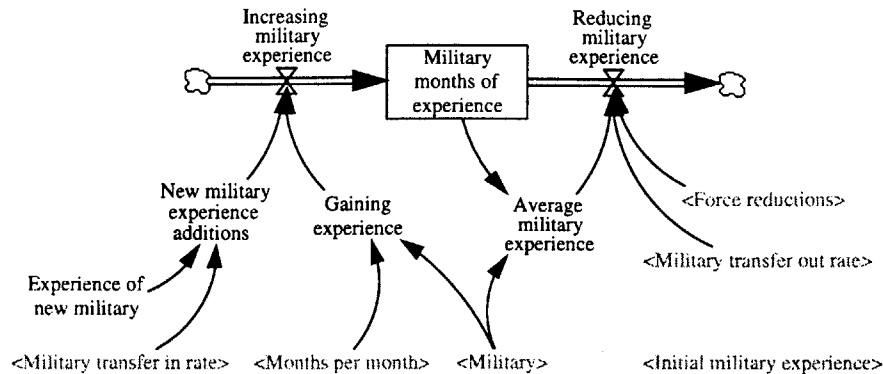


- (445) Average military tenure = 24  
 Units: Month  
 Uses: (453)Military transfer out rate -
- (446) Average transfer out rate = SMOOTH(Military transfer out rate,Time to recognize transfer rate)  
 Units: man/Month  
 Uses: (452)Military transfer in rate -
- (447) Force reductions = MIN(Military excess/Time to reduce force size,Military/TIME STEP)  
 Units: man/Month  
 Uses: (449)Military -  
 (465)Reducing military experience -
- (448) Initial SPO Military = 30  
 Units: man  
 Comment: Initial number of military personnel working project at SPO  
 Uses: (449)Military -  
 (463)Military months of experience -



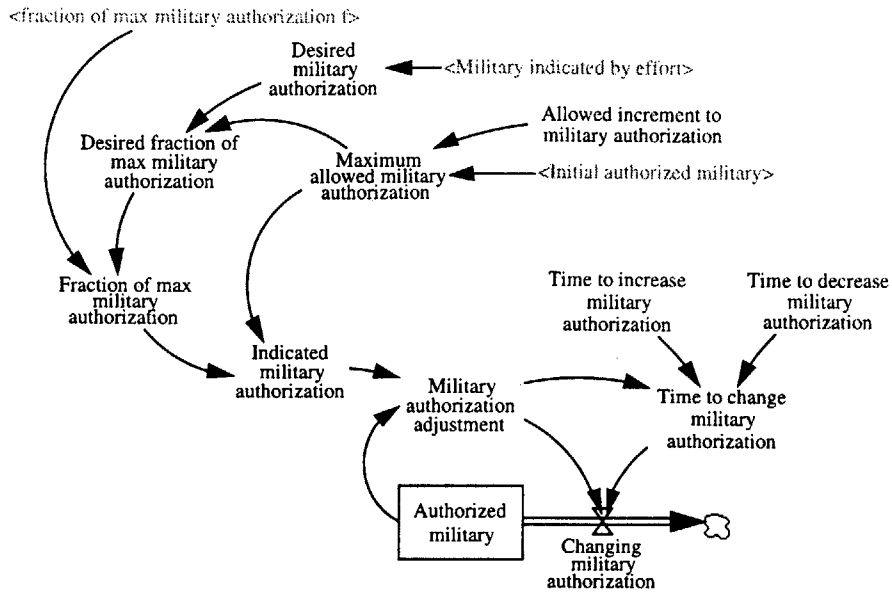
- (449)  $\text{Military} = \text{INTEG}(\text{Military transfer in rate} - \text{Military transfer out rate} - \text{Force reductions}, \text{Initial SPO Military})$   
 Units: man  
 Comment: Total military personnel at working on the project at SPO  
 Uses: (458)Average military experience -  
 (598)Average personnel productivity -  
 (613)Average personnel quality -  
 (639)Current military fraction of personnel -  
 (447)Force reductions -  
 (660)Fraction of overtime worked by civilians -  
 (460)Gaining experience -  
 (343)Military costs per month -  
 (450)Military deficit -  
 (451)Military excess -  
 (453)Military transfer out rate -  
 (571)SPO personnel -
- (450)  $\text{Military deficit} = \text{MAX}(0, \text{Indicated military} - \text{Military})$   
 Units: man  
 Uses: (452)Military transfer in rate -
- (451)  $\text{Military excess} = \text{MAX}(0, \text{Military} - \text{Indicated military})$   
 Units: man  
 Uses: (447)Force reductions -
- (452)  $\text{Military transfer in rate} = \text{Average transfer out rate} + \text{Military deficit} / \text{Time to increase force}$   
 Units: man/Month  
 Uses: (449)Military -  
 (464)New military experience additions -
- (453)  $\text{Military transfer out rate} = \text{MIN}(\text{Military} / \text{Average military tenure}, \text{Military} / \text{TIME STEP})$   
 Units: man/Month  
 Uses: (449)Military -  
 (446)Average transfer out rate -  
 (465)Reducing military experience -
- (454)  $\text{Time to increase force} = 6$   
 Units: Month  
 Comment: Col. Rutley's estimate  
 Uses: (452)Military transfer in rate -
- (455)  $\text{Time to recognize transfer rate} = 1$   
 Units: Month  
 Uses: (446)Average transfer out rate -
- (456)  $\text{Time to reduce force size} = 6$   
 Units: Month  
 Comment: Average time required to reduce the Military personnel on a project. Based upon Col. Rutley's estimated time to transfer of 6 months.  
 Uses: (447)Force reductions -

### 8.5.2.13 SPO Military Workforce Experience



- (458)  $\text{Average military experience} = \text{Military months of experience} / \text{MAX}(1e-005, \text{Military})$   
 Units: months  
 Uses: (585) Military fraction of normal productivity -  
 (586) Military quality -  
 (465) Reducing military experience -
- (459)  $\text{Experience of new military} = 0.1$   
 Units: months  
 Uses: (464) New military experience additions -
- (460)  $\text{Gaining experience} = \text{Military} * \text{Months per month}$   
 Units: man\*months/Month  
 Uses: (461) Increasing military experience -
- (461)  $\text{Increasing military experience} = \text{Gaining experience} + \text{New military experience additions}$   
 Units: man\*months/Month  
 Uses: (463) Military months of experience -
- (462)  $\text{Initial military experience} = 36$   
 Units: months  
 Uses: (463) Military months of experience -
- (463)  $\text{Military months of experience} = \text{INTEG} (+\text{Increasing military experience} - \text{Reducing military experience}, \text{Initial SPO Military} * \text{Initial military experience})$   
 Units: man\*months  
 Comment: Total man months of experience of military on the project.  
 Uses: (458) Average military experience -
- (464)  $\text{New military experience additions} = \text{Military transfer in rate} * \text{Experience of new military}$   
 Units: man\*Month/Month  
 Uses: (461) Increasing military experience -
- (465)  $\text{Reducing military experience} = (\text{Force reductions} + \text{Military transfer out rate}) * \text{Average military experience}$   
 Units: man\*months/Month  
 Uses: (463) Military months of experience -

### 8.5.2.14 SPO Military Authorization



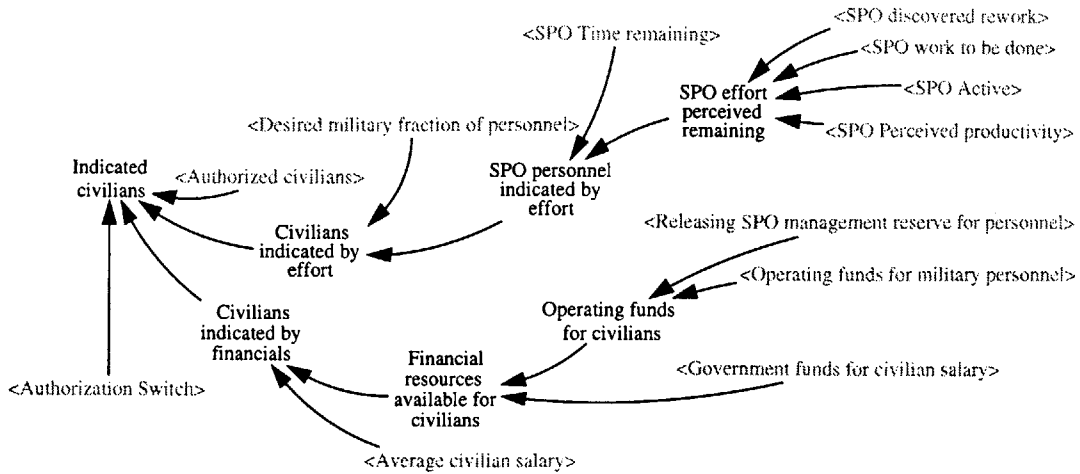
- (467) Allowed increment to military authorization = 0.1  
 Units: fraction  
 Comment: Fractional increase in the number of authorized military slots, from the initial authorization, allowed over the life of the project  
 Uses: (475)Maximum allowed military authorization -
- (468) Authorized military = INTEG (Changing military authorization, Initial authorized military)  
 Units: man  
 Comment: Number of military slots currently authorized for SPO.  
 Uses: (440)Indicated military -  
 (476)Military authorization adjustment -  
 (391)Military personnel shortfall -
- (469) Changing military authorization =  

$$\text{Military authorization adjustment} / \text{Time to change military authorization}$$
  
 Units: man/Month  
 Uses: (468)Authorized military -
- (470) Desired fraction of max military authorization =  

$$\text{IF THEN ELSE}(\text{Maximum allowed military authorization} = 0, 0, \text{Desired military authorization} / \text{Maximum allowed military authorization})$$
  
 Units: fraction  
 Comment: Maximum allowed authorization is the ceiling above which authorized civilians is not allowed to pass.  
 Uses: (472)Fraction of max military authorization -
- (471) Desired military authorization = Military indicated by effort  
 Units: man  
 Uses: (470)Desired fraction of max military authorization -

- (472) Fraction of max military authorization =  
 IF THEN ELSE(Desired fraction of max military authorization < 2,  
 fraction of max military authorization f(Desired fraction of max military authorization),  
 fraction of max military authorization f(2))  
 Units: fraction  
 Uses: (474) Indicated military authorization -
- (473) fraction of max military authorization f([(0,0)-(1.5,1)],(0,0),(1,1))  
 Units: dmnl  
 Comment: Ceiling function for authorizations  
 Uses: (472) Fraction of max military authorization -
- (474) Indicated military authorization =  
 Maximum allowed military authorization \* Fraction of max military authorization  
 Units: man  
 Uses: (476) Military authorization adjustment -
- (475) Maximum allowed military authorization =  
 Initial authorized military \* (1 + Allowed increment to military authorization)  
 Units: man  
 Comment: Maximum number of military personnel slots allocated to SPO.  
 Uses: (470) Desired fraction of max military authorization -  
 (474) Indicated military authorization -
- (476) Military authorization adjustment = Indicated military authorization - Authorized military  
 Units: man  
 Comment: The gap between actual and indicated authorization.  
 Uses: (469) Changing military authorization -  
 (477) Time to change military authorization -
- (477) Time to change military authorization = IF THEN ELSE(Military authorization adjustment >= 0,  
 Time to increase military authorization, Time to decrease military authorization)  
 Units: months  
 Uses: (469) Changing military authorization -
- (478) Time to decrease military authorization = 1000  
 Units: Month  
 Uses: (477) Time to change military authorization -
- (479) Time to increase military authorization = 12  
 Units: Month  
 Comment: Source: Kathey Watern, ASC  
 Uses: (477) Time to change military authorization -

### 8.5.2.15 SPO Civilian Workforce Sizing



- (481) Civilians indicated by effort =  

$$\text{SPO personnel indicated by effort} * (1 - \text{Desired military fraction of personnel})$$
 Units: man  
 Uses: (388)Civilian personnel shortfall -  
 (542)Desired authorization -  
 (484)Indicated civilians -
- (482) Civilians indicated by financials =  $\text{Financial resources available for civilians} / \text{Average civilian salary}$   
 Units: man  
 Uses: (388)Civilian personnel shortfall -  
 (484)Indicated civilians -
- (483) Financial resources available for civilians =  $\text{MAX}(\text{Government funds for civilian salary} + \text{Operating funds for civilians}, 0)$   
 Units: \$/Month  
 Comment: Financial resources available to pay civilian salaries exclusive of overtime pay.  
 Uses: (482)Civilians indicated by financials -
- (484) Indicated civilians =  $\text{MIN}(\text{Authorized civilians} * \text{Authorization Switch} + \text{Civilians indicated by effort} * (1 - \text{Authorization Switch}), \text{Civilians indicated by financials})$   
 Units: man  
 Comment: Civilian workforce is set to minimum of authorization or financial limits - Jerry Sutton  
 Uses: (555)Civilian correction -
- (485) Operating funds for civilians =  $\text{Releasing SPO management reserve for personnel} - \text{Operating funds for military personnel}$   
 Units: \$/Month  
 Uses: (483)Financial resources available for civilians -

(486) SPO effort perceived remaining =  
(( SPO work to be done+SPO discovered rework)/SPO Perceived productivity)\*SPO Active

