Effects of Resource Allocation Policies on Project Durations

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Abstract

Minimizing duration is critical to success in many construction projects. As a primary driver of progress and an effective management tool, resource allocation among development activities can strongly influence durations. Limitations and costs of improving development processes and increasing resource quantities and productivities make improving resource allocation policies an important source of schedule improvement. Policies for reduced project duration are difficult to design and implement because of closed loop flows of work that generate dynamic demand patterns and delays in shifting resources among activities. Resource demand estimates and resource adjustment times are two policy features that managers can readily impact and also influence project durations. These are used to describe allocation policies in a relatively simple project model. Myopic and foresighted policies are distinguished by their use (or lack thereof) of rework and multiple backlogs in allocation. Optimal policies under perfect and limited managerial control are described by testing myopic and foresighted policies across a range of project complexities and adjustment times under deterministic and uncertain conditions. Counter-intuitive results include that minimum delays do not produce minimum durations, myopic policies can produce shorter durations than foresighted policies, and increasing uncertainty decreases durations under certain conditions. The model is used to explain these results and future research topics are discussed.

Keywords: resource allocation, policy design, policy analysis, project management, product development, foresight, delay

1. Introduction

Completing construction projects after their deadlines is a common but expensive problem that has been well documented in the literature (e.g. Scott 1993). In construction and other types of development projects meeting schedule deadlines is often the most important concern for managers (Lyneis, Cooper, and Els 2001, Patterson 1993, Meyer 1993, Wheelwright and Clark 1992). Two approaches to improving schedule performance are process improvements and resource management. A variety of process improvement approaches to improving schedule performance have been explored, including fast track (concurrent development) processes (Pena-Mora and Park 2001**,** Backhouse and Brookes 1996), the use of information technology tools

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(Joglekar and Whitney 1999), and cross functional development teams (Moffatt 1998). But constraints imposed by cost, product architecture, and project participant relationships often constrain managers' ability to effectively improve projects through these means (e.g. see Joglekar et al. 2001). Therefore effective resource management is important to the timely completion of projects and reducing project durations.

Development project resource management can improve schedule performance by increasing the quantity of resources, productivity and utilization. Total resource quantities and associated productivities are often limited and difficult or expensive to improve, leaving resource utilization as a primary management tool to reduce project durations. Managers can have a large effect on resource utilization through the policies they use to allocate resources among development activities, even when the total quantity of resources is fixed. For example, a design manager can impact when all design components are completed by allocating the optimal fraction of the available designers to the initial design of components, the checking of designs to identify needed changes, and the correction or improvement of component designs. Applying too few resources to any given activity (the "resource starvation" problem) slows progress and applying too many can cause crowding that reduces productivity and wastes resources that could be used more efficiently by other activities. Therefore the allocation of scarce resources among development phases and among activities within phases is a realistic management opportunity for improving project schedule performance. The current work focuses on resource allocation policies as a means of reducing project duration and seeks to improve understanding of the impacts of these policies on project durations. Sterman's (2000) description of policies as decision-making rules is adopted here. In this context resource allocation policies are formal heuristics or guidelines which managers use to make individual decisions about where to apply resources. For example the critical path method mantra "Feed the critical path [with resources]." is an informal resource allocation heuristic that could be formalized into a policy of filling all resource needs of critical path activities before allocating resources to other activities. Resource allocation policies are described here with two managerial choices: 1) whether or not to include the effects of rework and multiple backlogs on future resource needs in allocating resources now and 2) how quickly to adjust resources. The current work focuses on how these policy parameters impact project durations**.**

2. Challenges in Project Resource Allocation Policy Design

Resource allocation policy design is difficult because of two inherent characteristics of development: iteration and delays in implementing allocation decisions. Development processes are iterative by nature. Iteration creates closed loop flows of work in which defects or optional changes for improvement are discovered, changes are made, and the work is checked or tested again for additional change requirements. Iteration can magnify the total work effort needed for completion because rework can expose or create additional change requirements. Effective resource allocation for iterative projects is difficult because of the challenges in accurately predicting the amounts of work to be initially completed, inspected or tested to discover change requirements, and reworked. These backlogs of work evolve during projects. Consider, for example, a project phase without the benefits or burdens of starting with previously developed work. At the beginning of the phase all work packages must be initially completed and none are yet available for quality assurance or rework. As packages are initially completed and subsequently inspected the backlog of work (and need for resources) for initial completion decreases and the backlogs of packages needing quality assurance and rework increase, but at different rates. The quality assurance and rework backlogs later decrease as work is approved and all work packages are initially completed, making additional resources available. When work backlogs will be specific sizes depends on the resource productivities of individual development activities, project complexity and the resulting likelihood of rework, scope, and other factors. Predicting work backlogs and the resulting demand for resources is difficult due to the dynamics of rework cycles, uncertainties in projects (e.g. changing likelihood that work being checked will need rework). Given the limitations of human cognition (Simon 1996), especially in managing dynamic systems (Senge 1990), managers cannot predict backlogs accurately enough for effective resource allocation.

