Operational Labor Productivity Model

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ABSTRACT

Construction processes inherently involve complex interactions among variables including, but not limited to, physical attributes, resource availability, budget restrictions, and management techniques. Labor productivity, a key variable in the profitability of a project, is influenced by complex and competing factors such as skill level, motivation, and schedule pressure. Contractors continue to struggle with a fragmented industry where competitive pricing and labor productivity are defining factor in their competitive advantage. The current management tools for the industry are inflexible and slow when planning and controlling work on a fast-track project where information is knowingly incomplete, both in final design and construction means and methods. Actual events and conditions are more challenging than anticipated, which demands rapidly pulling together resources to ensure the project is still delivered on-time and within the budget. The data used for the model was provided the subcontractor installing intelligent highway system components on Boston's Central Artery/Tunnel Project.

BACKGROUND

The current management tools for the construction industry are inflexible when planning and controlling work on a fast-track project where information is knowingly incomplete, both in final design and construction means and methods. This uncertainty may turn out to be benign in the overall execution of the project, but where actual conditions are more challenging than anticipated, this requires the team to pull together its resources more rapidly and execute with precision to ensure the project is still delivered on-time and within the budget.

Today, expectations for marked improvement and delivering a product faster and better continue to drive markets; the construction industry is no exception. Those in the industry providing design, construction and consulting services that embrace the tools that can make them more cost-effective and efficient have much to gain in this world-wide industry.

Construction processes inherently involve complex interactions among variables including but not limited to physical attributes, resource availability, budget restrictions, and management techniques. During project execution, these variables control and are controlled by the other closely related variables which change as the system moves through time. Imbalanced interactions among the variables can cause inefficiencies and uncertainties in the project execution [Paulson et. al., 1987], which can deteriorate planned construction sequences and increase total project costs. Moreover, as construction projects continue to increase in size and complexity the planning and control of the projects become more difficult; the larger and more complex the project, the more challenging it is for the project manager to coordinate the resources to reach the common goal. As a result, the industry needs a more efficient planning and control method to supplement, enhance or replace the traditional methods.

CASE EXAMPLE

The subcontractor installing the intelligent highway system components for Boston's Central Artery/Tunnel Project provided the project data used to test the model. The Project Owner is the Massachusetts Turnpike Authority. The Prime Contractor was responsible for providing engineering drawings and materials to the subcontractor and a fully-functional system, including the software to manage and control the system, to the Project Owner. The subcontractor was responsible for providing the labor to install the various system devices and pull fiber optic cable for the system. The original subcontract price was $27 million with a planned duration of four years. This contract had multiple interfaces with predecessor civil/structural contracts as well as other follow-on contracts such as the tunnel lighting contractor and the tunnel finishes contractor. As a result, the release of work areas was contractually constrained.

During the subcontractor's bidding process, it assumed to receive from the Prime Contractor installation drawings to support its planned work coinciding with the release of access restraints and the overall schedule demand. The subcontractor would be responsible to plan its labor and equipment needs while the Prime Contractor would additionally be responsible for providing the material to support the work. A review of the contract documents and drawings revealed problems with constructability, both technical and physical. However, the subcontractor planned its labor resource utilization in a manner to take advantage of learning. The work would commence in year 1 with a small crew. Resource demands would increase in year 2 and 3 to a peak of 60 electricians, then decline in year 4 to a smaller crew until project completion.

The subcontractor's plan was impacted with changes from the start of the project. The release of access restraints by the Project Owner was delayed approximately one year and where access was granted, engineering and procurement - both responsibilities of the Prime Contractor - did not support the available access. In year 2, after limited buildup and accumulation of work experience, the Project Owner directed an acceleration effort to recover 6 months of time. Material availability, quality of field conditions, deficient installation drawings, Owner-directed changes (which not only included scope increases but demands to increase manpower), smaller work areas, overtime, and unrealistic schedule demand contributed to the results experienced by the subcontractor. The results included increased cost of labor, decreased productivity, and schedule recovery not fully realized. In total, the planned manhours were 200,000, the change orders added 250,000 manhours, and the lost productivity totaled 130,000 manhours.

Our objective in the development of this model was to determine the events that resulted in the loss of productivity to determine appropriate allocation of responsibility. The advantage gained by modeling the labor dynamics and productivity in this case example is to have available for future projects a tool that can be used as a predicative model to better forecast productivity losses to improve decision-making and optimize performance.