Units: man\*months

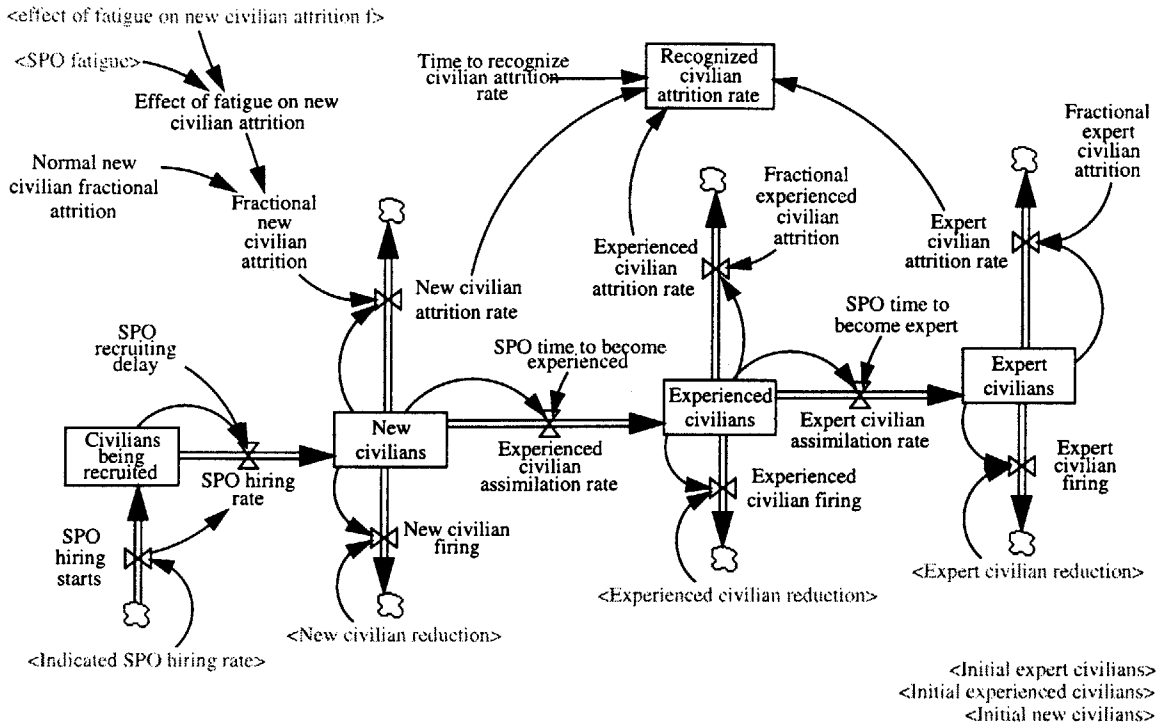
Uses: (630)SPO perceived time required -  
(487)SPO personnel indicated by effort -

(487) SPO personnel indicated by effort = SPO effort perceived remaining/SPO Time remaining

Units: man

Uses: (481)Civilians indicated by effort -  
(641)Desired SPO overtime personnel -  
(441)Military indicated by effort -

### 8.5.2.16 SPO Civilian Workforce



- (489) Civilians being recruited = INTEG(+SPO hiring starts-SPO hiring rate,SPO attritors replacement)  
 Units: man  
 Uses: (561)SPO attrition correction -  
 (511)SPO hiring rate -
- (490) Effect of fatigue on new civilian attrition = effect of fatigue on new civilian attrition f(SPO fatigue)  
 Units: dmn1  
 Uses: (502)Fractional new civilian attrition -
- (491) effect of fatigue on new civilian attrition f([(-0.2,0)-(0.5,2)],(-0.2,0.99),(0,1),(0.1,1.03),(0.2,1.08),  
 (0.3,1.13),(0.5,1.25))  
 Units: dmn1  
 Comment: Fractional attrition increases as fatigue accumulates. Author's estimate.  
 Uses: (490)Effect of fatigue on new civilian attrition -
- (492) Experienced civilian assimilation rate = MAX(0,New civilians/SPO time to become experienced)  
 Units: man/months  
 Uses: (495)Experienced civilians -  
 (508)New civilians -  
 (526)Increasing experienced civilian experience -

- (493) Experienced civilian attrition rate =  
 $\text{MAX}(0, \text{Experienced civilians} * \text{Fractional experienced civilian attrition})$   
 Units: man/months  
 Uses: (495)Experienced civilians -  
 (510)Recognized civilian attrition rate -  
 (534)Reducing experienced civilian experience -
- (494) Experienced civilian firing =  $\text{MIN}(\text{Experienced civilian reduction}, \text{Experienced civilians} / \text{TIME STEP})$   
 Units: man/Month  
 Uses: (495)Experienced civilians -  
 (534)Reducing experienced civilian experience -
- (495) Experienced civilians =  $\text{INTEG}(\text{+Experienced civilian assimilation rate} - \text{Expert civilian assimilation rate} - \text{Experienced civilian attrition rate} - \text{Experienced civilian firing}, \text{Initial experienced civilians})$   
 Units: man  
 Uses: (518)Average experienced civilian experience -  
 (598)Average personnel productivity -  
 (613)Average personnel quality -  
 (493)Experienced civilian attrition rate -  
 (494)Experienced civilian firing -  
 (556)Experienced civilian reduction -  
 (523)Experienced civilians gaining experience -  
 (496)Expert civilian assimilation rate -  
 (557)Expert civilian reduction -  
 (560)New civilian reduction -  
 (563)SPO civilians -
- (496) Expert civilian assimilation rate =  $\text{Experienced civilians} / \text{SPO time to become expert}$   
 Units: man/Month  
 Uses: (495)Experienced civilians -  
 (499)Expert civilians -  
 (527)Increasing expert civilian experience -
- (497) Expert civilian attrition rate =  $\text{MAX}(0, \text{Expert civilians} * \text{Fractional expert civilian attrition})$   
 Units: man/months  
 Uses: (499)Expert civilians -  
 (510)Recognized civilian attrition rate -  
 (535)Reducing expert civilian experience -
- (498) Expert civilian firing =  $\text{MIN}(\text{Expert civilian reduction}, \text{Expert civilians} / \text{TIME STEP})$   
 Units: man/Month  
 Uses: (499)Expert civilians -  
 (535)Reducing expert civilian experience -

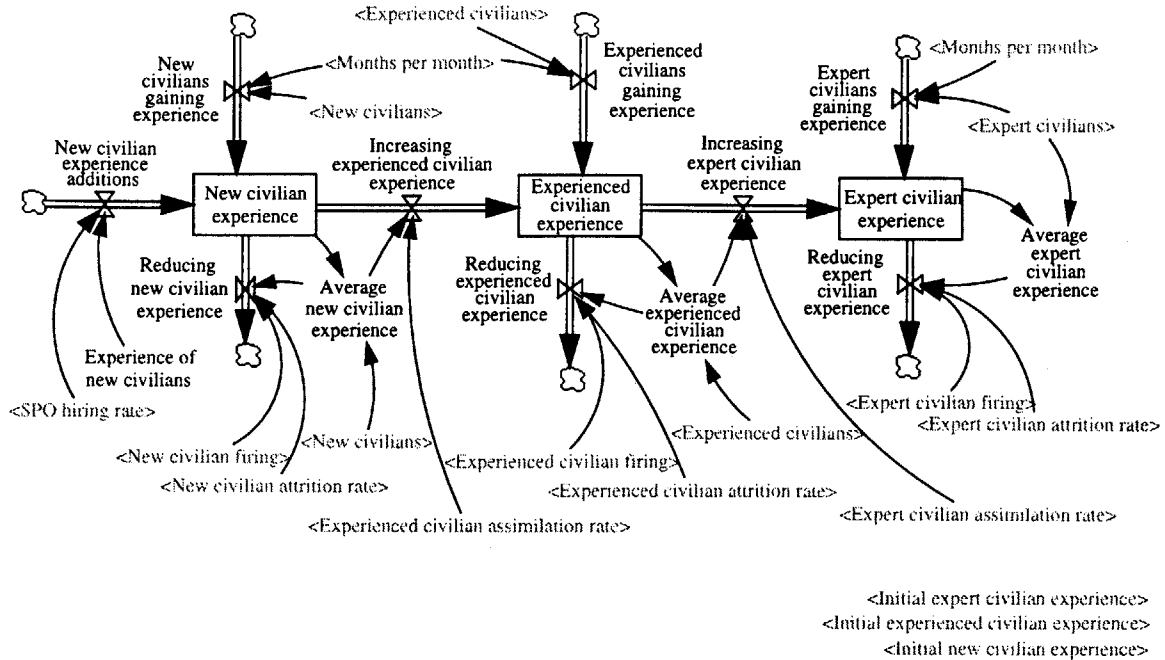


- (499)  $\text{Expert civilians} = \text{INTEG}(+\text{Expert civilian assimilation rate} - \text{Expert civilian attrition rate} - \text{Expert civilian firing, Initial expert civilians})$   
 Units: man  
 Uses: (519)Average expert civilian experience -  
 (598)Average personnel productivity -  
 (613)Average personnel quality -  
 (556)Experienced civilian reduction -  
 (497)Expert civilian attrition rate -  
 (498)Expert civilian firing -  
 (557)Expert civilian reduction -  
 (525)Expert civilians gaining experience -  
 (560)New civilian reduction -  
 (563)SPO civilians -
- (500) Fractional experienced civilian attrition = 0.005  
 Units: 1/Month  
 Comment: Fraction of experienced civilian which chooses to leave each month.  
 Uses: (493)Experienced civilian attrition rate -
- (501) Fractional expert civilian attrition = 0.005  
 Units: 1/Month  
 Comment: Fraction of expert civilian which chooses to leave each month.  
 Uses: (497)Expert civilian attrition rate -
- (502) Fractional new civilian attrition =  
 $\text{Normal new civilian fractional attrition} * \text{Effect of fatigue on new civilian attrition}$   
 Units: 1/Month  
 Comment: Fraction of new civilian which chooses to leave each month.  
 Uses: (506)New civilian attrition rate -
- (503) Initial experienced civilians = 1  
 Units: man  
 Uses: (522)Experienced civilian experience -  
 (495)Experienced civilians -
- (504) Initial expert civilians = 68  
 Units: man  
 Uses: (524)Expert civilian experience -  
 (499)Expert civilians -
- (505) Initial new civilians = 1  
 Units: man  
 Uses: (531)New civilian experience -  
 (508)New civilians -
- (506)  $\text{New civilian attrition rate} = \text{MAX}(0, \text{New civilians} * \text{Fractional new civilian attrition})$   
 Units: man/months  
 Uses: (508)New civilians -  
 (510)Recognized civilian attrition rate -  
 (536)Reducing new civilian experience -

- (507)  $\text{New civilian firing} = \text{MIN}(\text{New civilian reduction}, \text{New civilians}/\text{TIME STEP})$   
 Units: man/Month  
 Comment: This construction is intended to keep firing from draining New civilians below zero.  
 Uses: (508)New civilians -  
 (536)Reducing new civilian experience -
- (508)  $\text{New civilians} = \text{INTEG}(-\text{Experienced civilian assimilation rate}-\text{New civilian attrition rate}$   
 $\quad\quad\quad -\text{New civilian firing}+\text{SPO hiring rate}, \text{Initial new civilians})$   
 Units: man  
 Uses: (520)Average new civilian experience -  
 (598)Average personnel productivity -  
 (613)Average personnel quality -  
 (492)Experienced civilian assimilation rate -  
 (556)Experienced civilian reduction -  
 (557)Expert civilian reduction -  
 (506)New civilian attrition rate -  
 (507)New civilian firing -  
 (560)New civilian reduction -  
 (533)New civilians gaining experience -  
 (563)SPO civilians -
- (509) Normal new civilian fractional attrition = 0.01  
 Units: 1/Month  
 Comment: Normal fraction of new civilian which chooses to leave each month.  
 Uses: (502)Fractional new civilian attrition -
- (510)  $\text{Recognized civilian attrition rate} = \text{SMOOTH}(\text{Expert civilian attrition rate}$   
 $\quad\quad\quad +\text{Experienced civilian attrition rate}+\text{New civilian attrition rate},$   
 $\quad\quad\quad \text{Time to recognize civilian attrition rate})$   
 Units: man/Month  
 Uses: (554)Base SPO hiring rate -  
 (562)SPO attritors replacement -
- (511)  $\text{SPO hiring rate} =$   
 $\text{DELAY3I}(\text{SPO hiring starts}, \text{SPO recruiting delay}, \text{Civilians being recruited}/\text{SPO recruiting delay})$   
 Units: man/Month  
 Comment: A third order material delay used to simulate the delay from initiating hiring to beginning work.  
 Uses: (489)Civilians being recruited -  
 (508)New civilians -  
 (532)New civilian experience additions -
- (512)  $\text{SPO hiring starts} = \text{Indicated SPO hiring rate}$   
 Units: man/Month  
 Uses: (489)Civilians being recruited -  
 (511)SPO hiring rate -

- (513) SPO recruiting delay = 3  
Units: Month  
Comment: Source: Col. Rutley  
Uses: (562)SPO attritors replacement -  
(511)SPO hiring rate -
- (514) SPO time to become experienced = 24  
Units: Month  
Uses: (492)Experienced civilian assimilation rate -
- (515) SPO time to become expert = 24  
Units: Month  
Uses: (496)Expert civilian assimilation rate -
- (516) Time to recognize civilian attrition rate = 1  
Units: Month  
Uses: (510)Recognized civilian attrition rate -

### 8.5.2.17 SPO Civilian Workforce Experience



(518) Average experienced civilian experience =  $\frac{\text{Experienced civilian experience}}{\text{MAX}(1e-005, \text{Experienced civilians})}$

Units: months

- Uses: (581)Experienced civilian fraction of normal productivity -  
 (582)Experienced civilian quality -  
 (527)Increasing expert civilian experience -  
 (534)Reducing experienced civilian experience -

(519) Average expert civilian experience =  $\frac{\text{Expert civilian experience}}{\text{MAX}(1e-005, \text{Expert civilians})}$

Units: months

- Uses: (583)Expert civilian fraction of normal productivity -  
 (584)Expert civilian quality -  
 (535)Reducing expert civilian experience -

(520) Average new civilian experience =  $\frac{\text{New civilian experience}}{\text{MAX}(1e-005, \text{New civilians})}$

Units: months

- Uses: (526)Increasing experienced civilian experience -  
 (587)New civilian fraction of normal productivity -  
 (588)New civilian quality -  
 (536)Reducing new civilian experience -