Resource allocation can be based on a simple approach: allocate resources to each development activity in the same proportion that the activity's current backlog contributes to the total amount of work waiting to be done. Although reasonable and easy to understand, such a policy has at least two important defects: 1) it fails to account for future changes in backlogs due to the stock and flow structure of the project that creates inflows from upstream activities and outflows from downstream activities, and 2) it fails to account for rework that increases some backlogs compared to their current levels.

In contrast to basing allocations on *current* backlogs, the closed conserved flows of work in rework cycles and the delays inherent in development suggest that allocation should include the impacts of the stock and flow nature of development and rework. Joglekar and Ford (2004) refer to policies that incorporate information on multiple backlogs for demand estimates of all activities and rework "foresighted" and policies that use only current backlogs as the basis for resource allocation as "myopic" (i.e. relatively short-sighted) and discuss the use and challenges of foresight by practitioners. The same nomenclature is used in the current research. This definition is consistent with "look ahead" policies and other similar terms used by resource allocation researchers (e.g. Holstein and Berry 1970, Gere 1966). The use of "foresight" to describe allocation policies in the current work does not imply the explicit prediction of future backlog sizes. But the foresighted policies in the current work do include future conditions when compared to myopic policies by including contributions to backlogs due to the stock-flow structure and the impacts of rework over the entire project duration. Joglekar and Ford (2004) specify how these are used to develop foresighted policies.

Delays in making allocation decisions, implementing reallocations, and productivity ramp-up of re-allocated resources also make resource allocation policy design difficult. Total resource adjustment delays can be large due to the number of information and physical activities that must occur for a complete change in allocation, the time requirements for those activities, and the prerequisite information needs in those processes. For example, reallocating ironworkers from correcting flawed structural steel connections to inspecting new connections requires observing and collecting backlog sizes and current workforce allocations, forecasting demands for iron workers, determining desired allocations, informing the supervisor of the new targets, selecting and instructing the affected ironworkers, relocation of ironworkers and necessary equipment and tools, and the ramp-up of iron workers to full productivity in their new assignments. As will be demonstrated, the size of resource adjustment times can have large impacts on project duration. The sizes of resource adjustment times can also represent the flexibility available in shifting or adjustment resources, with smaller delays representing more flexibility and visa versa. The use of resource adjustment times as managerial tools is investigated with the model.

Delays are often perceived as unfortunate realities of development processes and management. But smaller delays do not necessarily generate better performance. Figure 1 shows the results of simulating project durations for the same project across a range of resource adjustment times using the model described later. The project with the adjustment time of 10 days completes the project 4% faster (in 58.75 days) than the project with an adjustment time of 5 days (in 61.25 days), indicating an optimal resource allocation delay closer to 10 days than 5 days. Identifying and applying resource adjustment times that minimize durations, referred to here as the optimal delay or time, should be important goals of project managers because project durations can potentially be reduced at little or no additional cost. The model is used later to describe the impacts of several project characteristics on the size of optimal resource adjustment delays.

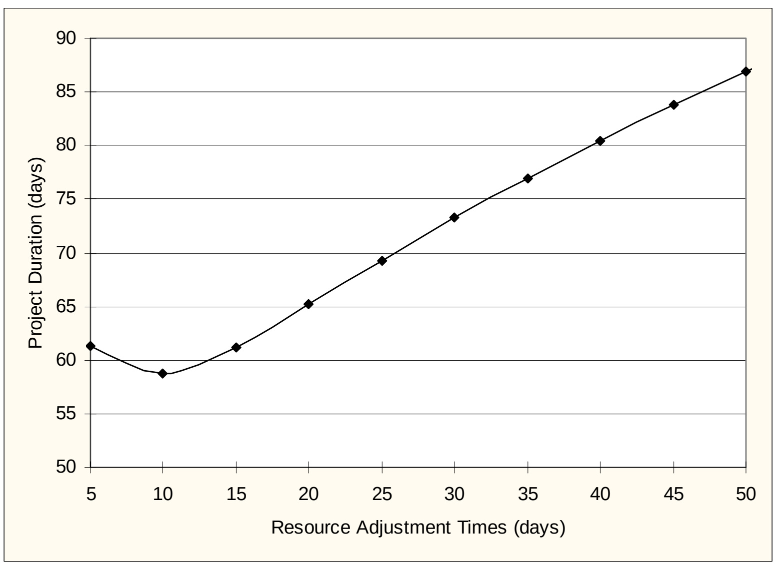

Figure 1: Project Duration and Resource Adjustement Delay

Intuitively, managers should incorporate resource adjustment delays into allocation policies. As a simple example, assume quality assurance currently (in week 92) needs 25% of the resources but the project manager expects that fraction to increase to 50% in week 100. Further assume that it takes 8 weeks to implement target allocation decisions and that (for simplicity) delays take effect completely and instantaneously after the delay. To best meet resource needs the project manager should set the target allocation for quality assurance in week 92 to 50%, not 25% as indicated by current demand, and not wait until week 100 when the quality assurance level of demand actually reaches 50%. Several types of managerial errors can thwart perfectly attaining the goals of this allocation policy. If the project manager's forecast of quality assurance demand (50%) or when it will occur (week 100) are flawed or the delay is not 8 weeks and fully effective instantly after the delay and demand changes quickly the quality assurance activity will probably not have the right amounts of resources at the right times. Avoiding these errors is difficult because of the previously discussed challenges in predicting the sizes of multiple interacting backlogs, the uncertain sizes of actual delays, and the lack of understanding of how demand forecasting and allocation delays impact performance. In the next section we explore the extent literature on how foresight in estimating resource demands and resource adjustment delays impact project schedule performance.