LITERATURE REVIEW

As stated by Bhandari (1977), to keep proper tabs and stay on top of managerial issues, one must have:

1. The ability to get quick and reliable answers to computational and statistical questions, including those of forecasting with rapidly changing inputs.
2. The ability to recover or retrieve information, often in new combinations or contents, that has already been produced but is now filed away.
3. The ability to amass and interpret the greatest number of relevant facts and relationships upon which to base administrative decisions.
4. The ability to foresee the consequences of current or impending decisions and policies on future behavior of the system so devised.

The management of construction processes is particularly complex given the combination of both fixed and dynamic resources, procurement and delivery time constraints, and project "ramp-up" time that is often unpredictable, as well as selected management techniques.

In contrast to the manufacturing industry, there currently exists little opportunity for scalability in the construction industry since most projects are "one of a kind" products - each project has its own distinct layout, unique site location and generally customized program requirements. As a result, there is only a narrow basis for a fundamental approach to production control and effective use of information technology. Adding to the complexity of construction management is the multitude of project participants - there are lead designers and their specialty engineers (e.g. structural engineer, mechanical engineer) and there are lead constructors and their specialty subcontractors (e.g. vendors, suppliers, installers) for the various functional elements of the project. With an increase in the number of project participants comes an undisputed increase in the amount of information to manage. These and other factors contribute to the extreme fragmentation of the construction industry, which has plagued purposeful integration and process improvements [Brandon et. al., 1998].

Notwithstanding the challenges stated above there is ample room for vast process improvements in the industry. While other construction industry research objectives are focused on process improvements through enhanced process and product visualization and enhanced means of communication, this research addresses enhancements to process execution utilizing knowledge-based expert systems to expose and quantify the impacts of change on project performance.

It is unreasonable to expect no impacts or changes once a project commences. More realistically, the initial plan is challenged from the start and continuously through the project duration. For the schedule to serve as an effective tool it must represent a reasonable and current plan to accomplish the work while sustaining sufficient flexibility to address potential execution challenges. As the project proceeds, unexpected progress, delays, and technical conditions challenge the plan and adjustments are required to keep the schedule accurate. If appropriate, the current plan requires logic network modifications to properly represent how the work is actually being performed and how the work remaining is expected to be performed. If the project schedule does not reflect past project performance, it may misrepresent the contemporaneous to-go completion plan. This planning cycle is a continuous effort, which for it to be effective must consider the true performance history and accurately forecast the expected performance capacity.

Common process dynamics such as variable productivity rates, the effect of worker fatigue and process feedback effects will be discussed in this paper. In addition, this paper will introduce the concept of a system dynamics modeling environment and its ability to capture and process dynamic relationships and present them through graphical means.

As discussed in the Modification Impact Evaluation Guide (July 1979) developed by the U.S. Army Corps of Engineers (USACE), two major impacts upon labor costs are reduced productivity and pay scale increases. The latter is a factor when changes delay progress such that work that would have otherwise been completed during a planned construction phase and is required to be performed at a time when higher wages are in effect. Reduced productivity takes many forms, but implies a loss from some established normal or anticipated level of productivity.

Although multi-disciplined resources do not exactly allow for definitive measurements of labor productivity, there are methods a contractor can use to quantify anticipated labor costs when preparing a bid. The most common technique draws heavily on data derived from the contractor's past experiences, including any indicated trends, present labor pay rates, and anticipated labor rate increases during the life of the project.

That portion of the Contract Price devoted to labor costs indicates the contractor's anticipated level of labor productivity. Whether or not the anticipated profit is realized is significantly dependent on the contractor's ability to maintain the planned labor productivity. With effective management and a little bit of luck, the contractor may achieve labor productivity that exceeds its expectations. Alternatively, labor inefficiencies may be realized due to many uncontrollable factors. Labor productivity is optimal when there is good "job rhythm."

Productivity disruption occurs when workers are prematurely moved from one assigned task to another. Regardless of the competency of the workers involved, some loss in productivity is inevitable during a period of orientation to the new assignment. This loss is repeated if workers are later returned to their original job assignment. Learning curves that graph the relationship between production rate and the repeated performance of the same task have been developed for various industrial tasks. The basic principle of all learning curve studies is that efficiency increases as an individual or team repeats an operation over and over; assembly lines are excellent demonstrations of this principle. Although over time this efficiency can erode unless innovation occurs and job satisfaction increases. However, although construction work involves the repetition of similar or related tasks, these tasks are seldom identical. Skilled construction workers are trained to perform a wide variety of tasks related to their specific trade. Therefore, in construction, it is more appropriate to consider the time required to become oriented to the task rather than acquiring the skill necessary to perform it.