(521) Experience of new civilians = 0.1

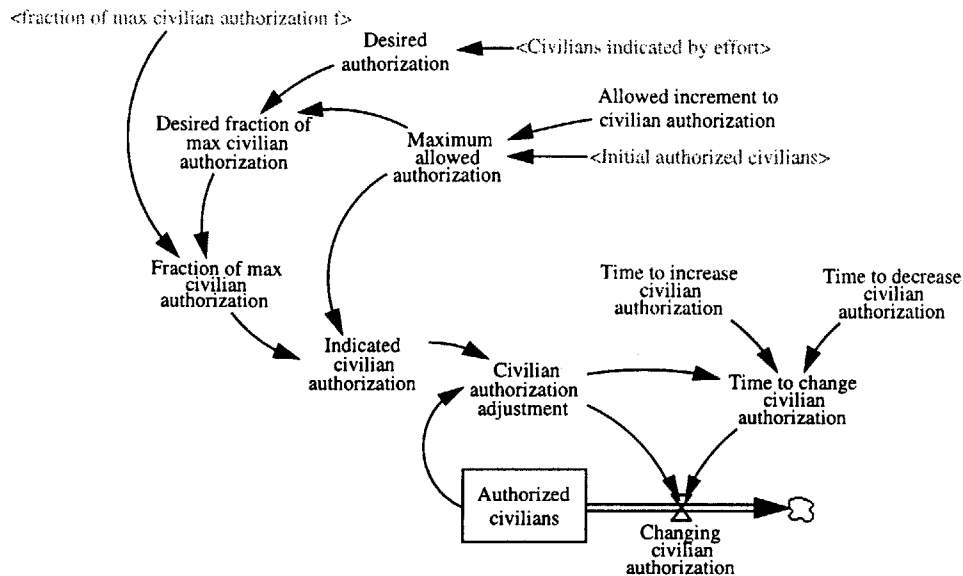
Units: months

- Uses: (532)New civilian experience additions -

- (522) Experienced civilian experience = INTEG (+Increasing experienced civilian experience  
-Increasing expert civilian experience-Reducing experienced civilian experience  
+Experienced civilians gaining experience,  
Initial experienced civilians\*Initial experienced civilian experience)  
Units: man\*months  
Comment: Total man-months of experience of experienced civilian.  
Uses: (518)Average experienced civilian experience -
- (523) Experienced civilians gaining experience = Experienced civilians\*Months per month  
Units: man\*months/Month  
Uses: (522)Experienced civilian experience -
- (524) Expert civilian experience = INTEG (+Increasing expert civilian experience  
-Reducing expert civilian experience+Expert civilians gaining experience,  
Initial expert civilians\*Initial expert civilian experience)  
Units: man\*months  
Comment: Total man-months of experience of expert civilian.  
Uses: (519)Average expert civilian experience -
- (525) Expert civilians gaining experience = Expert civilians\*Months per month  
Units: man\*months/Month  
Uses: (524)Expert civilian experience -
- (526) Increasing experienced civilian experience =  
Average new civilian experience\*Experienced civilian assimilation rate  
Units: man\*months/Month  
Uses: (522)Experienced civilian experience -  
(531)New civilian experience -
- (527) Increasing expert civilian experience =  
Average experienced civilian experience\*Expert civilian assimilation rate  
Units: man\*months/Month  
Uses: (522)Experienced civilian experience -  
(524)Expert civilian experience -
- (528) Initial experienced civilian experience = 24  
Units: Month  
Uses: (522)Experienced civilian experience -
- (529) Initial expert civilian experience = 48  
Units: Month  
Uses: (524)Expert civilian experience -
- (530) Initial new civilian experience = 1  
Units: Month  
Uses: (531)New civilian experience -
- (531) New civilian experience = INTEG (+New civilians gaining experience  
+New civilian experience additions-Reducing new civilian experience  
-Increasing experienced civilian experience, Initial new civilians \*Initial new civilian experience)  
Units: man\*months  
Comment: Total man months of experience of new civilian.  
Uses: (520)Average new civilian experience -

- (532) New civilian experience additions = SPO hiring rate\*Experience of new civilians  
 Units: man\*Month/Month  
 Uses: (531)New civilian experience -
- (533) New civilians gaining experience = New civilians\*Months per month  
 Units: man\*months/Month  
 Uses: (531)New civilian experience -
- (534) Reducing experienced civilian experience = (Experienced civilian attrition rate  
 +Experienced civilian firing)\*Average experienced civilian experience  
 Units: man\*months/Month  
 Uses: (522)Experienced civilian experience -
- (535) Reducing expert civilian experience = (Expert civilian attrition rate+Expert civilian firing)  
 \*Average expert civilian experience  
 Units: man\*months/Month  
 Uses: (524)Expert civilian experience -
- (536) Reducing new civilian experience =  
 (New civilian attrition rate+New civilian firing)\*Average new civilian experience  
 Units: man\*months/Month  
 Uses: (531)New civilian experience -

### 8.5.2.18 SPO Civilian Authorization



- (538)  $\text{Allowed increment to civilian authorization} = 0.1$   
 Units: fraction  
 Comment: Fractional increase in the number of authorized civilian slots, from the initial authorization, allowed over the life of the project  
 Uses: (547)Maximum allowed authorization -
- (539)  $\text{Authorized civilians} = \text{INTEG}(\text{Changing civilian authorization}, \text{Initial authorized civilians})$   
 Units: man  
 Comment: Number of civilian slots currently authorized for SPO.  
 Uses: (541)Civilian authorization adjustment -  
 (388)Civilian personnel shortfall -  
 (738)Funding available for civilian overtime -  
 (484)Indicated civilians -
- (540)  $\text{Changing civilian authorization} = \frac{\text{Civilian authorization adjustment}}{\text{Time to change civilian authorization}}$   
 Units: man/Month  
 Uses: (539)Authorized civilians -
- (541)  $\text{Civilian authorization adjustment} = \text{Indicated civilian authorization} - \text{Authorized civilians}$   
 Units: man  
 Comment: The gap between actual and indicated authorization.  
 Uses: (540)Changing civilian authorization -  
 (548)Time to change civilian authorization -
- (542)  $\text{Desired authorization} = \text{Civilians indicated by effort}$   
 Units: man  
 Uses: (543)Desired fraction of max civilian authorization -

- (543) Desired fraction of max civilian authorization =  

$$\text{IF THEN ELSE}(\text{Maximum allowed authorization} = 0, 0, \text{Desired authorization}/\text{Maximum allowed authorization})$$
Units: fraction  
Comment: Maximum allowed authorization is the ceiling above which authorized civilians is not allowed to pass.  
Uses: (544)Fraction of max civilian authorization -
- (544) Fraction of max civilian authorization =  

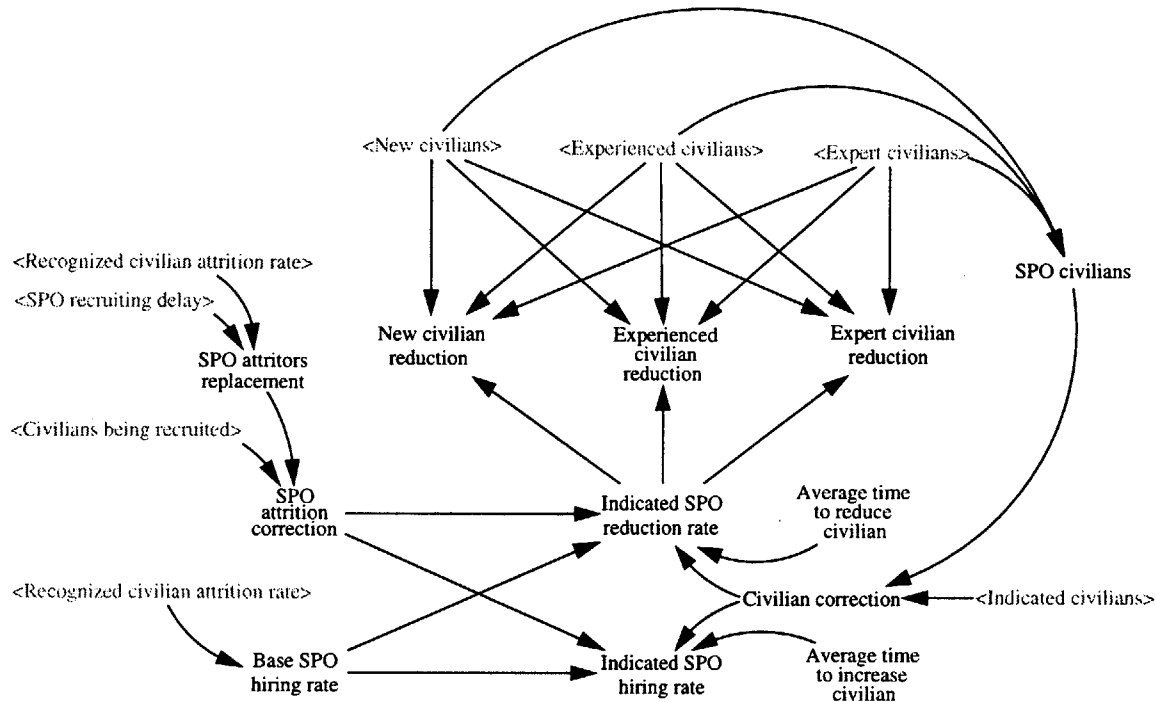
$$\text{IF THEN ELSE}(\text{Desired fraction of max civilian authorization} < 2, \text{fraction of max civilian authorization } f(\text{Desired fraction of max civilian authorization}), \text{fraction of max civilian authorization } f(2))$$
Units: fraction  
Uses: (546)Indicated civilian authorization -
- (545) fraction of max civilian authorization  $f([(0,0)-(2,1)],(0,0),(1,1))$   
Units: dmnl  
Comment: Ceiling function for authorizations.  
Uses: (544)Fraction of max civilian authorization -
- (546) Indicated civilian authorization =  

$$\text{Maximum allowed authorization} * \text{Fraction of max civilian authorization}$$
Units: man  
Uses: (541)Civilian authorization adjustment -
- (547) Maximum allowed authorization =  

$$\text{Initial authorized civilians} * (1 + \text{Allowed increment to civilian authorization})$$
Units: man  
Comment: Maximum number of civilian slots allocated to SPO.  
Uses: (543)Desired fraction of max civilian authorization -  
(546)Indicated civilian authorization -
- (548) Time to change civilian authorization =  $\text{IF THEN ELSE}(\text{Civilian authorization adjustment} >= 0, \text{Time to increase civilian authorization}, \text{Time to decrease civilian authorization})$   
Units: months  
Uses: (540)Changing civilian authorization -
- (549) Time to decrease civilian authorization = 1000  
Units: months  
Comment: A very long time.  
Uses: (548)Time to change civilian authorization -
- (550) Time to increase civilian authorization = 12  
Units: months  
Comment: Source: Kathey Watern, ASC  
Uses: (548)Time to change civilian authorization -



### 8.5.2.19 SPO Civilian Workforce Management



- (552) Average time to increase civilian = 2  
 Units: Month  
 Uses: (558)Indicated SPO hiring rate -
- (553) Average time to reduce civilian = 1  
 Units: Month  
 Uses: (559)Indicated SPO reduction rate -
- (554) Base SPO hiring rate = Recognized civilian attrition rate  
 Units: man/Month  
 Comment: The base-hiring rate required to maintain the civilian at a constant level.  
 (compensating for attrition)  
 Uses: (558)Indicated SPO hiring rate -  
 (559)Indicated SPO reduction rate -
- (555) Civilian correction = Indicated civilians-SPO civilians  
 Units: man  
 Comment: Difference between the actual civilian size and the desired civilian size.  
 Uses: (558)Indicated SPO hiring rate -  
 (559)Indicated SPO reduction rate -
- (556) Experienced civilian reduction = Indicated SPO reduction rate  

$$*(\text{Experienced civilians}/(\text{Expert civilians}+\text{Experienced civilians}+\text{New civilians}))$$
  
 Units: man/Month  
 Uses: (494)Experienced civilian firing -

- (557) Expert civilian reduction = Indicated SPO reduction rate  

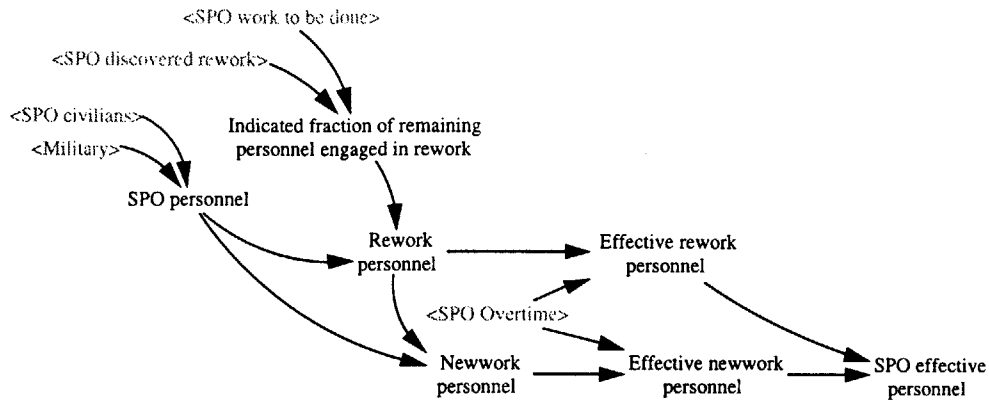
$$*(\text{Expert civilians}/(\text{Expert civilians}+\text{Experienced civilians}+\text{New civilians}))$$
Units: man/Month  
Uses: (498)Expert civilian firing -
- (558) Indicated SPO hiring rate = MAX(0, Base SPO hiring rate  

$$+(\text{Civilian correction}+\text{SPO attrition correction})/\text{Average time to increase civilian})$$
Units: man/Month  
Uses: (512)SPO hiring starts -
- (559) Indicated SPO reduction rate = (-1)\*MIN(0, Base SPO hiring rate  

$$+(\text{Civilian correction}+\text{SPO attrition correction})/\text{Average time to reduce civilian})$$
Units: man/Month  
Uses: (556)Experienced civilian reduction -  
(557)Expert civilian reduction -  
(560)New civilian reduction -
- (560) New civilian reduction = Indicated SPO reduction rate\*(New civilians/(Expert civilians  

$$+\text{Experienced civilians}+\text{New civilians}))$$
Units: man/Month  
Uses: (507)New civilian firing -
- (561) SPO attrition correction = SPO attritors replacement-Civilians being recruited  
Units: man  
Uses: (558)Indicated SPO hiring rate -  
(559)Indicated SPO reduction rate -
- (562) SPO attritors replacement = Recognized civilian attrition rate\*SPO recruiting delay  
Units: man  
Uses: (489)Civilians being recruited -  
(561)SPO attrition correction -
- (563) SPO civilians = Expert civilians+Experienced civilians+New civilians  
Units: man  
Comment: The total number of non-military personnel working on the project.  
Uses: (555)Civilian correction -  
(656)Civilians not paid for overtime -  
(657)Civilians paid for overtime -  
(639)Current military fraction of personnel -  
(344)Normal civilian labor cost per month -  
(345)SPO overtime cost per month -  
(571)SPO personnel -