3. Literature Review

Resource allocation research often focuses on a single resource type (e.g. money, labor, equipment, managerial effort) because of the unique impacts of different resource types on performance. For example Shohet and Perelstein (2004) propose a methodology for prioritizing rehabilitation projects for the allocation of funding. Within individual construction projects resource allocation is often studied as a special case of scheduling problems (e.g. the resource-constrained scheduling problem) in which the resource is labor or equipment. These studies have used heuristics (Gordon 1983, Hong 2001) and genetic algorithms (Chan and David 1996) in connection with activity modeling to allocate resources. Frequently activity priorities are used to fully meet one activity's demand before allocating remaining resources to lower priority activities. This approach appears unlikely to be used extensively in practice because managers would be forced to completely neglect some activities that need resources while completely satisfying others and it increases the discontinuity of allocations, which Joglekar and Ford (2004) found problematic. These approaches focus on scheduling, not resource allocation policies, and therefore cannot fully address the issues described above.

In contrast, Joglekar and Ford (2004) recommend continuously adjusting resource allocations for a generic development resource based on backlog sizes. They develop and use the two-dimensional Resource Allocation Policy Matrix (Figure 2) to describe policies as the set of relationships between individual work backlogs and the development processes that service those backlogs. Each cell value in a Resource Allocation Policy Matrix defines the relative importance of a backlog (Wc, Wqa, or Wrw in Figure 2) on the resources for a development process (Initial Completion, Quality Assurance, and Rework in Figure 2). The product of each cell value and the size of the appropriate backlog determine the relative demand for resources by the activity (the cell's row) due to the backlog (the cell's column). Allocation fractions are the fraction of the total relative demand (sum of all nine relative demands) needed for each activity (sum of each row of three relative demands). Allocations continuously change during a project due to the evolution of backlogs and thereby relative demands for resources. Myopic policies in which allocation fractions are directly proportional to only the current size of the backlog serviced are described with diagonal terms of equal value and zeros as non-diagonal terms (e.g. Figure 2). Assuming equal productivities, myopic resource allocation policies allocate resources to each activity in the same fraction that the activity’s current backlog contributes to the total amount of work waiting to be done. Foresighted allocation policies are described with non-zero off-diagonal terms, which account for the rework in the stock and flow structure and use backlogs in addition to the one serviced in setting each activity's resources. Joglekar and Ford (2004) developed and applied a linear control theory model to develop the foresighted resource allocation policies used in the current work.

Work Backlog

Development Activity		Wc	Wqa	Wrw
	Initial Completion (c)	1	0	0
	Quality Assurance (qa)	0	1	0
	Rework (rw)	0	0	1

Figure 2: A Resource Allocation Matrix representing a myopic policy
(Joglekar and Ford 2004)

As described, resource adjustment delays represent the time required to move resources among development activities. Joglekar and Ford (2004) modeled the often-desired (and perhaps often-assumed in practice) instantaneous adjustment discussed above in developing foresighted policies and simulated projects that experienced a single, fixed resource adjustment time during actual operations. They found foresighted policies that generated shorter durations than myopic policies. However, because resource adjustment delays can strongly impact durations (e.g. Figure 1), the effects of relaxing Joglekar and Ford's resource adjustment delay assumptions needs to be investigated. The current work focuses on the impacts of relaxing their assumption of a single, fixed operational resource adjustment time. Structural control system researchers have studied how delays between signals from sensors and actuators impact structural behavior (Udwadia, Bremen, Kumar, and Hosseini 2003) and found that purposeful time delays can improve structural system behavior over eliminating time delays (Mahmoud and Al-Muthairi 1994, Udwadia et al. 2003). This suggests that managers can improve schedule performance by tuning resource adjustment delays to the characteristics of development projects. No research is known to develop or test this concept as a potentially significant and inexpensive means of improving construction projects.

Despite the potential of improving resource allocation policies to reduce development durations, relatively little research has investigated allocation policy design. Previous research (Joglekar and Ford 2004) has identified foresight (or lack thereof) as an important feature of resource allocation policies but has not described how foresight impacts durations across project characteristics. The current work expands previous research to describe how foresight impacts durations. Control theory and model simulations suggest that the size of resource adjustment delays can also significantly impact durations. But little research has been done to investigate the impact of resource adjustment delays on project performance. Our literature survey shows that the concept of designing delay sizes for improved performance through the tuning of managerial delays to project features and characteristics has not been applied within project management research. The current work proposes the purposeful tuning of managerial delays to projects for improved performance as a potentially important advancement in project management and initially investigates its application to resource allocation policy design. It therefore extends Joglekar and Ford's (2004) work by introducing the concept of tuning delays from control theory to project management through managerial choices of resource adjustment times.