One of the attributes of the construction worker is the ability to perform the duties of this trade in a variety of environments. How long it will take the worker to adjust to a new task and environment depends on how closely related the task is to his experience or how typical it is to the work usually performed by his craft. The time required for a worker (or crew) to reach full productivity in a new assignment is not constant. It will vary with skill, experience, and the difference between the old and new task. For example, an ironworker is moved from placing reinforcing bars to the structural steel erection crew. The ironworker is qualified by past training to work on structural steel, but the vast majority of his experience has been with rebars, and the two tasks are significantly different. As a second example, the same ironworker is moved from placing reinforcing bars for Building A to the same work in Building B, which is similar but not identical to Building A. In this second example, the loss of productivity would be significantly less. In the pricing of the original bid, the contractor should have factored its own loss of productivity when moving from one task to another under its planned project execution.

The optimum crew size is the minimum number of workers required to perform the task within the allocated time frame. Optimum crew size for a project or activity represents a balance between an acceptable rate of progress and the maximum return from the labor dollars invested. Increasing the crew size above optimum can sometimes produce a higher rate of progress, but at a higher unit cost. As more workers are added to the optimum crew, each new worker will increase crew productivity less than the previously added worker. Carried to the extreme, adding more workers will contribute nothing to overall crew productivity.

Working more hours per day or more days per week than the standard 8-hours, five-days a week (Monday through Friday) introduces premium pay rates and efficiency losses. Workers tend to pace themselves for longer shifts and more days per week. Longer shifts will produce some gain in production, but at a higher unit cost than at a normal hour of work. With overtime work, some of the labor costs produce no return because of inefficiencies. Occasionally, the contractor must offer overtime work to attract sufficient manpower. In this case, this additional cost must be borne by the contractor.

The responsibility for motivating the work force and providing a psychological environment conducive to optimum productivity rests with the contractor. Morale does exert an influence on productivity, but so many factors interact on morale that their individual effects defy quantification. Normally, pricing of changed work does not include loss of worker morale. The degree to which this may affect productivity, and consequently the cost of performing the work, would normally be very minor when compared to the other causes of productivity loss. A contractor would probably find that it would cost more to maintain the records necessary to document productivity losses from lowered morale than justified by the amount he might recover. Moreover, the level of morale is a factor in determining the effectiveness of the contractor in its labor relation responsibilities.

In the Modification Impact Evaluation Guide, the USACE presents its derivation of productivity losses, which are often relied upon and utilized for pricing of changed work. While these productivity losses are supported by relevant research conducted by the USACE, challenging these notions and assumptions are justified.

Construction is inherently dynamic and involves multiple feedback processes that produce self-correcting or self-reinforcing side effects of decisions [Sterman, 1992]. Under a fast-track environment these dynamics are further exaggerated and more complex. For this reason, fast-tracking construction usually involves more diversified and dynamic feedback processes than sequential construction [Peña-Mora and Park, 2001].

System dynamics models are treated as formal models to replace mental models. A mental model is typically the understanding and intuition of the construction process derived from years of experience and observations in the field [Peña-Mora and Li, 1999]. However, the mental model is insufficient to analyze complex systems and in particular to analyze impacts and changes to this system. Moreover, the system dynamics model is capable of clearly demonstrating the effects of these impacts to capture true cost and performance results.

The foremost utilization of the system dynamics model is to represent the interdependencies among the different project components. Such interdependencies often complicate the problem since a subtle change in one part of the system can trigger an effect on other parts of the system. This change can be severely detrimental to the overall system if it leads to delays to other tasks that find themselves dependent on the completion of the deferred activity. System dynamics is capable of tracing the interdependencies and in turn the causal impacts of changes [Peña-Mora and Li, 1999]. The system dynamics model enhances the user's understand when in a multi-loop environment the loop dominance can shift from one loop to another, for example, when the loop dominance shifts from balancing to reinforcing.

The ability to formulate and develop an effective plan ahead of time helps dampen the effect of hard-to-control variations, while keeping control efforts to a minimum. This will be especially beneficial for large-scale projects, which involve a high degree of uncertainties. Consequently, the successful development of this model would help ensure that large-scale capital projects can be delivered on-time within the established budget by enhancing the planning and control capabilities of project management. It would also help increase the applicability of the simulation-based scheduling to construction projects by providing a reliable and flexible simulation methodology based on one of the most important variables, productivity.