### 8.5.2.20 SPO Personnel Distribution

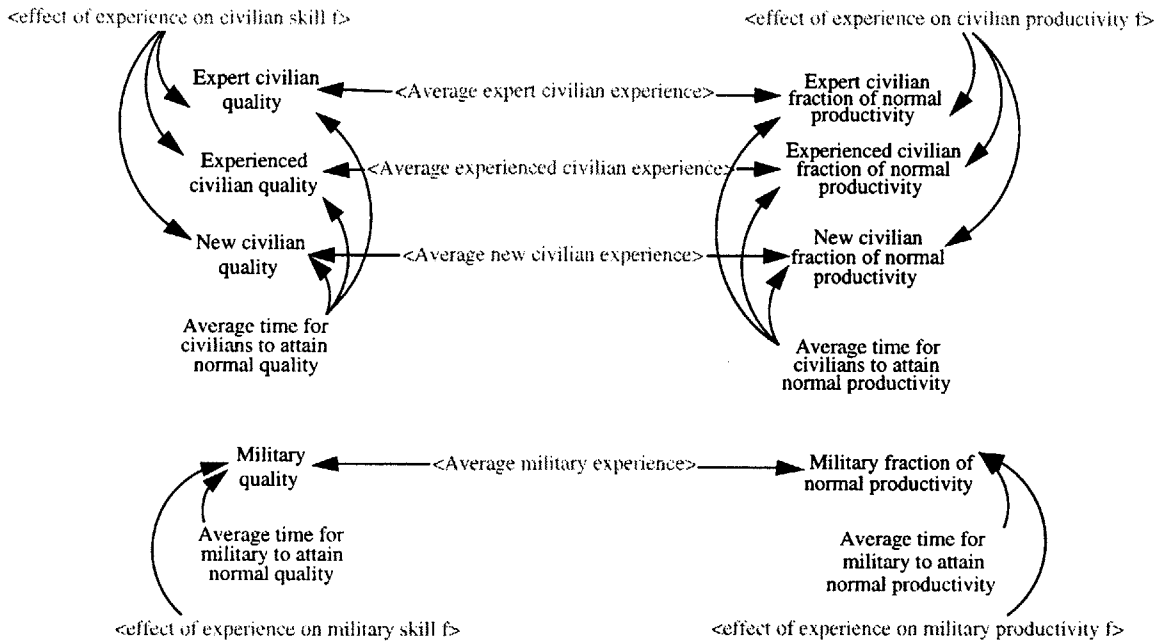


- (565) Effective newwork personnel = Newwork personnel\*(1+SPO Overtime )  
 Units: man  
 Uses: (412)SPO apparent development progress rate -  
 (570)SPO effective personnel -
- (566) Effective rework personnel = Rework personnel\*(1+SPO Overtime)  
 Units: man  
 Uses: (414)SPO apparent rework progress rate -  
 (570)SPO effective personnel -
- (567) Indicated fraction of remaining personnel engaged in rework =  

$$\frac{\text{SPO discovered rework}}{\text{SPO work to be done} + \text{SPO discovered rework}}$$
  
 Units: fraction  
 Uses: (569)Rework personnel -
- (568) Newwork personnel = SPO personnel - Rework personnel  
 Units: man  
 Uses: (565)Effective newwork personnel -
- (569) Rework personnel = Indicated fraction of remaining personnel engaged in rework \* SPO personnel  
 Units: man  
 Uses: (566)Effective rework personnel -  
 (568)Newwork personnel -
- (570) SPO effective personnel = Effective newwork personnel + Effective rework personnel  
 Units: man  
 Comment: Effective number of SPO personnel if overtime hours were worked by additional individuals rather than the existing personnel.  
 Uses: (683)SPO Cumulative manhours effort -

(571) SPO personnel = Military+SPO civilians  
Units: man  
Comment: Total personnel available.  
Uses: (641)Desired SPO overtime personnel -  
(568)Newwork personnel -  
(569)Rework personnel -  
(649)SPO Indicated overtime -  
(630)SPO perceived time required -

### 8.5.2.21 Effect of Civilian and Military Experience on Quality and Productivity

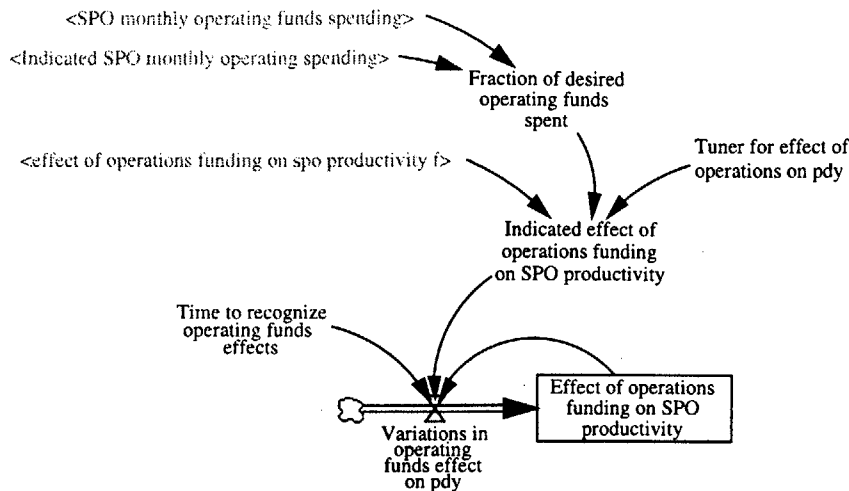


- (573) Average time for civilians to attain normal productivity = 0.1  
 Units: Month  
 Comment: The average time required for an individual new to the project to fully learn the project's tools and methods. That is, to attain the expected level of productivity. (Based upon Col. Rutley's estimate of 12-18 months to 70-80% of full potential which equates to an average of 60 months)  
 Uses: (581)Experienced civilian fraction of normal productivity -  
 (583)Expert civilian fraction of normal productivity -  
 (587)New civilian fraction of normal productivity -
- (574) Average time for civilians to attain normal quality = 0.1  
 Units: Month  
 Comment: The average time required for an individual new to the project to fully learn the project's tools and methods. That is, to attain the expected level of skill. (Based upon Col. Rutley's estimate of 12-18 months to 70-80% of full potential which equates to an average of 60 months)  
 Uses: (582)Experienced civilian quality -  
 (584)Expert civilian quality -  
 (588)New civilian quality -
- (575) Average time for military to attain normal productivity = 0.1  
 Units: Month  
 Comment: The average time required for an individual new to the project to fully learn the project's tools and methods. That is, to attain the expected level of productivity. (Based upon Col. Rutley's estimate of 12-18 months to 70-80% of full potential which equates to an average of 60 months)  
 Uses: (585)Military fraction of normal productivity -

- (576) Average time for military to attain normal quality = 0.1  
 Units: Month  
 Comment: The average time required for an individual new to the project to fully learn the project's tools and methods. That is, to attain the expected level of skill. (Based upon Col. Rutley's estimate of 12-18 months to 70-80% of full potential which equates to an average of 60 months)  
 Uses: (586)Military quality -
- (577) effect of experience on civilian productivity  $f([(0,0)-(1.5,1)],(0,0.3),(0.1,0.5),(0.2,0.625), (0.3,0.73),(0.4,0.8),(0.5,0.86),(0.6,0.9),(0.7,0.94),(0.8,0.965),(0.9,0.99),(1,1),(1.5,1))$   
 Units: dmnl  
 Comment: After James James Lyneis.  
 Uses: (581)Experienced civilian fraction of normal productivity -  
 (583)Expert civilian fraction of normal productivity -  
 (587)New civilian fraction of normal productivity -
- (578) effect of experience on civilian skill  $f([(0,0)-(1.5,1)],(0,0.3),(0.1,0.5),(0.2,0.625),(0.3,0.73), (0.4,0.8),(0.5,0.86),(0.6,0.9),(0.7,0.94),(0.8,0.965),(0.9,0.99),(1,1),(1.5,1))$   
 Units: dmnl  
 Comment: After James James Lyneis.  
 Uses: (582)Experienced civilian quality -  
 (584)Expert civilian quality -  
 (588)New civilian quality -
- (579) effect of experience on military productivity  $f([(0,0)-(1.5,1)],(0,0.3),(0.1,0.5),(0.2,0.625), (0.3,0.73),(0.4,0.8),(0.5,0.86),(0.6,0.9),(0.7,0.94),(0.8,0.965),(0.9,0.99),(1,1),(1.5,1))$   
 Units: dmnl  
 Comment: After James James Lyneis.  
 Uses: (585)Military fraction of normal productivity -
- (580) effect of experience on military skill  $f([(0,0)-(1.5,1)],(0,0.3),(0.1,0.5),(0.2,0.625), (0.3,0.73),(0.4,0.8),(0.5,0.86),(0.6,0.9),(0.7,0.94),(0.8,0.965),(0.9,0.99),(1,1),(1.5,1))$   
 Units: dmnl  
 Comment: After James James Lyneis.  
 Uses: (586)Military quality -
- (581) Experienced civilian fraction of normal productivity =  
 effect of experience on civilian productivity  $f(\text{Average experienced civilian experience} / \text{Average time for civilians to attain normal productivity})$   
 Units: fraction  
 Uses: (598)Average personnel productivity -
- (582) Experienced civilian quality =  
 effect of experience on civilian skill  $f(\text{Average experienced civilian experience} / \text{Average time for civilians to attain normal quality})$   
 Units: fraction  
 Comment: Fraction of work completed correctly by the average experienced worker.  
 Uses: (613)Average personnel quality -
- (583) Expert civilian fraction of normal productivity =  
 effect of experience on civilian productivity  $f(\text{Average expert civilian experience} / \text{Average time for civilians to attain normal productivity})$   
 Units: fraction  
 Uses: (598)Average personnel productivity -

- (584) Expert civilian quality =  $\frac{\text{effect of experience on civilian skill } f(\text{Average expert civilian experience})}{\text{Average time for civilians to attain normal quality}}$   
 Units: fraction  
 Comment: Fraction of work completed correctly by the average expert worker.  
 Uses: (613)Average personnel quality -
- (585) Military fraction of normal productivity =  $\frac{\text{effect of experience on military productivity } f(\text{Average military experience})}{\text{Average time for military to attain normal productivity}}$   
 Units: fraction  
 Uses: (598)Average personnel productivity -
- (586) Military quality =  $\frac{\text{effect of experience on military skill } f(\text{Average military experience})}{\text{Average time for military to attain normal quality}}$   
 Units: fraction  
 Uses: (613)Average personnel quality -
- (587) New civilian fraction of normal productivity =  $\frac{\text{effect of experience on civilian productivity } f(\text{Average new civilian experience})}{\text{Average time for civilians to attain normal productivity}}$   
 Units: fraction  
 Uses: (598)Average personnel productivity -
- (588) New civilian quality =  $\frac{\text{effect of experience on civilian skill } f(\text{Average new civilian experience})}{\text{Average time for civilians to attain normal quality}}$   
 Units: fraction  
 Comment: Fraction of work completed correctly by the average new worker.  
 Uses: (613)Average personnel quality -

### 8.5.2.22 SPO Operating Funds Effect on Productivity



(590) Effect of operations funding on SPO productivity =  
 $\text{INTEG}(\text{Variations in operating funds effect on pdy}, 1)$

Units: dmnl

Uses: (603)Effective SPO productivity -  
 (373)SPO manager's willingness to spend operating reserve on operations -  
 (596)Variations in operating funds effect on pdy -

(591) effect of operations funding on spo productivity  $f([(0,0)-(1.1,1)],(0,0),(0.45,0.625),(0.6,0.8),$   
 $(0.8,0.95),(1,1),(1.1,1))$

Units: dmnl

Comment: Estimate by author.

Uses: (593)Indicated effect of operations funding on SPO productivity -

(592) Fraction of desired operating funds spent =  
 $\text{IF THEN ELSE}(\text{Indicated SPO monthly operating spending} \leq 0, 1,$   
 $\text{SPO monthly operating funds spending} / \text{Indicated SPO monthly operating spending})$

Units: fraction

Comment: The ratio of actual spending to desired spending of operating funds

Uses: (593)Indicated effect of operations funding on SPO productivity -

(593) Indicated effect of operations funding on SPO productivity =  
 $\text{effect of operations funding on spo productivity } f(\text{Fraction of desired operating funds spent})$   
 $* \text{Tuner for effect of operations on pdy} + (1 - \text{Tuner for effect of operations on pdy})$

Units: dmnl

Comment: Indicated reduction in productivity of the SPO as a result of insufficient spending on operations

Uses: (596)Variations in operating funds effect on pdy -

(594) Time to recognize operating funds effects = 36

Units: Month

Comment: The average time for the effects of insufficient operating funds to be felt