4. Research Methodology

Research Approach

The system dynamics methodology (Sterman 2000, Forrester 1961) was applied to model the flows and accumulations of work, delayed information feedback, and the nonlinear relationships that characterize construction projects (Ford and Sterman 1998, Cooper 1993). System dynamics is a methodology for studying the design and management of dynamically complex systems by building and applying simulation models. Forrester (1961) develops the methodology's philosophy and Sterman (2000) specifies the modeling process with examples and describes numerous applications. When applied to projects system dynamics focuses on how performance evolves in response to interactions between managerial decision-making and development processes. System dynamics has been successfully applied to a variety of project management issues, including failures in project fast track implementation (Ford and Sterman 1998), poor schedule performance (Abdel-Hamid 1988), and the impacts on project performance of changes (Rodriguez and Williams 1997, Cooper 1980) and concealing rework requirements (Ford and Sterman 2003a).

A model that is very simple relative to actual practice is used to expose the relationships between policy structures and project behaviors. Therefore, although many development processes and the features of project participants interact to determine project schedule performance, only those features that describe resource allocation policies and the fundamental processes they impact are included. For example, total resource quantities and productivities are assumed fixed and all work in backlogs is assumed to be available for development. Simulated performances using different policies are, therefore, considered relative and useful for comparing allocation policies and developing insights, but not sufficient for final policy design. These assumptions (as well as others made in modeling) allow the investigation to focus on how specific policy choices and project characteristics impact durations. Potential impacts of relaxing modeling assumptions on results are discussed in the conclusions.

Research Design

Resource allocation policies are described here with two features over which project managers have significant influence: 1) the use of myopic or foresighted resource allocation policies and 2) the size and uncertainty of resource adjustment delays. Schedule performance under different project conditions are investigated to better describe the impacts of resource allocation policies on performance and project conditions on policy effectiveness. Several project conditions can impact project progress and policy effectiveness, including uncapacitated development activity process durations, total resource quantities, resource productivities, and project complexity. The current work focuses on project complexity, which can significantly impact project progress through the rework cycle and which managers can compare across projects and therefore use in policy design. Different amounts of uncertainty in resource adjustment times during a project are also modeled to reflect levels of managerial control.

Project durations were simulated using myopic and foresighted policies with project complexities ranging from 0% to 80% likelihood of rework and resource adjustment delays experienced by the project (the operational delay) from 5 to 75 days. For each policy and complexity the optimal operational delay was identified as the delay generating the minimum project duration. As a graphic example of this analysis, in Figure 1 the minimum duration (58.75 days) occurs with a resource adjustment delay of 10 days. For foresighted policies this reflects projects in which the manager assumed instantaneous adjustment but experienced significantly longer adjustment times, from 5 to 75 days, which are potentially realistic scenarios. The simpler myopic policy requires no explicit assumption about the adjustment time.

Uncertainty in resource adjustment times during a project can reflect the amount of control managers exert over operations to keep adjustment times near a targeted value. Uncertainty can take the form of the mean operational adjustment time differing from the optimal value or variation in the adjustment time around its mean during the project. To investigate policy design implications when mean resource adjustment delays do not match optimal operational values durations were simulated using mean operational delays from 5 to 75 days. To investigate policy design implications when delays vary around their operational mean during a project, durations were simulated that were either 50% greater than the optimal value or 50% less than the optimal operational value over a range of levels of variation in delays during the project. Variance was changed using coefficients of variation (= standard deviation / mean) to normalize variances to mean values. Three hundred possible projects were simulated for each mean resource adjustment delay value with four coefficient of variation (0%, 10%, 20%, and 30%) and the durations averaged for each condition.

5. A Model of Resource Allocation in Development Projects

The model structure is based on previously validated models of development project processes and management as referenced below. The model maps the backlogs and flows of work in a project and the information structures and policies used to allocate resources. The interactions among the work and information components of the model describe the use of project information (e.g. work backlog sizes) and policies to control project progress. Individual relationships are specified with differential and relatively simple algebraic equations that reflect the interactions among project components. Because closed form solutions are unknown the behavior of the system was simulated over time.

The model has two sectors: a work flow sector and a resource allocation sector. The work flow sector models project processes through the flows of work (in small fungible work packages) and the resulting changes of backlogs, as influenced by project characteristics such as project complexity. The resource allocation sector describes policies for allocating resources and their implementation. The interaction between the work flow and resource allocation sectors describe the use of resources and information to control project schedule performance. The model structure is described next. Joglekar and Ford (2004) provide a complete equation listing.