The traditional construction project literature has focused on the management and sequencing of events in order to deliver projects in the least time and at the lowest costs. These traditional methods include critical path analysis and PERT charts originally developed by the RAND Corporation for military uses during World War II. PERT charts focus on identifying the length of projects, sequence of events and resources (e.g. materials, equipment, and labor) necessary to achieve planned goals. Critical path analysis identifies those components and their sequence in which any delay will result in schedule slippage of the whole project. These tools are widely used yet cost and schedule overruns continue to create problems for the construction industry.

Homer et. al. (1993) examined the reduction of delivery time of pulp mills that required engineering, procurement and construction that is similar to the design, bid, and build format undertaken in many large-scale construction projects. Homer et. al. (1993) developed a system dynamics model that added what they labeled gate functions to capture critical path notions that would stop all work if critical components were not completed in the proper sequence.

Richardson and Pugh (1981), Ford and Sterman (2003), Sterman (2000), and Ledet and Maroulis (1998) have all developed system dynamics models to deal with project management issues. The projects ranged from construction projects to software development, yet all had the concept of rework and undiscovered rework as key components driving dynamics that resulted in projects being behind schedule and over budget. Ford and Sterman (2003) used a system dynamics model that replicated historical data of the "90 percent syndrome"[1] and identified management behavior that contributed to iteration cycles in the development process that resulted in the "90 percent syndrome." Although the Ford and Sterman (2003) article specifically dealt with concurrent development research in industry the lessons are applicable to rework issues, change orders, and design issues in the construction industry.

Ledet and Maroulis (1998) also discuss the "90 percent syndrome" but focus on the role of teams and argue that practice fields (simulation models) should be used to promote teamwork and understanding. They also argue that project performance across industries have similar problems of completion delays and cost overruns. They therefore believe that generic lessons through the use of practice fields can be learned.

STOCK-AND-FLOW STRUCTURE FOR PROJECT WORKFLOW

Figure 1 depicts the stock and flow structure contained in the workflow sector of the Capital Project Management Model (CPMM). This model constraints neither the type of construction project nor the type of project delivery method. Developed with generic parameters, this model characterizes a specific construction project and its associated level of project management at either higher-level milestone management or lower-level process management.

The CPMM defines a construction project as the number of tasks that are either completed or to be completed. The number of tasks that defines the project is captured in the stock labeled Project Scope in Figure 1.