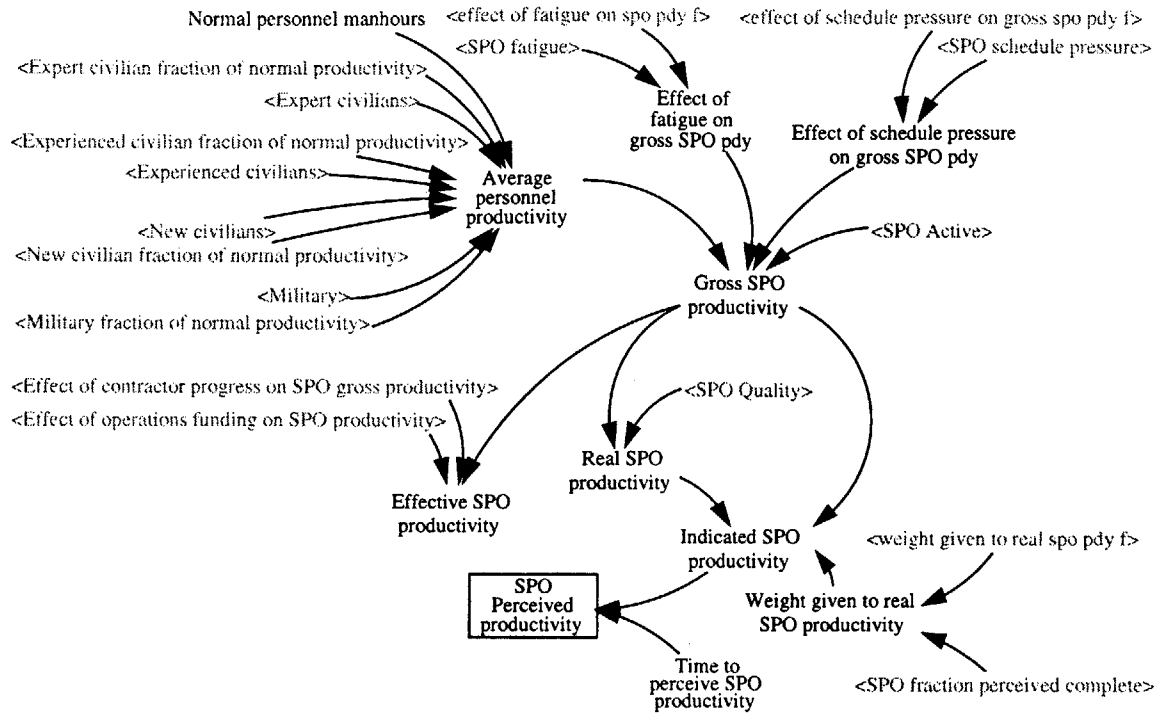
Uses: (596)Variations in operating funds effect on pdy -



- (595) Tuner for effect of operations on pdy = 1  
 Units: dmnl  
 Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the full strength of the function, while a value of 0 results in a complete negation of the function. e.g.  $\text{Effect} = \text{Function}(\text{Variable}) * \text{Tuner} + (1 - \text{Tuner})$   
 Uses: (593) Indicated effect of operations funding on SPO productivity -
- (596) Variations in operating funds effect on pdy =  

$$\frac{(\text{Indicated effect of operations funding on SPO productivity} - \text{Effect of operations funding on SPO productivity})}{\text{Time to recognize operating funds effects}}$$
  
 Units: 1/Month  
 Uses: (590) Effect of operations funding on SPO productivity -

### 8.5.2.23 SPO Productivity



(598) Average personnel productivity =  

$$\frac{((\text{Military} * \text{Military fraction of normal productivity} + \text{Expert civilians} * \text{Expert civilian fraction of normal productivity} + \text{Experienced civilians} * \text{Experienced civilian fraction of normal productivity} + \text{New civilians} * \text{New civilian fraction of normal productivity}) * \text{Normal personnel manhours})}{(\text{Military} + \text{Expert civilians} + \text{Experienced civilians} + \text{New civilians})}$$

Units: manhours/(Month\*man)

Uses: (604)Gross SPO productivity -

(599) Effect of fatigue on gross SPO pdy = effect of fatigue on spo pdy f(SPO fatigue)

Units: fraction

Comment: Represents the slow down in worker productivity when fatigued they just can't work as fast.

Uses: (604)Gross SPO productivity -

(600) effect of fatigue on spo pdy f  $(([-0.5,0)-(1,2]),(-0.488402,0.921348),(-0.4,0.9545),(-0.2,1.04869),(-0.1,1.01),(0,1),(0.1,0.9545),(0.2,0.8698),(0.3,0.774),(0.512887,0.47191))$

Units: fraction

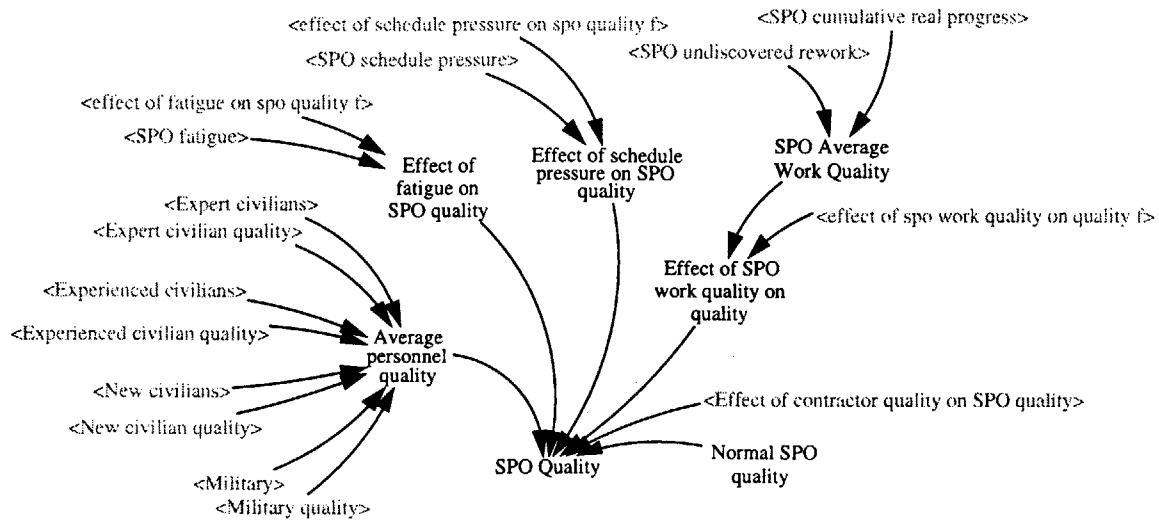
Comment: The fraction of normal productivity possible as a function of fatigue. Numbers for positive part of curve based on Jack Nevison's data. Negative portion is estimated from experience.

Uses: (599)Effect of fatigue on gross SPO pdy -



- (610) weight given to real spo pdy f  $f([(0,0)-(1,1)],(0,0),(0.2,0.1),(0.4,0.25),(0.6,0.5),(0.8,0.9),(1,1))$   
 Units: dmnl  
 Comment: Weight given to real productivity as a function of fraction perceived completed taken from Pugh & Richardson.  
 Uses: (611)Weight given to real SPO productivity -
- (611) Weight given to real SPO productivity =  
 weight given to real spo pdy f(SPO fraction perceived complete)  
 Units: dmnl  
 Uses: (605)Indicated SPO productivity -

### 8.5.2.24 SPO Quality



(613) Average personnel quality = (Expert civilians\*Expert civilian quality +Experienced civilians\*Experienced civilian quality +New civilians\*New civilian quality+Military\*Military quality) / (Expert civilians+Experienced civilians+New civilians+Military)

Units: fraction

Comment: Normal fraction of work completed correctly

Uses: (622)SPO Quality -

(614) Effect of fatigue on SPO quality = effect of fatigue on spo quality f(SPO fatigue)

Units: fraction

Uses: (622)SPO Quality -

(615) effect of fatigue on spo quality f [((-0.4,0)-(1,2)],(-0.21,1.01),(0,1),(0.219072,0.970787), (0.469072,0.894382),(1,0.5))

Units: fraction

Uses: (614)Effect of fatigue on SPO quality -

(616) Effect of schedule pressure on SPO quality = effect of schedule pressure on spo quality f(SPO schedule pressure)

Units: dmnl

Uses: (622)SPO Quality -

(617) effect of schedule pressure on spo quality f([(0,0.6)-(0.7,1)],(0,1),(0.1,0.975),(0.2,0.925), (0.3,0.85),(0.4,0.75),(0.5,0.675),(0.6,0.625),(0.7,0.6))

Units: dmnl

Comment: Taken from Jim James Lyneis' project model presented in 15.976 fall 1997

Uses: (616)Effect of schedule pressure on SPO quality -

(618) Effect of SPO work quality on quality = effect of spo work quality on quality f(SPO Average Work Quality)

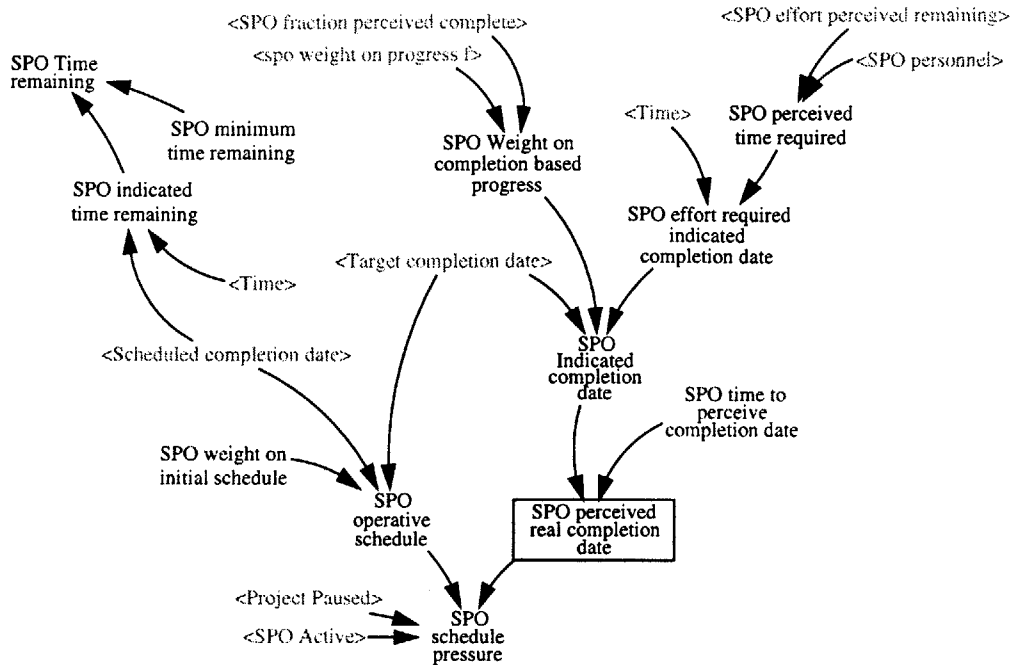
Units: dmnl

Uses: (622)SPO Quality -

- (619) effect of spo work quality on quality  $f([(0,0)-(1,1)],(0,0.1),(0.1,0.25),(0.2,0.35),(0.3,0.45),$   
 $(0.4,0.55),(0.5,0.65),(0.6,0.74),(0.7,0.83),(0.8,0.9),(0.9,0.95),(1,1))$   
 Units: dmn1  
 Comment: Taken from James James Lyneis' project model from 15.962 fall 1997  
 Uses: (618)Effect of SPO work quality on quality -
- (620) Normal SPO quality = 1  
 Units: fraction  
 Comment: Normal fraction of work done correctly by a very experienced individual.  
 Uses: (622)SPO Quality -
- (621) SPO Average Work Quality =  

$$\text{IF THEN ELSE}(\text{SPO cumulative real progress} = 0, 1, \text{SPO cumulative real progress} / \text{MAX}(0.0001, \text{SPO undiscovered rework} + \text{SPO cumulative real progress}))$$
  
 Units: dmn1  
 Uses: (281)Effect of SPO quality on contractor quality -  
 (618)Effect of SPO work quality on quality -
- (622) SPO Quality = Average personnel quality\*Effect of fatigue on SPO quality  
 \*Effect of schedule pressure on SPO quality\*Effect of SPO work quality on quality  
 \*Effect of contractor quality on SPO quality \*Normal SPO quality  
 Units: fraction  
 Comment: Fraction of work completed with acceptable quality.  
 Uses: (607)Real SPO productivity -  
 (423)SPO real progress rate -  
 (424)SPO rework generation rate -

### 8.5.2.25 SPO Schedule



(624) SPO effort required indicated completion date = SPO perceived time required+Time

Units: Month

Uses: (625)SPO Indicated completion date -

(625) SPO Indicated completion date =

SPO effort required indicated completion date\*SPO Weight on completion based progress  
+Target completion date\*(1-SPO Weight on completion based progress)

Units: Month

Uses: (629)SPO perceived real completion date -

(626) SPO indicated time remaining = Scheduled completion date-Time

Units: Month

Uses: (632)SPO Time remaining -

(627) SPO minimum time remaining = 1

Units: Month

Comment: a minimum time remaining of 1 week = 0.25

Uses: (632)SPO Time remaining -

(628) SPO operative schedule = Target completion date\*SPO weight on initial schedule

+(1-SPO weight on initial schedule)\*Scheduled completion date

Units: Month

Uses: (631)SPO schedule pressure -

- (629) SPO perceived real completion date =  $\text{SMOOTH}(\text{SPO Indicated completion date}, \text{SPO time to perceive completion date}, \text{Initial completion date})$   
 Units: Month  
 Uses: (631)SPO schedule pressure -  
 (686)SPO schedule slip -
- (630) SPO perceived time required =  $\text{SPO effort perceived remaining} / \text{SPO personnel}$   
 Units: Month  
 Uses: (624)SPO effort required indicated completion date -
- (631) SPO schedule pressure =  $(\text{MAX}(0, (\text{SPO perceived real completion date} - \text{SPO operative schedule}) / \text{SPO operative schedule})) * \text{SPO Active} * (1 - \text{Project Paused})$   
 Units: dmn1  
 Uses: (601)Effect of schedule pressure on gross SPO pdy -  
 (616)Effect of schedule pressure on SPO quality -  
 (432)Effect of schedule pressure on SPO rework detection -
- (632) SPO Time remaining =  $\text{MAX}(\text{SPO indicated time remaining}, \text{SPO minimum time remaining})$   
 Units: Month  
 Uses: (487)SPO personnel indicated by effort -
- (633) SPO time to perceive completion date = 1  
 Units: Month  
 Uses: (629)SPO perceived real completion date -
- (634) SPO Weight on completion based progress =  
 $\text{spo weight on progress } f(\text{SPO fraction perceived complete})$   
 Units: dmn1  
 Uses: (625)SPO Indicated completion date -
- (635) SPO weight on initial schedule = 0.25  
 Units: dmn1  
 Uses: (628)SPO operative schedule -
- (636) spo weight on progress  $f([(0,0)-(1,1)],(0,0),(0.1,0.1),(0.2,0.3),(0.3,0.5),(0.4,0.7),(0.5,0.85), (0.6,0.95),(0.7,1),(0.8,1),(0.9,1),(1,1))$   
 Units: dmn1  
 Comment: Taken from James James Lyneis' project model for 15.962 fall 1997  
 Uses: (634)SPO Weight on completion based progress -