Modeling Work Flows, Development Processes, and Resource Impacts

The core of the model simulates the flow of work packages through a project with a rework cycle in a value chain of four development activities that are generically named initial completion, rework discovery, rework, and approval and release (Figure 3). The rework cycle has been modeled and used extensively to explain and improve project management (Cooper 1980, 1993a,b,c, 1994, Cooper and Mullen 1993). The work flow structure used here was developed for projects by Ford and Sterman (1998) and has been applied to explain concurrent development implementation failure (Ford and Sterman 2003b) and the role of managerial behavior in project performance (Ford and Sterman 2003a). The initial completion, rework discovery, rework, and approval and release activities (shown with arrows between boxes in Figure 3) move work from their own backlogs to their successor's backlogs (boxes in Figure 3). Initial completion develops each work package the first time. Quality assurance drives two work flows, rework discovery and the approval of work. Quality assurance discovers rework needs with a variable describing the probability of each work package needing rework. Quality assurance approves and releases work not found to require rework. The fraction of work discovered to require rework is used to model project complexity. More complex problems are assumed to require more iteration for completion and quality assurance efforts are assumed to identify all rework needs. See Ford and Sterman (2003a,b) for a more detailed model of iteration and studies of the impacts of imperfect quality assurance. After being reworked, work packages are inspected or tested again because hidden errors or needed improvements can be exposed or created during rework.

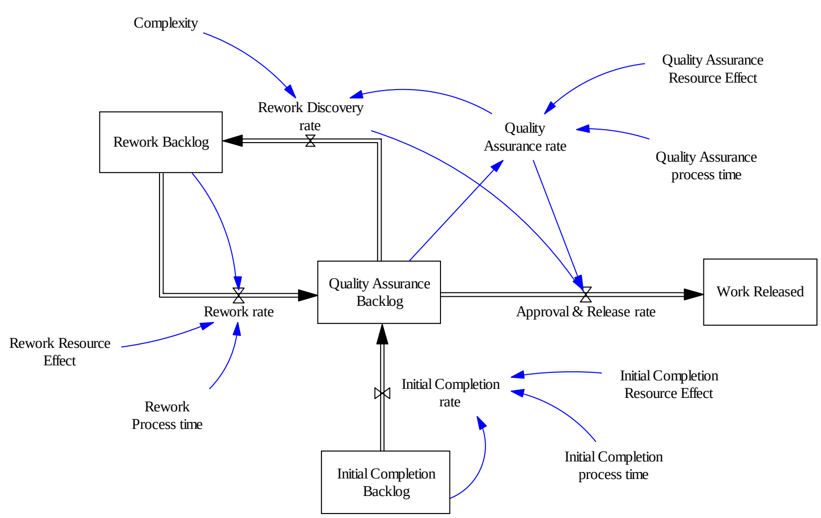

Figure 3: A Capacitated Project Model

(Joglekar and Ford 2004)

The progress rates for initial completion, quality assurance, and rework are consistent with the control theory and system dynamics models used to develop the foresighted policies (Joglekar and Ford 2004). Those rates are each a fraction of the uncapacitated rates allowed by the process, as described with minimum processing times (assumed equal for simplicity). The fraction that reduces progress from the uncapacitated rate is the progress rate allowed by resources divided by the maximum resource rate, which is the resource rate if that activity was allocated all the resources. This formulation allows uncapacitated progress by an activity if it is allocated all of the resources, no progress if no resources are allocated, and progress directly proportional to resources in between these boundary conditions. The model generates realistic and complex behavior despite the simplicity of this formulation. This formulation and simplifying assumptions elucidate the impacts of resource allocation policies by isolating the quantity of resources allocated as the driver of differences in model behavior.

Modeling Resource Allocation Policies

Progress rates for the three development activities (initial completion, quality assurance, and rework) allowed by resources are modeled as the product of the total available resources (assumed constant), productivities (assumed constant and equal), and applied resource allocation fractions. Therefore resources impact progress through the application of allocation fractions to individual development activities. The application of allocation fraction targets are delayed with first order exponential adjustments that move applied allocation fractions toward targets a fixed portion of the difference between the applied and target fractions each time period. The speed of adjustment is defined by the resource adjustment delay, with large delays generating slower adjustments and visa versa. Target fractions are proportional to the indicated demand for resources by each activity. As described previously, myopic policies are described by indicated demands for each activity that are equal to the current backlog of the activity and foresighted policies are described by indicated demands based on work backlogs that are weighted according to the policy reflected in the Resource Allocation Matrix. See Joglekar and Ford (2004) for additional details.

Model Validation and Behavior

The model was tested for usefulness in evaluating resource allocation policies using three types of tests of system dynamics models suggested by Forrester and Senge (1980) and described by Sterman (2000): 1) structural similarity to the actual system; 2) reasonable behavior over a wide range of input values; and 3) behavior similarity to actual systems. Basing the model on previously validated project models and the literature improves the model's structural similarity to development processes and practices, as do unit consistency tests. As recommended by Sterman (2000) simulations using extreme parameter values (e.g. no resources) were performed in addition to the inspection of model equations. Model behavior remained reasonable with extreme input values and across changes in individual parameter values. For example reducing the needed rework decreases project duration. The model's behavior for typical conditions (Figure 4) is consistent with previous project models and practice (e.g. the "S" shaped growth of work released). Based on these tests the model was assessed to be useful for investigating the impacts of resource allocation policies on project schedule performance.