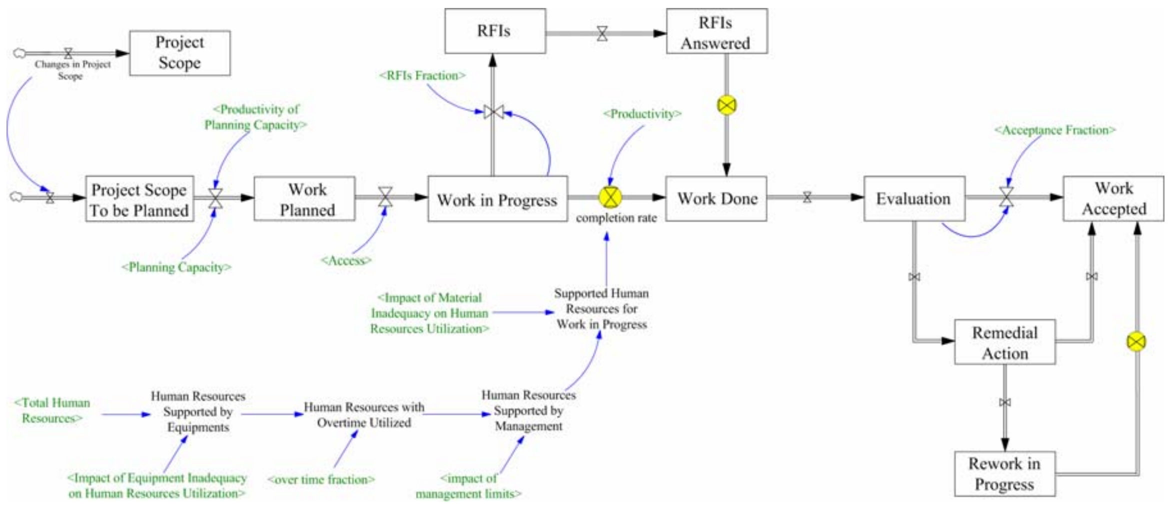

Figure 1: Stock and Flow Structure of Project Workflow

Initially, all the tasks are in the first stock – Project Scope To be Planned – and they move to the Work Planned stock once the planning is completed. The planning completion rate depends on Planning Capacity and the Productivity of Planning Capacity. Tasks, upon the completion of planning, are transferred to the Work in Progress stock if access to the work area is granted. This Work in Progress stock should be considered the work available to complete, given adequate resources. Access to the work area is assumed exogenous as project managers have no control over this aspect of the project. The number of tasks in the stock of Work in Progress decreases due to tasks moving to the RFIs stock, which need clarification, or through the Completion Rate. RFI's maybe caused by ambiguity in the work plans or inexperience of the workers. Those tasks that move through the RFIs stock are clarified, moved to the RFIs Answered stock, completed and then moved to the Work Done stock. Colored in yellow in Figure 1, the Completion Rate of Work in Progress, Rework in Progress, and RFIs Answered

[1] The "90 percent syndrome" refers to the common problem of projects remaining on schedule for the first 90 percent of the project before serious delays arise and push the project back by approximately 100 percent.

depend on Productivity and the number of human resources supported by material, management capacity and equipment (captured as Supported Human Resources for Work in Progress in Figure 1). Inadequacy in one or more of the required resources leads to the underutilization of labor. The available resources are allocated proportionally for the completion of Work in Progress, Rework in Progress, and RFIs Answered. All tasks in the stock of Work Done are either accepted, based on an Acceptance Fraction, or they are not accepted and require Remedial Action. Tasks in the process of Remedial Action may also move to the stock of Work Accepted or that of Rework in Progress. Once all the tasks are completed and accepted the project is complete.

RESOURCES

In the CPMM, there five difference resources that control the rate at which the tasks are moved from Project Scope To be Planned to Work in Progress, to Work Done, to Remedial Action, to Rework in Progress and finally to Work Accepted. These resources are labor, material, equipment, planning and management capacity. Actual labor productivity will appear to be less than originally planned if there are constraints in any of these resources. The stock-and-flow structure of these resources is shown below.

STOCK-AND-FLOW STRUCTURE FOR LABOR

Total Human Resources are disaggregated into New Employees and Experienced Employees. New Employees are hired from the Human Resources Pool and move to Experienced Employees as they gain experience working on the project. Experienced Employees are more productive than New Employees. Both New Employees and Experienced Employees are laid off when the project is complete.

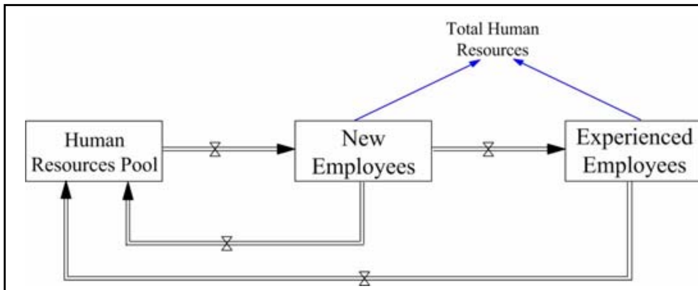

Figure 2: Human Resources

STOCK-AND-FLOW STRUCTURE FOR MATERIAL

Materials needed for the project are initially ordered based on the Project Scope. Orders received first enter the stock labeled Material at the Warehouse. Material at the warehouse is delivered to the worksite based on the number of tasks in the stock of Work in Progress, Rework in Progress and RFIs Answered. As tasks are completed, Material at the Worksite is depleted and this increases the stock of Cumulative Material Used. If the project completion rate is low, Material at the Worksite will not be used and will be returned to the warehouse. Inadequate Material at the Worksite leads to the underutilization of human resources, and therefore, slows down the Completion Rate (See the Impact of Material Inadequacy on Human Resources Utilization in Figure 1).

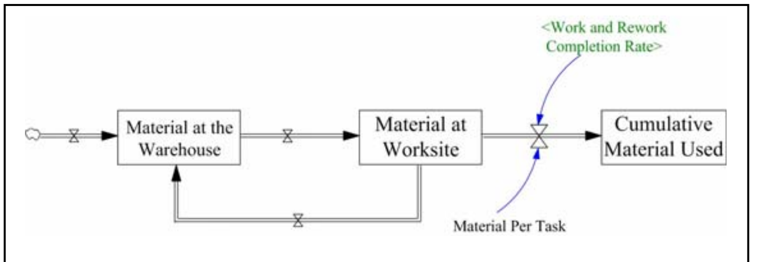

Figure 3: Material

STOCK-AND-FLOW STRUCTURE FOR EQUIPMENT

The structure for equipment is similar to that of material. However, equipment is utilized and can wear out, but it is not consumed in the same manner as materials. Equipment is ordered and delivered to the warehouse and is then sent to the worksite as needed. A change in the Project Scope may require ordering new equipment. If Equipments at the Worksite is underutilized it is returned to the warehouse. Lack of equipment at the worksite leads to the underutilization of human resources, and therefore, slows down the Completion Rate (See the Impact of Equipment Inadequacy on Human Resources Utilization in Figure 1).