- (643) Indicated fraction of max SPO overtime =  

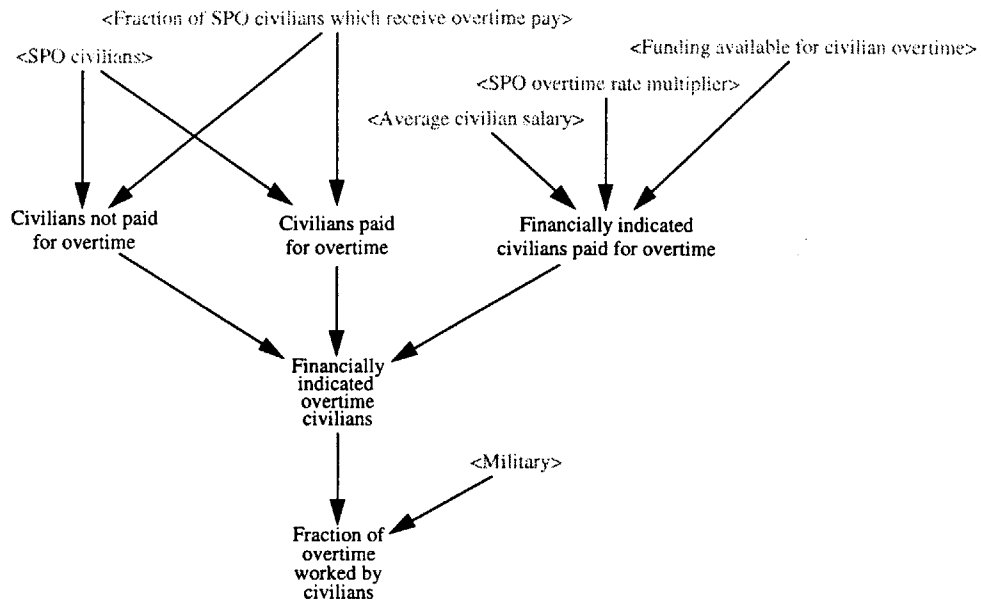
$$\text{IF THEN ELSE}(\text{SPO Maximum allowed overtime} = 0, 0, \text{SPO Indicated overtime} / \text{SPO Maximum allowed overtime})$$
Units: fraction  
Comment: Maximum allowed OT is the ceiling above which OT is not allowed to pass.  
Uses: (648)SPO fraction of max overtime -
- (644) Indicated overtime civilians =  

$$\text{MIN}(\text{Financially indicated overtime civilians}, \text{Desired overtime civilians})$$
Units: man  
Uses: (649)SPO Indicated overtime -
- (645) Indicated overtime military =  

$$\text{Desired SPO overtime personnel} * \text{Current military fraction of personnel}$$
Units: man  
Uses: (640)Desired overtime civilians -  
(649)SPO Indicated overtime -
- (646) SPO fatigue = INTEG(SPO fatiguing, 0)  
Units: fraction  
Comment: The fraction of the normal work period for which normal rest has been denied.  
Uses: (599)Effect of fatigue on gross SPO pdy -  
(490)Effect of fatigue on new civilian attrition -  
(614)Effect of fatigue on SPO quality -  
(647)SPO fatiguing -
- (647) SPO fatiguing = (SPO Overtime - SPO fatigue) / SPO time to get fatigued  
Units: fraction / Month  
Uses: (646)SPO fatigue -
- (648) SPO fraction of max overtime = IF THEN ELSE(Indicated fraction of max SPO overtime < 2,  
fraction of spo overtime multiplier f(Indicated fraction of max SPO overtime),  
fraction of spo overtime multiplier f(2))  
Units: fraction  
Uses: (651)SPO Overtime -
- (649) SPO Indicated overtime = IF THEN ELSE(SPO personnel = 0, 0,  
(Indicated overtime military + Indicated overtime civilians) / SPO personnel)  
Units: fraction  
Uses: (643)Indicated fraction of max SPO overtime -
- (650) SPO Maximum allowed overtime = 0.5  
Units: fraction  
Comment: Maximum fraction of regular work week which can be worked as overtime (hr/hr or man/man).  
Uses: (643)Indicated fraction of max SPO overtime -  
(651)SPO Overtime -

- (651)  $\text{SPO Overtime} = \text{SPO Maximum allowed overtime} * \text{SPO fraction of max overtime}$   
 Units: fraction  
 Comment: Fraction of the normal work week which is worked in addition to the normal work week.  
 Uses: (638)Average SPO overtime -  
 (565)Effective newwork personnel -  
 (566)Effective rework personnel -  
 (647)SPO fatiguing -  
 (345)SPO overtime cost per month -
- (652)  $\text{SPO time to get fatigued} = 3$   
 Units: months  
 Comment: Estimate by author, based upon experience and anecdotal evidence.  
 Uses: (647)SPO fatiguing -
- (653)  $\text{Time to average SPO overtime} = 0.5$   
 Units: Month  
 Uses: (638)Average SPO overtime -
- (654)  $\text{Time to recognize desired overtime personnel} = 1$   
 Units: Month  
 Uses: (641)Desired SPO overtime personnel -

### 8.5.2.27 SPO Civilian Overtime Fraction



(656) Civilians not paid for overtime =  $SPO\ civilians * (1 - \text{Fraction of SPO civilians which receive overtime pay})$

Units: man

Uses: (659) Financially indicated overtime civilians -

(657) Civilians paid for overtime =  $SPO\ civilians * \text{Fraction of SPO civilians which receive overtime pay}$

Units: man

Uses: (659) Financially indicated overtime civilians -

(658) Financially indicated civilians paid for overtime =  $\frac{\text{Funding available for civilian overtime}}{(\text{Average civilian salary} * \text{SPO overtime rate multiplier})}$

Units: man

Uses: (659) Financially indicated overtime civilians -

(659) Financially indicated overtime civilians =  $\text{Civilians not paid for overtime} + \text{MIN}(\text{Civilians paid for overtime}, \text{Financially indicated civilians paid for overtime})$

Units: man

Uses: (660) Fraction of overtime worked by civilians -

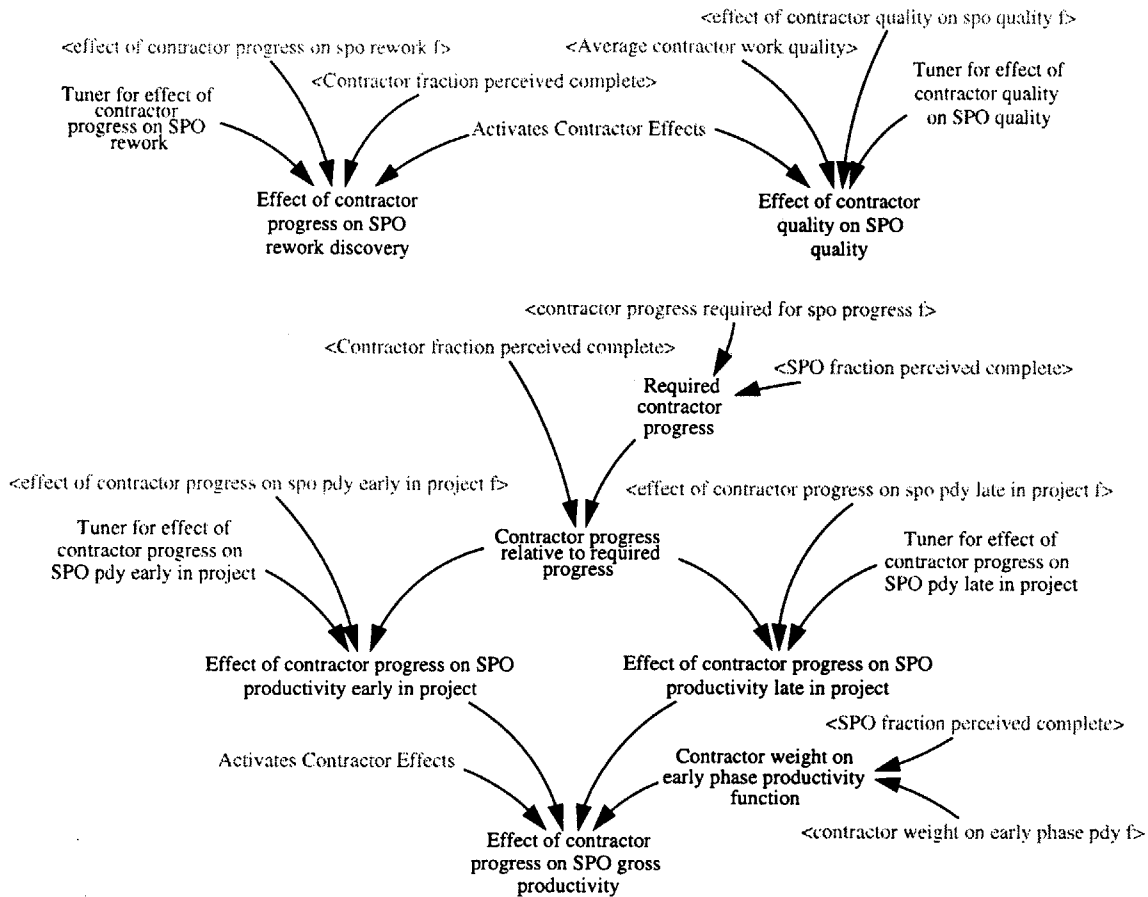
(644) Indicated overtime civilians -

(660) Fraction of overtime worked by civilians =  $\frac{\text{Financially indicated overtime civilians}}{(\text{Military} + \text{Financially indicated overtime civilians})}$

Units: fraction

Uses: (345) SPO overtime cost per month -

### 8.5.2.28 Contractor Effects on SPO Quality, Productivity, and Rework Discovery Time



(662) Contractor progress relative to required progress =  

$$\text{MIN}(1, \text{IF THEN ELSE}(\text{Required contractor progress} = 0$$
  

$$:\text{OR}:\text{Contractor fraction perceived complete} = 0, 1,$$
  

$$\text{Contractor fraction perceived complete}/\text{Required contractor progress}))$$

Units: fraction

Uses: (669)Effect of contractor progress on SPO productivity early in project -  
 (670)Effect of contractor progress on SPO productivity late in project -

(663) contractor progress required for spo progress  $f([(0,0)-(1,1)],(0,0),(1,1))$

Units: fraction

Comment: Functional relationship for the required contractor progress for a given level of spo progress.

Uses: (675)Required contractor progress -

(664) contractor weight on early phase pdy  $f([(0,0)-(1,1)],(0,1),(1,0))$

Units: dmnl

Uses: (665)Contractor weight on early phase productivity function -

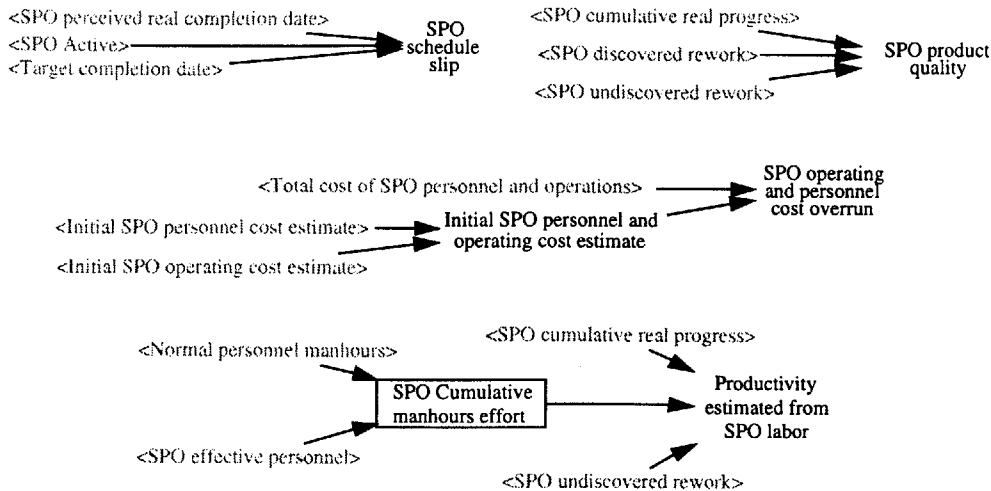
- (665) Contractor weight on early phase productivity function =  
 contractor weight on early phase pdy f(SPO fraction perceived complete)  
 Units: dmn1  
 Comment: Relative importance of the contractors work as the SPO progresses through the project.  
 Uses: (666)Effect of contractor progress on SPO gross productivity -
- (666) Effect of contractor progress on SPO gross productivity =  
 (Effect of contractor progress on SPO productivity early in project  
 \*Contractor weight on early phase productivity function  
 +Effect of contractor progress on SPO productivity late in project  
 \*(1-Contractor weight on early phase productivity function))\*Activates Contractor Effects  
 +(1-Activates Contractor Effects)  
 Units: dmn1  
 Comment: Reduction in contractor gross productivity as determined by the contractor's current progress, resulting from the SPO's real progress relative to its scheduled progress  
 Uses: (603)Effective SPO productivity -
- (667) effect of contractor progress on spo pdy early in project  $f([(0,0)-(1,1)],(0,0),(0.1,0.3),(0.2,0.55),(0.3,0.7),(0.4,0.8),(0.5,0.875),(0.6,0.92),(0.7,0.95),(0.8,0.975),(0.9,0.99),(1,1))$   
 Units: dmn1  
 Comment: Relationship determining the reduction in spor gross productivity as determined by the spo's current progress, resulting from the contractor's real progress relative to its scheduled progress early in the project. Estimated.  
 Uses: (669)Effect of contractor progress on SPO productivity early in project -
- (668) effect of contractor progress on spo pdy late in project  $f([(0,0)-(1,1)],(0,0),(0.5,0.05),(0.75,0.1),(0.8,0.125),(0.85,0.175),(0.9,0.25),(0.95,0.5),(0.98,0.75),(1,1))$   
 Units: dmn1  
 Comment: Relationship determining the reduction in spor gross productivity as determined by the spo's current progress, resulting from the contractor's real progress relative to its scheduled progress late in the project. Estimated.  
 Uses: (670)Effect of contractor progress on SPO productivity late in project -
- (669) Effect of contractor progress on SPO productivity early in project =  
 effect of contractor progress on spo pdy early in project f  
 (Contractor progress relative to required progress)  
 \*Tuner for effect of contractor progress on SPO pdy early in project  
 +(1-Tuner for effect of contractor progress on SPO pdy early in project)  
 Units: dmn1  
 Uses: (666)Effect of contractor progress on SPO gross productivity -
- (670) Effect of contractor progress on SPO productivity late in project =  
 effect of contractor progress on spo pdy late in project f  
 (Contractor progress relative to required progress)  
 \*Tuner for effect of contractor progress on SPO pdy late in project  
 +(1-Tuner for effect of contractor progress on SPO pdy late in project)  
 Units: dmn1  
 Uses: (666)Effect of contractor progress on SPO gross productivity -