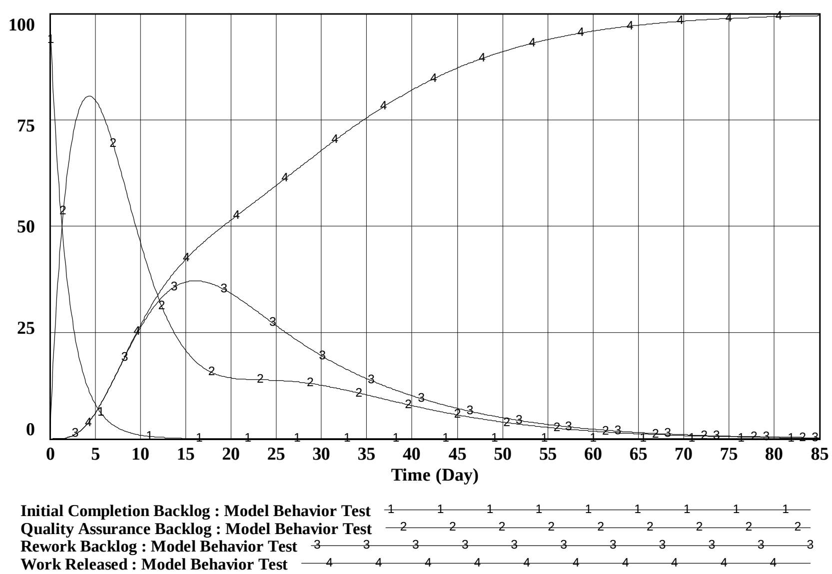

Figure 4 – Work backlogs (50% rework and myopic policy)

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6. Results

Impacts of Resource Allocation Delays and Project Conditions on Project Schedule Performance

Impacts of mean operational resource allocation delay size and project complexity on project duration are shown in Figure 5 for rework fractions of 10%, 30%, and 50% using myopic and foresighted policies and resource allocation delays from 5 to 75 days[4]. Impacts on durations vary from a range of just 17% of their minimum value (50% rework with a foresighted policy) to over 165% (10% rework with a myopic policy). Optimal operational resource adjustment times also vary, from 10 to 40 days. These results suggest that the operational resource adjustment time is an important feature of resource allocation policy effectiveness and that the selection of target resource adjustment times is an important part of resource allocation policy design.

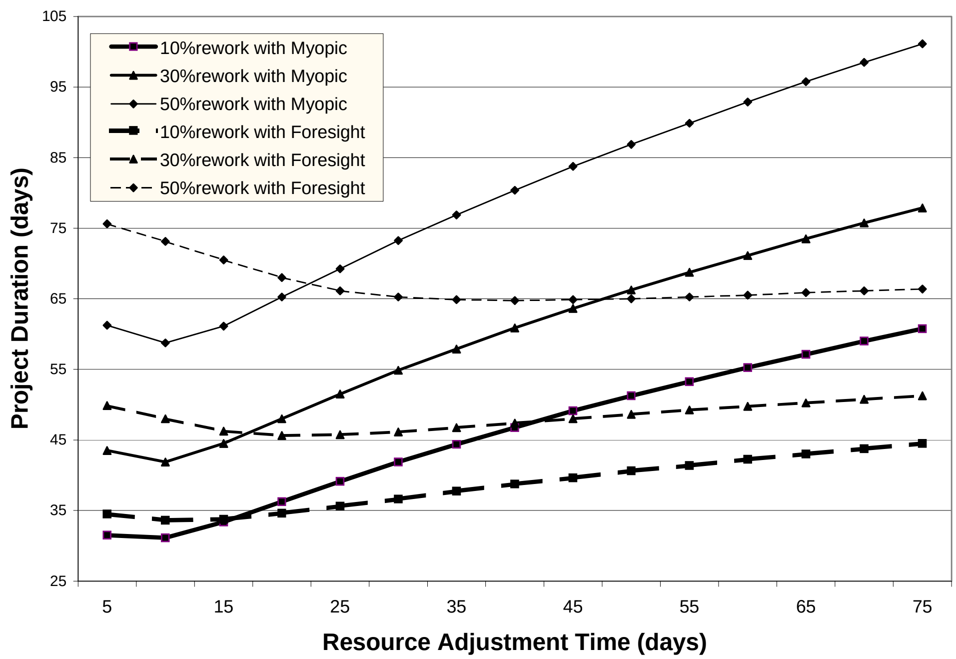

Figure 5: Project Durations versus Resource Adjustment Time

Notice that the relationship between the resource adjustment time and project duration is consistently convex, across differences in durations with complexity, optimal operational adjustment times, and rates of duration increase as adjustment times deviate from optimal values. These results are consistent across the simulated rework range (0% to 80%). This result suggests that improving resource allocation policies by changing adjustment times is not simply a matter

[4] Additional comparisons, such as across policy type (myopic vs. foresighted) are not justified due to the assumption of instantaneous resource adjustment in the control theory model used to develop foresighted policies.

of reducing adjustment times as much as possible. For example, reducing an adjustment time below it's operational optimal value will increase project duration.