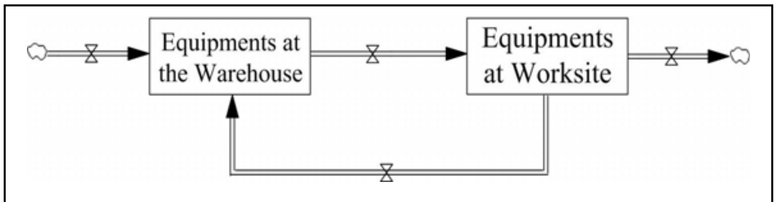

Figure 4: Equipment

STOCK-AND-FLOW STRUCTURE FOR MANAGEMENT CAPACITY

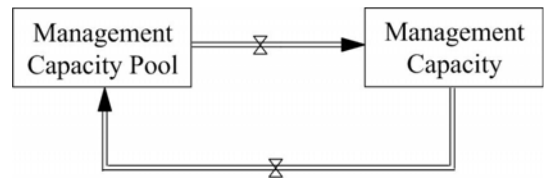

Figure 5: Management Capacity

Management Capacity can be expanded until people in the Management Capacity Pool have moved to the Management Capacity stock. The Management Capacity Pool represents the limit to which Management Capacity can be increased. Good management, however, is more than just the number of management personnel and retaining good management is challenging, particularly when there is a sudden demand to increase Management Capacity. Inadequate Management Capacity causes human resources to be underutilized (See the Impact of Management Limits on Human Resources Utilization in Figure 1).

STOCK-AND-FLOW STRUCTURE FOR PLANNING CAPACITY

The structure of the Planning Capacity is very similar to the structure of the Management Capacity structure described above.

BALANCING PROCESSES: GOOD JOB RHYTHM

There are several very important balancing processes that create good rhythms on the job and contribute to the completion of the project. Human Resources, Material, Equipment, Planning Capacity and Management Capacity are made available through a two-tier balancing process. Management's role is to bring together labor, material, and equipment in just the right proportions so that the project can be completed on time. When unexpected events occur, good project management allows adjustments to occur in all the necessary components. A balance between labor, materials, equipment and management capacity can therefore be maintained.

Figure 6 shows the two balancing processes that are involved in Human Resources. (Re) Work in Progress, Average Productivity and Completion Time Left determine the Desired Human Resources. The Human Resources Gap determines Net Hiring which increases (in the case of hiring) Total Human Resources. As the headcount rises the gap gets closed and the hiring of new employees stops. A higher headcount also increases the Completion Rate which, in turn, decreases (Re) Work in Progress. Figure 6 makes the point that these two balancing processes work to complete the project on time regardless of the level of productivity or the size of the project. Higher productivity or a longer completion time will reduce Desired Human Resources. The Completion Time Left variable adjusts the Desired Human Resources, and therefore, the headcount and Completion Rate, so that tasks in the stock of (Re) Work in Progress are completed on time.

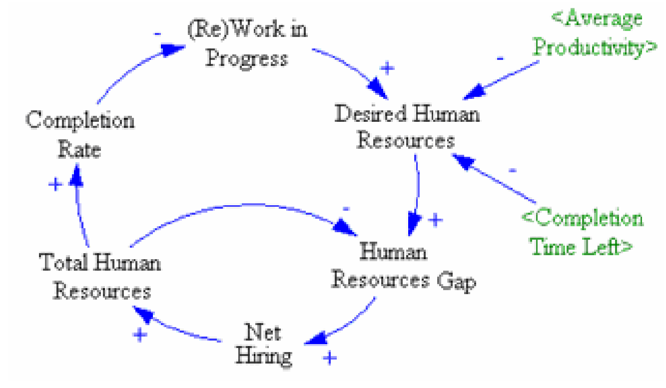

Figure 6: The Two-tier Balancing Process

HINDERANCE AND EXPEDIENCE OF THE GOOD JOB RHYTHM

1. Space (Area) Limit

The two-tier balancing process shown in Figure 6 can yield on time completion of the project even in the presence of a serious delay, provided there are no other resource constraints. The delay is offset by increasing labor, materials and equipment. However, due to space or area limitations, it may not be feasible to permit more than a fixed number of workers onto the site at any one time. If there is a physical space constraint, the project may not be completed on time.