- (671) Effect of contractor progress on SPO rework discovery =  
 (effect of contractor progress on spo rework  $f(\text{Contractor fraction perceived complete})$   
 $\times \text{Tuner for effect of contractor progress on SPO rework}$   
 $+ (1 - \text{Tuner for effect of contractor progress on SPO rework})$   
 $\times \text{Activates Contractor Effects} + (1 - \text{Activates Contractor Effects})$ )
- Units: dmnl  
 Comment: The increase in rework discovery caused by contractor progress  
 Uses: (437)SPO time to detect rework -
- (672) effect of contractor progress on spo rework  $f([(0,0)-(1,1)],(0,1),(0.1,1),(0.2,0.96),(0.3,0.88),$   
 $(0.4,0.75),(0.5,0.55),(0.6,0.4),(0.7,0.3),(0.8,0.26),(0.9,0.25),(1,0.25))$
- Units: dmnl  
 Uses: (671)Effect of contractor progress on SPO rework discovery -
- (673) Effect of contractor quality on SPO quality = (effect of contractor quality on spo quality  $f$   
 (Average contractor work quality) $\times \text{Tuner for effect of contractor quality on SPO quality}$   
 $+ (1 - \text{Tuner for effect of contractor quality on SPO quality})$ ) $\times \text{Activates Contractor Effects}$   
 $+ (1 - \text{Activates Contractor Effects})$ )
- Units: dmnl  
 Uses: (622)SPO Quality -
- (674) effect of contractor quality on spo quality  $f([(0,0)-(1,1)],(0,0.1),(0.1,0.25),(0.2,0.35),(0.3,0.45),$   
 $(0.4,0.55),(0.5,0.65),(0.6,0.74),(0.7,0.83),(0.8,0.9),(0.9,0.95),(1,1))$
- Units: dmnl  
 Comment: Functional relationship between the quality of work done by the contractor and the  
 quality of work done by the spo.  
 Uses: (673)Effect of contractor quality on SPO quality -
- (675) Required contractor progress =  
 contractor progress required for spo progress  $f(\text{SPO fraction perceived complete})$
- Units: fraction  
 Comment: Determines the progress which the spo must have achieved to all the contractor to  
 continue at its current rate of productivity  
 Uses: (662)Contractor progress relative to required progress -
- (676) Tuner for effect of contractor progress on SPO pdy early in project = 1
- Units: dmnl  
 Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the  
 full strength of the function, while a value of 0 results in a complete negation of the  
 function. e.g. Effect =  $\text{Function}(\text{Variable}) \times \text{Tuner} + (1 - \text{Tuner})$   
 Uses: (669)Effect of contractor progress on SPO productivity early in project -
- (677) Tuner for effect of contractor progress on SPO pdy late in project = 1
- Units: dmnl  
 Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the  
 full strength of the function, while a value of 0 results in a complete negation of the  
 function. e.g. Effect =  $\text{Function}(\text{Variable}) \times \text{Tuner} + (1 - \text{Tuner})$   
 Uses: (670)Effect of contractor progress on SPO productivity late in project -

- (678) Tuner for effect of contractor progress on SPO rework = 1  
Units: dmnl  
Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the full strength of the function, while a value of 0 results in a complete negation of the function. e.g.  $\text{Effect} = \text{Function}(\text{Variable}) * \text{Tuner} + (1 - \text{Tuner})$   
Uses: (671)Effect of contractor progress on SPO rework discovery -
- (679) Tuner for effect of contractor quality on SPO quality = 1  
Units: dmnl  
Comment: Tuner sets the relative level of influence of the function. A value of 1 results in the full strength of the function, while a value of 0 results in a complete negation of the function. e.g.  $\text{Effect} = \text{Function}(\text{Variable}) * \text{Tuner} + (1 - \text{Tuner})$   
Uses: (673)Effect of contractor quality on SPO quality -



### 8.5.2.29 SPO Slips



(681) Initial SPO personnel and operating cost estimate =  

$$\text{Initial SPO operating cost estimate} + \text{Initial SPO personnel cost estimate}$$

Units: \$

Uses: (684)SPO operating and personnel cost overrun -

(682) Productivity estimated from SPO labor = IF THEN ELSE(SPO Cumulative manhours effort > 0,  

$$(\text{SPO undiscovered rework} + \text{SPO cumulative real progress}) / \text{SPO Cumulative manhours effort}, 1)$$

Units: fraction

(683) SPO Cumulative manhours effort = INTEG (Normal personnel manhours \* SPO effective personnel, 0)

Units: manhours

Uses: (682)Productivity estimated from SPO labor -

(684) SPO operating and personnel cost overrun =  

$$\frac{(\text{Total cost of SPO personnel and operations} - \text{Initial SPO personnel and operating cost estimate})}{\text{Initial SPO personnel and operating cost estimate}}$$

Units: fraction

Comment: Fraction of initial cost estimate by which operating and personnel costs exceed the original estimate.

(685) SPO product quality = SPO cumulative real progress / MAX(0.0001,  

$$\text{SPO undiscovered rework} + \text{SPO discovered rework} + \text{SPO cumulative real progress})$$

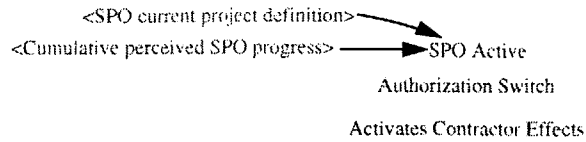
Units: dmnl

(686) SPO schedule slip = (( SPO perceived real completion date - Target completion date) / Target completion date) \* SPO Active

Units: fraction

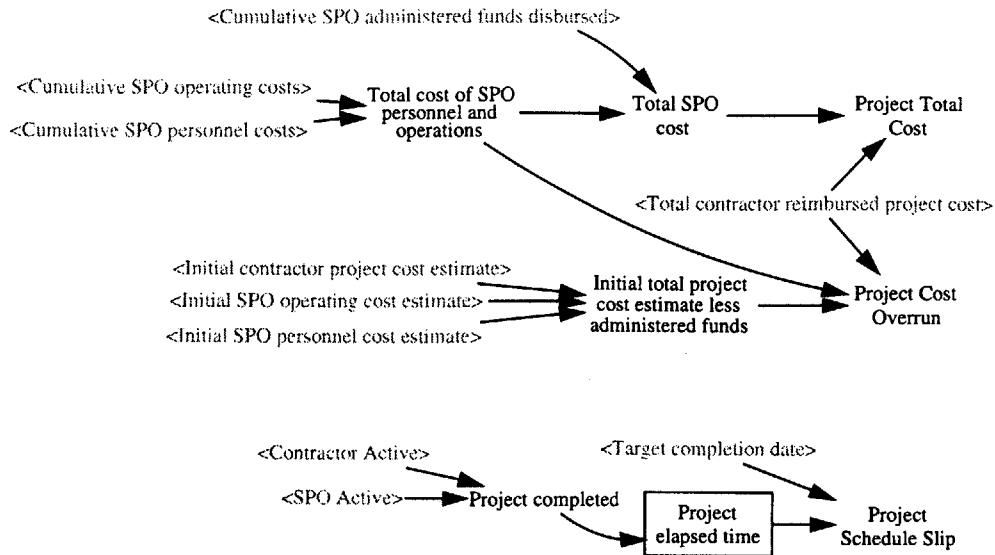
Comment: The fraction of the initial completion date by which the schedule has slipped.

### 8.5.2.30 Simulation Control Switches for SPO Section



- (688) Activates Contractor Effects = 1  
 Units: dmn1  
 Comment: Setting "Activates contractor effects" switch to 1 activates contractor effects on the SPO  
 Uses: (666)Effect of contractor progress on SPO gross productivity -  
 (671)Effect of contractor progress on SPO rework discovery -  
 (673)Effect of contractor quality on SPO quality -
- (689) Authorization Switch = 1  
 Units: dmn1  
 Comment: Setting "Authorization switch" to 1 causes the system to ignore the civilian & military personnel levels indicated by the initially indicated work effort.  
 Uses: (388)Civilian personnel shortfall -  
 (484)Indicated civilians -  
 (440)Indicated military -  
 (332)Initial SPO operating cost estimate -  
 (333)Initial SPO personnel cost estimate -  
 (391)Military personnel shortfall -
- (690) SPO Active =  
 IF THEN ELSE(Cumulative perceived SPO progress>0.995\*SPO current project definition,0,1)  
 Units: dmn1  
 Comment: Logical variable to signal project termination in the event of perceived completion of work. A value of 1 indicates the SPO portion of the project is complete.  
 Uses: (339)Civilian costs per month -  
 (604)Gross SPO productivity -  
 (355)Indicated SPO monthly operating spending -  
 (343)Military costs per month -  
 (693)Project completed -  
 (419)SPO discovering rework -  
 (486)SPO effort perceived remaining -  
 (631)SPO schedule pressure -  
 (686)SPO schedule slip -

### 8.5.2.31 Aggregate Program Performance Metrics



(692) Initial total project cost estimate less administered funds = Initial contractor project cost estimate + Initial SPO operating cost estimate + Initial SPO personnel cost estimate

Units: \$

Uses: (694)Project Cost Overrun -

(693) Project completed = IF THEN ELSE(SPO Active = 1:OR:Contractor Active = 1,0,1)

Units: dmnl

Comment: If either the spo or the contractor is still active then the project has not been completed.

Uses: (694)Project Cost Overrun -

(695)Project elapsed time -

(696)Project Schedule Slip -

(002)FINAL TIME -

(369)Indicated SPO management reserve cash outflow -

(381)Indicated SPO management reserve cash outflow for personnel -

(694) Project Cost Overrun = DELAY INFORMATION (((Total contractor reimbursed project cost + Total cost of SPO personnel and operations) / Initial total project cost estimate less administered funds - 1), IF THEN ELSE(Project completed = 1, 1e+006 , TIME STEP), -1)

Units: fraction

Comment: The difference between the total cost of the project to the Government and the initial estimate of project cost as a fraction of the initial estimate of project cost. As a simplification for this model, SPO administered funds and SPO overtime are assumed to have been exactly on budget.

(695) Project elapsed time = INTEG ((1-Project completed), 0)

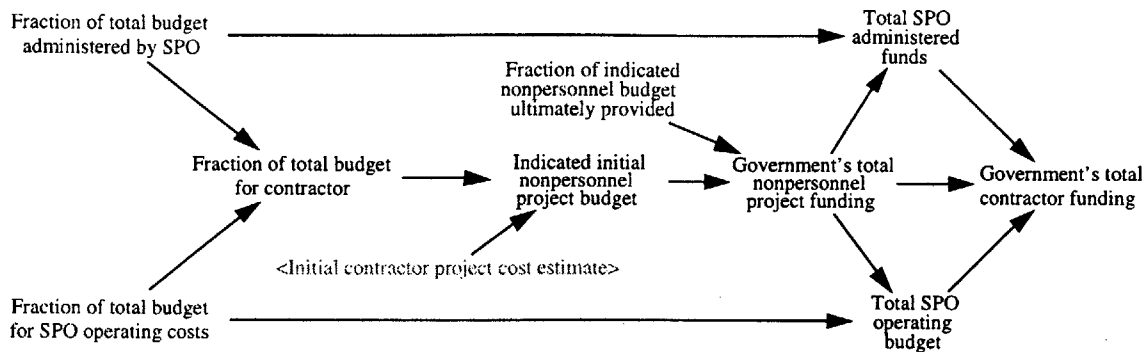
Units: Month

Uses: (696)Project Schedule Slip -

- (696) Project Schedule Slip =  
 DELAY INFORMATION (IF THEN ELSE(Project elapsed time > = Target completion date,  
 (Project elapsed time/Target completion date-1),0),IF THEN ELSE(Project completed = 1,  
 1e+006,TIME STEP),0)  
 Units: fraction
- (697) Project Total Cost = Total contractor reimbursed project cost+Total SPO cost  
 Units: \$
- (698) Total cost of SPO personnel and operations =  
 Cumulative SPO personnel costs+Cumulative SPO operating costs  
 Units: \$  
 Comment: The total cost of operating the SPO  
 Uses: (694)Project Cost Overrun -  
 (684)SPO operating and personnel cost overrun -  
 (699)Total SPO cost -
- (699) Total SPO cost =  
 Total cost of SPO personnel and operations+Cumulative SPO administered funds disbursed  
 Units: \$  
 Comment: Total non-contractor cost of project  
 Uses: (697)Project Total Cost -