Imperfect Control of Resource Adjustment Delays

Project managers often cannot perfectly control how close actual resource adjustment times remain to a target time. Therefore resource adjustment times may vary during a project. Managers may impact the amount of variation in actual adjustment times with the amount of influence they exert on adjustment processes. Firmly controlling adjustment times would generate smaller variation and visa versa. Uncertainty in resource adjustment delays during a project can reflect the imperfections and purposeful manipulation of managerial control over resource adjustment times. As shown in Figure 6 for a myopic policy with 50% rework, when resource adjustment delays are not optimal increasing the variance of the delay generates unusual changes in duration. Intuitively duration is expected to monotonically increase with increasing variance because more uncertain systems are considered more difficult to manage. But simulated durations increase or remain essentially constant when the cost of variance increases from 0% to 10%, decrease for coefficients of variance from 10% to 20%, and then increase again for coefficients of variance of 30%.

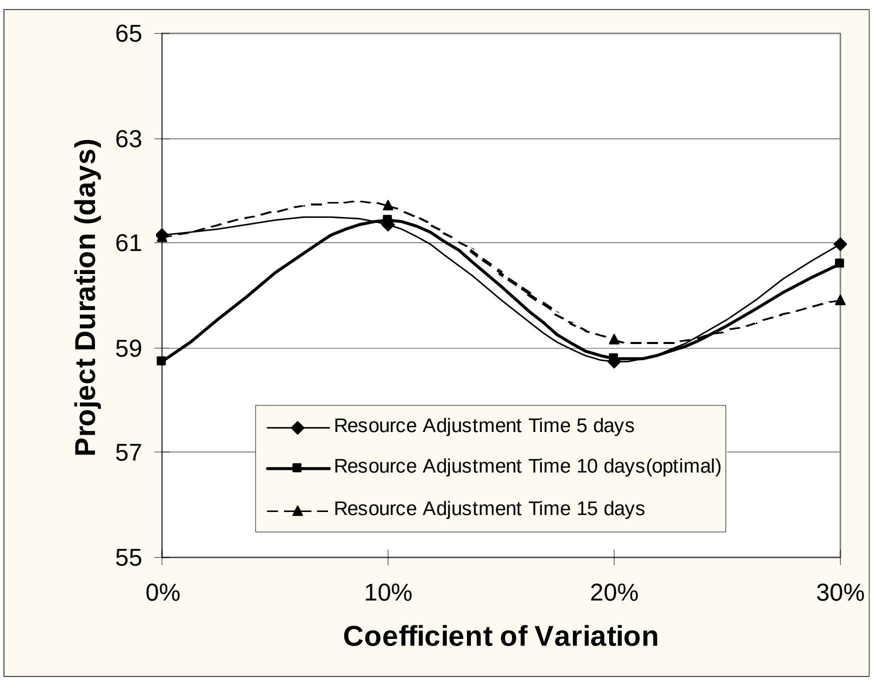

Figure 6: Average Project Durations across Range of Variance in Resource Adjustment Times

This behavior can be explained by scrutinizing how distributions of resource adjustment times interact with the project's adjustment time / duration relationship (e.g. Figure 5), as shown in Figure 7 for 50% rework and myopic demand estimating. Results for other complexities and foresighted policies are similar. The impact of a change in the distribution of adjustment times experienced during a project on duration depends on whether it activates more adjustment times that increase duration more or less than it activates adjustment times that decrease duration, and the sizes of those impacts. The average duration increases when changing the variance of the adjustment time adds more times to the sample that increase durations more than the change adds times that decrease durations more, and visa versa. The adjustment time: duration relationship describes the size of impacts. For example, in Figure 7 increasing the variance from 10% to 20% adds more adjustment times near the optimal time of 10 days (below the mean delay of 15 days) that decrease average durations more than it adds above the mean time that increase durations. This explains the reduction in average duration when variance increases from 10% to 20%. In contrast, increasing the variance from 20% to 30% extends the lower portion of the distribution of adjustment times beyond the optimal value, thereby including times that increase average duration above the minimum. Recognizing and using the convex nature of the adjustment delay:duration relationship and overlaying the distributions of times on that relationship can explain why average durations decrease and then increase with increasing variance. These results suggest that when resource adjustment delays are not optimal increasing variation can reduce duration by including more resource adjustment times nearer the optimal value.