2. Availability of Resources

The five resources identified in the model as critical for labor productivity can be scarce. It is often cost-prohibitive to obtain access to an unlimited supply of material and equipment in a short period of time. The pool of labor is often very limited, particularly when skilled labor is necessary. And there can be stiff competition amongst firms to retain good management and planning resources. If the project suffers from a schedule delay, Desired Human Resources needed to complete a project on time may exceed management's capacity to adequately manage the labor and the project may not be able to overcome the schedule delay.

3. Overtime

Allowing the use of overtime can increase the Completion Rate without hiring additional labor. The use of overtime (expending more than eight hours in a workday and/or working on weekends) is a management decision. Naturally, there is a limit to overtime - no one is able to work more than twenty-four hours in a single day. The extended use of overtime may have an adverse impact on productivity, which will be discussed below.

4. Learning Curve

As New Employees gain experience, their productivity increases which, in turn, raises the Completion Rate. The less time New Employees need to gain experience, the less need to hire additional people to complete the project on time. In the CPPM, the rate at which new employees gain experience depends on the number of new employees and a constant, the Time to Gain Experience. An increase in the Time to Gain Experience leads to a lower rate of flow from New Employees to Experienced Employees.

5. Willingness to Hire

Project managers may not be willing to hire additional labor at the end of a project. Therefore, they have to rely on overtime at some point rather than going through the process of hiring and training new people for a short period of time. It also captures the idea that labor may be unwilling to commit to working on a project if for only a short time. In the CPMM, management's willingness to increase labor declines towards the end of the project.

SIDE EFFECT AND TRAPS: BAD JOB RHYTHM CYCLES

1. Orchestration of Resources

The five essential resources needed for project must come together to complete a project on time. Lack of material will hinder the utilization of human resources. The time lag needed to obtain additional resources such as labor is different than that of equipment or material. While it may be easier to hire additional labor, expanding management capacity can be very time consuming and unrealistic. The imbalance between resources leads to underutilization one type of resource and the over utilization of another, which can distort the job rhythm.

In the CPMM, material and equipment availability as well a management capacity are measured on a scale between zero (0) and one (1), where zero is inadequate and one is adequate. If the influences from materials, equipment, and management capacity are all ones, labor is not constrained by these resources. If there is no material (equipment or management capacity), the impact has a zero value and available human resources will be underutilized.

2. Team Structure and its Impact on Productivity of New Employees

Hiring new employees increases the ratio of New Employees to Experienced Employees. Aggressive hiring strategies can lead to a team with relatively few Experienced Employees. Maintaining good productivity requires a balance between New and Experienced Employees. If this balance is skewed toward New Employees, the productivity of the new employees may be reduced further as they may receive less supervision. In the extreme case, there are no Experienced Employees to mentor the New Employees.

In the CPMM, as the ratio of New Employees to Experienced Employees exceeds the Acceptable Supervisory Ratio, Productivity of New Employees begins to decline and drops considerably if the ratio is significantly large.

The Vicious Cycle: The loss of productivity due to an imbalance between New Employees and Experienced Employees can go through a vicious cycle and lead to additional losses of productivity. Aggressive hiring increases New Employees relative to the Experienced Employees, which reduces the Productivity Generated by New Human Resources as well as the Average Productivity. As Average Productivity falls, there is a need for more employees in order to complete the project on time. Additional hiring of New Employees results in further reduction of productivity and the vicious cycle begin again.

3. Diseconomy of Scale and its Impact on Productivity

Project managers often expect a flat distribution of labor over the duration of the project. Expected number of employees depends on the Average Productivity and the Project Completion Time. Diseconomy of scale occurs when the number of human resources in the project exceeds the expected labor. When the total headcounts significantly exceeds the expected number of labor, productivity begins to fall.

In the CPMM, the Expected Human Resource Needs is determined by the Project Scope, Expected Productivity, and the Project Completion Time. This remains constant thought out the simulation unless there are changes in the Project Scope. If total headcount rises to 40 percent more than Expected Human Resources Needs, the Average Productivity falls.