### 8.5.3 Government Model Documentation

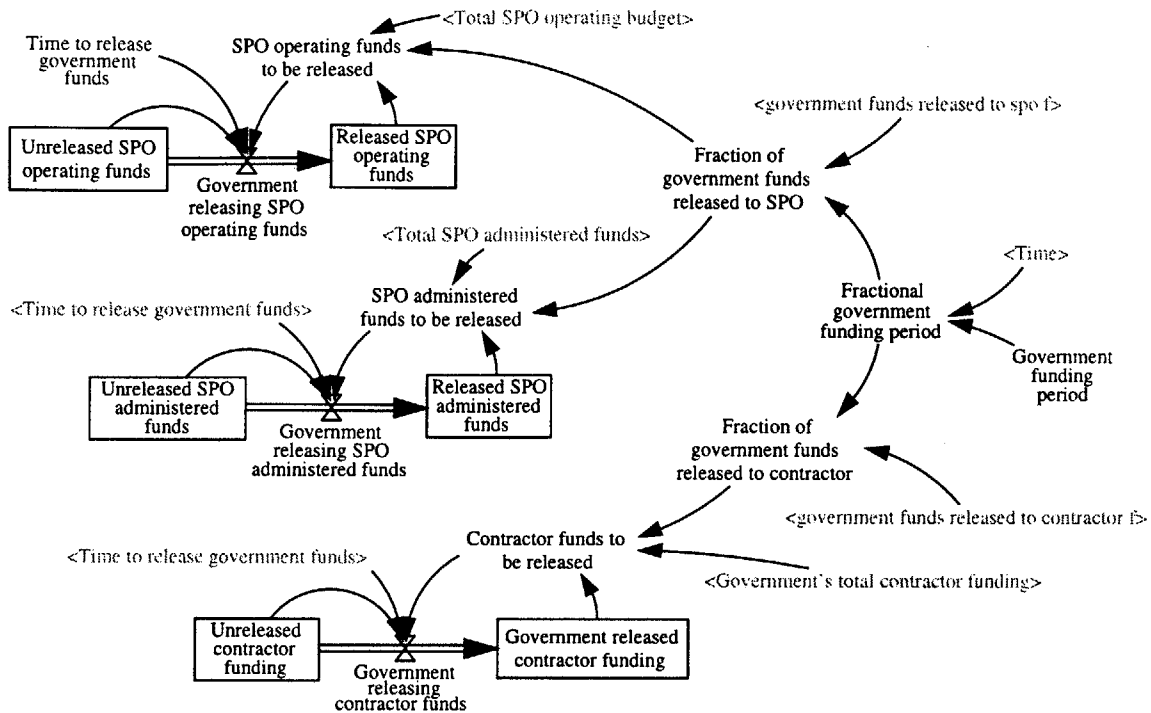
#### 8.5.3.1 Government Budget Estimates



- (702) Fraction of indicated nonpersonnel budget ultimately provided = 1  
 Units: fraction  
 Comment: Adjustment to indicated budget, as suggested by contractor's initial estimate of project cost. (For example, a 10% increase or decrease) This will determine the total funding provided over the life of the project.  
 Uses: (707)Government's total non-personnel project funding -
- (703) Fraction of total budget administered by SPO = 0.0675  
 Units: fraction  
 Comment: Source: Kathey Watern, ASC  
 Uses: (704)Fraction of total budget for contractor -  
 (709)Total SPO administered funds -
- (704) Fraction of total budget for contractor = 1-(Fraction of total budget administered by SPO  
 +Fraction of total budget for SPO operating costs)  
 Units: fraction  
 Uses: (708)Indicated initial nonpersonnel project budget -
- (705) Fraction of total budget for SPO operating costs = 0.0085  
 Units: fraction  
 Comment: 0.85% of total budget -- Source: Kathey Watern, ASC  
 Uses: (704)Fraction of total budget for contractor -  
 (710)Total SPO operating budget -
- (706) Government's total contractor funding = Government's total nonpersonnel project funding  
 -(Total SPO operating budget+Total SPO administered funds)  
 Units: \$  
 Comment: Government's total contractor funding is defined as the total dollars made available to the contractor by the government to support the project.  
 Uses: (729)Unreleased contractor funding -  
 (712)Contractor funds to be released -

- (707) Government's total nonpersonnel project funding = Indicated initial nonpersonnel project budget  
\*Fraction of indicated nonpersonnel budget ultimately provided  
Units: \$  
Comment: The total funding provided by the government for the project. This would include any additions to an initial budget.  
Uses: (706)Government's total contractor funding -  
(709)Total SPO administered funds -  
(710)Total SPO operating budget -
- (708) Indicated initial nonpersonnel project budget = Initial contractor project cost estimate  
/Fraction of total budget for contractor  
Units: \$  
Uses: (707)Government's total nonpersonnel project funding -
- (709) Total SPO administered funds = Government's total nonpersonnel project funding  
\*Fraction of total budget administered by SPO  
Units: \$  
Comment: The SPO administered funds budget is defined as funds sent to other government agencies that support the project. An example is flight test costs, where funding is sent to another agency (flight test centers for example) outside of the SPO.  
Uses: (730)Unreleased SPO administered funds -  
(398)Contractor indicated cumulative disbursement of administered funds -  
(706)Government's total contractor funding -  
(726)SPO administered funds to be released -
- (710) Total SPO operating budget = Government's total nonpersonnel project funding  
\*Fraction of total budget for SPO operating costs  
Units: \$  
Comment: The SPO operating budget is defined to include: administrative and assistance cost (support contractors), travel, training, supplies, and some other miscellaneous expenses. For this model civilian and military pay are accounted for separately.  
Uses: (731)Unreleased SPO operating funds -  
(706)Government's total contractor funding -  
(727)SPO operating funds to be released -  
(330)Theoretical operating cost multiplier -

### 8.5.3.2 Government Funding Profiles



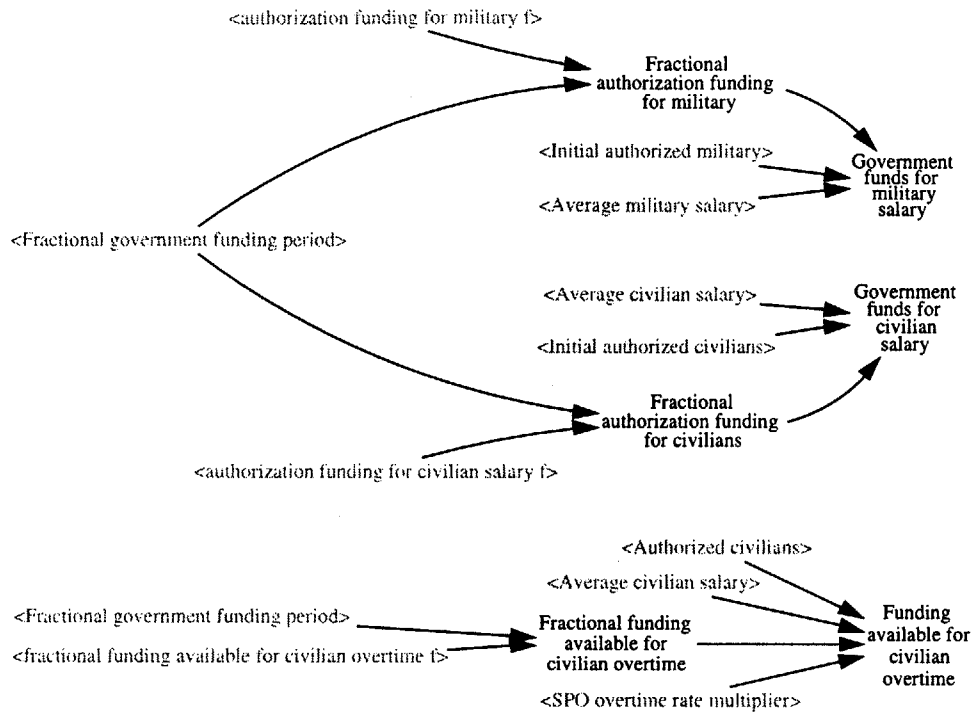
- (712) Contractor funds to be released =  $\text{MAX}(\text{Fraction of government funds released to contractor} * \text{Government's total contractor funding} - \text{Government released contractor funding}, 0)$   
 Units: \$  
 Uses: (721)Government releasing contractor funds -
- (713) Fraction of government funds released to contractor =  $\text{government funds released to contractor} / \text{f(Fractional government funding period)}$   
 Units: fraction  
 Comment: The fraction of funds released to the contractor as a function of the Government funding period.  
 Uses: (712)Contractor funds to be released -
- (714) Fraction of government funds released to SPO =  $\text{government funds released to spo} / \text{f(Fractional government funding period)}$   
 Units: fraction  
 Comment: The fraction of funds released as a function of the Government funding period.  
 Uses: (726)SPO administered funds to be released -  
 (727)SPO operating funds to be released -
- (715) fractional funding available for civilian overtime  $f([(0,0)-(1,1)],(0,1),(0.999,1),(1,0))$   
 Units: fraction  
 Comment: function defining the fraction of full civilian overtime funding available during the government funding period  
 Uses: (737)Fractional funding available for civilian overtime -

- (716) Fractional government funding period =  $\text{MIN}(\text{Time}/\text{Government funding period}, 1)$   
 Units: fraction  
 Uses: (713)Fraction of government funds released to contractor -  
 (714)Fraction of government funds released to SPO -  
 (024)Fraction of unreimbursed funds to be released -  
 (735)Fractional authorization funding for civilians -  
 (736)Fractional authorization funding for military -  
 (737)Fractional funding available for civilian overtime -
- (717) Government funding period = 60  
 Units: Month  
 Comment: Total number of months over which the Government actually, or is willing to provide funding to the project. (Note that this may exceed the initial completion date and also that the contractor may complete the project before the government's willingness to pay expires.)  
 Uses: (716)Fractional government funding period -
- (718) government funds released to contractor  $f([(0,0)-(1,1)],(0,0.025),(0.975,1),(1,1))$   
 Units: dmnl  
 Comment: Function governing the release of government funds to the contractor which determines the spending profile.  
 Uses: (713)Fraction of government funds released to contractor -
- (719) government funds released to spo  $f([(0,0)-(1,1)],(0,0.025),(0.975,1),(1,1))$   
 Units: dmnl  
 Comment: Function governing the release of government funds to the SPO, which determines the spending profile.  
 Uses: (714)Fraction of government funds released to SPO -
- (720) Government released contractor funding = INTEG (Government releasing contractor funds, 0)  
 Units: \$  
 Uses: (712)Contractor funds to be released -
- (721) Government releasing contractor funds =  $\text{MIN}(\text{Contractor funds to be released} / \text{Time to release government funds, Unreleased contractor funding}/\text{TIME STEP})$   
 Units: \$/Month  
 Uses: (720)Government released contractor funding -  
 (729)Unreleased contractor funding -  
 (051)Aggregating financial resources -
- (722) Government releasing SPO administered funds =  $\text{MIN}(\text{SPO administered funds to be released} / \text{Time to release government funds, Unreleased SPO administered funds}/\text{TIME STEP})$   
 Units: \$/Month  
 Uses: (724)Released SPO administered funds -  
 (730)Unreleased SPO administered funds -  
 (404)Incrementing administered funds -



- (723) Government releasing SPO operating funds =  $\text{MIN}(\text{SPO operating funds to be released} / \text{Time to release government funds, Unreleased SPO operating funds/TIME STEP})$   
 Units: \$/Month  
 Comment: A simplifying assumption.  
 Uses: (725)Released SPO operating funds -  
 (731)Unreleased SPO operating funds -  
 (349)Accruing operating funds resources -  
 (350)Accruing SPO management reserve -
- (724) Released SPO administered funds =  $\text{INTEG}(\text{Government releasing SPO administered funds, 0})$   
 Units: \$  
 Uses: (726)SPO administered funds to be released -
- (725) Released SPO operating funds =  $\text{INTEG}(\text{Government releasing SPO operating funds, 0})$   
 Units: \$  
 Uses: (727)SPO operating funds to be released -
- (726) SPO administered funds to be released =  $\text{MAX}(\text{Fraction of government funds released to SPO} * \text{Total SPO administered funds-Released SPO administered funds, 0})$   
 Units: \$  
 Uses: (722)Government releasing SPO administered funds -
- (727) SPO operating funds to be released =  $\text{Fraction of government funds released to SPO} * \text{Total SPO operating budget-Released SPO operating funds}$   
 Units: \$  
 Uses: (723)Government releasing SPO operating funds -
- (728) Time to release government funds = 0.5  
 Units: Month  
 Uses: (721)Government releasing contractor funds -  
 (722)Government releasing SPO administered funds -  
 (723)Government releasing SPO operating funds -
- (729) Unreleased contractor funding =  $\text{INTEG}(-\text{Government releasing contractor funds, Government's total contractor funding})$   
 Units: \$  
 Uses: (721)Government releasing contractor funds -
- (730) Unreleased SPO administered funds =  $\text{INTEG}(-\text{Government releasing SPO administered funds, Total SPO administered funds})$   
 Units: \$  
 Uses: (722)Government releasing SPO administered funds -
- (731) Unreleased SPO operating funds =  $\text{INTEG}(-\text{Government releasing SPO operating funds, Total SPO operating budget})$   
 Units: \$  
 Uses: (723)Government releasing SPO operating funds -

### 8.5.3.3 Government Personnel Funding



- (733) authorization funding for civilian salary  $f([(0,0)-(1,1)],(0,1),(0.999,1),(1,0))$   
 Units: fraction  
 Comment: Function defining the fraction of initial authorization funding for civilian personnel salary provided over the government funding period.  
 Uses: (735)Fractional authorization funding for civilians -
- (734) authorization funding for military  $f([(0,0)-(2,1)],(0,1),(0.9999,1),(1,0))$   
 Units: fraction  
 Comment: Function defining the fraction of initial authorization funding for military personnel provided over the government funding period.  
 Uses: (736)Fractional authorization funding for military -
- (735) Fractional authorization funding for civilians =  
 authorization funding for civilian salary  $f(\text{Fractional government funding period})$   
 Units: fraction  
 Comment: Fraction of initial authorization funding for civilian personnel provided over the government funding period  
 Uses: (739)Government funds for civilian salary -
- (736) Fractional authorization funding for military =  
 authorization funding for military  $f(\text{Fractional government funding period})$   
 Units: fraction  
 Comment: Fraction of initial authorization funding for military personnel provided over the government funding period  
 Uses: (740)Government funds for military salary -

- (737) Fractional funding available for civilian overtime =  
fractional funding available for civilian overtime f(Fractional government funding period)  
Units: fraction  
Comment: Fraction of full civilian overtime funding available over the government funding  
period.  
Uses: (738)Funding available for civilian overtime -
- (738) Funding available for civilian overtime = Fractional funding available for civilian overtime  
\*Authorized civilians\*Average civilian salary\*SPO overtime rate multiplier  
Units: \$/Month  
Uses: (658)Financially indicated civilians paid for overtime -
- (739) Government funds for civilian salary = Initial authorized civilians\*Average civilian salary  
\*Fractional authorization funding for civilians  
Units: \$/Month  
Comment: Government funds for civilian personnel is funding provided for civilian personnel  
salaries.  
Uses: (483)Financial resources available for civilians -
- (740) Government funds for military salary = Initial authorized military\*Average military salary  
\*Fractional authorization funding for military  
Units: \$/Month  
Comment: Government funds for military personnel is funding provided for military personnel  
salaries.  
Uses: (439)Financial resources available for military -