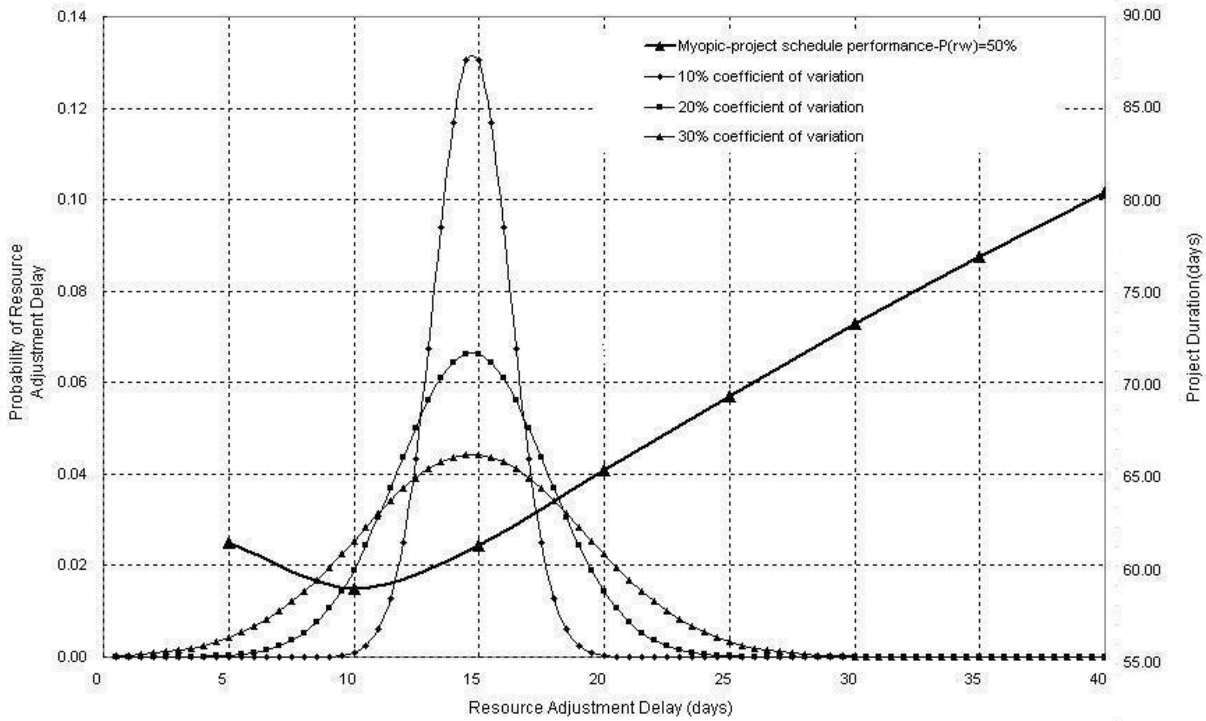

Figure 7: Resource Adjustment Delay distributions and Project Duration versus Mean Delays

7. Discussion and Conclusions

A relatively simple dynamic model was used to investigate the characteristics of effective resource allocation policies on project durations. Foresight and delays in adjusting resources among development activities were used to describe resource allocation policies. The work generated two counter-intuitive results that suggest changes for improved project management practice and research.

First, the results showing that durations are minimized with resource adjustment times greater than their minimum values support a conclusion that projects have optimal managerial delays that may be positive. This recommends against the common perception and practice that everything should be done as quickly as possible to minimize durations. The result also implies that managers should seek to identify optimal delay sizes and use them as targets in decision-making. Some experienced managers may do this tacitly and intuitively for some development processes, adding to the list of cognitive functions performed by practicing project managers but not yet captured in formal models. The current work identifies optimal managerial delays as a potentially important concept for practitioners and a topic for future research.

Second, results showed that increasing uncertainty can decrease durations if delays are not optimal and the delay:duration relationship is convex by increasing the net amount of work performed near optimal conditions. Analogous to the insight concerning optimal mean managerial delay sizes, this result supports a conclusion that sub-optimal managerial delays have optimal, positive levels of uncertainty that managers should seek to identify and use as targets. Optimal positive levels of uncertainty in applied delays indicate the existence of optimal levels of managerial control (versus perfect control) around mean resource adjustment times sizes. The distinction made here between control over mean values and control over variance around that mean is used in robust design (Taguchi 2000), but the current results suggest a very different (and even more counter-intuitive) recommendation for managers. If managers cannot perfectly control mean delay sizes to their optimal values they may improve performance by *increasing* the variance around their actual mean with *less* control. Managers who know that their mean resource adjustment times are sub-optimal may find it difficult to purposefully exert less control over those delays to improve performance. However the insight can provide managerial guidance. Effectively using this insight would likely include managerial attempts to manipulate the reduction of control to apply more adjustment times that are closer to the optimal value than further from the optimal, thereby improving performance more than indicated by the normal distributions used here. However, this would require an awareness of the convex nature of the adjustment delay:duration relationship, an understanding of the impacts of delay uncertainty on duration, and knowing at least the direction of the optimal value from the mean applied value. This reinforces the criticality of identifying and specifying delay:duration relationships and optimal delay sizes and their impacts on performance.

The conclusions of the current work are limited by its focus on only one dimension of project performance (schedule) and model assumptions. Other models of forecasting demands for resources and setting managerial delays have been proposed and are likely to be impacted by other project factors such as the cost of moving to or maintaining delays of specific sizes. Future research can also use the model to investigate the impacts of other project characteristics on resource allocation policy effectiveness and can improve the model to reflect more aspects of projects.

Tuning managerial delays to project characteristics can improve development project performance. However, this requires an understanding of the impacts of the dynamic structures of project processes and their management on behavior and performance. Projects can be improved by continuing to develop a deep understanding of those impacts, how they influence projects, and how projects can be changed to exploit that understanding.

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