<u>*The Vicious Cycle*</u>: Diseconomy of scale can fall into a reinforcing process trap. A lower Productivity caused by headcounts exceeding expectations may lead project management to hire more labor to compensate for the loss of productivity and this further decreases Productivity due to higher diseconomy of scale.

4. Fatigue and its Impact on Productivity

Utilizing overtime can increase the Completion Rate and decrease the demand for New Employees. However, extended use of overtime results in fatigue and thus lower Productivity and a reduced Completion Rate. When this occurs, demand for New Employees may be higher in the long-run.

<u>*The Vicious Cycle:*</u> The loss of productivity due to fatigue may become a vicious cycle. That is, project managers may use more overtime to compensate for the loss of productivity in an attempt to get the project back on schedule. This may work in the short-run, but if overtime is used to the point where severe fatigue sets in, Productivity will decrease and will result in a loss of overtime's initial gains.

5. Fatigue and its Impact on Rework

Overtime has a second way of hurting Productivity in the long-run. This occurs when overtime generates fatigue and fatigue generates mistakes that must be reworked before being accepted. Overall Productivity falls if the work on tasks must be performed more than once before the work is accepted.

6. Impact of Management Limits on Acceptance Fraction

Inadequacy of management capacity can also lead to a lower Acceptance Fraction of initially completed work and therefore more rework. In the absence of adequate management capability the standards of the quality of the work may decline and therefore the client may not accept the work.

7. Quality of Planning and its Impact on RFIs Fraction

If planning is rushed or if Planning Capacity is not adequate, it may hold up the project in a number of ways. It may delay the release of work to Work in Progress. Inadequate planning may lead to an increase in the number of RFI's submitted for clarifications. Additionally, inadequate planning may lead to submission of RFI’s just before the work is scheduled to be completed and thereby increasing the criticality of responding to the RFI’s in an expedited manner.

BEHAVIORAL IMPLICATIONS OF THE MODEL

The stock-and-flow structures and feedback loops are formulated and parameterized in order to analyze the behavioral consequences of the structure. In this section, we will examine four scenarios with the model: 1) Base Run; 2) Delayed Access; 3) Delayed Access and Aggressive Overtime; and 4) Delayed Access and No Overtime.

1. *Base Run, Good Job Rhythm*

Figure 7 shows the behavior of model under a “Good Job Rhythm” scenario. The model is initialized to represent a project that is just beginning with some planning already completed. Of the 7000 tasks that define the Project Scope, 6000 tasks are in the planning process and 1000 tasks that have already been planned are in the Work in Progress stock. The Project Completion Time is 20 weeks. As shown in Figure 7, planning is complete in Week 3 and access to the worksite is provided at the completion of planning. As a result, all 6000 tasks are moved to the Work in Progress stock (the red line in Figure 7) by Week 4. This stock should be considered as the work available to complete. A sufficient number of human resources (Human Resources Total) are initially available to complete the initial 1000 tasks. However, with the release of tasks from Work Planned to Work in Progress the Human Resources Total initially available is not adequate to complete the project on time. Therefore, the number of Human Resources Total (the gray line in Figure 7) begins to rise in Week 4 and levels off at about 300 people by Week 10. Work in Progress approaches zero at Week 20 as the project is completed as planned and on time. Work Accepted (the green line in Figure 7) continues to increase, although at a slower rate, due to evaluation of work done, remedial action and rework.

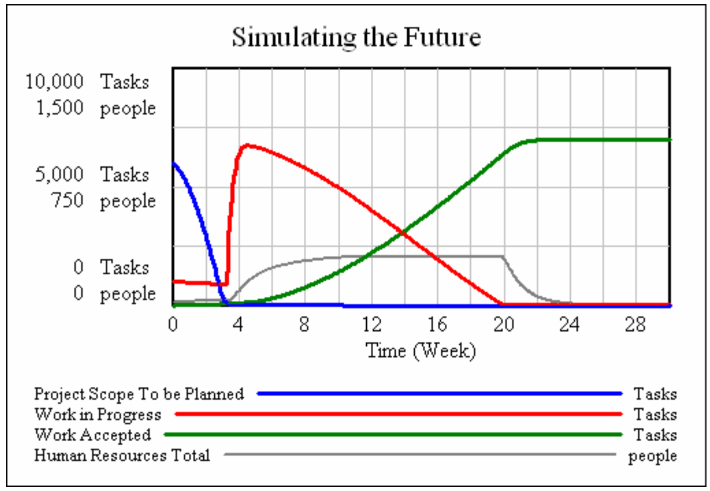

Figure 7: Model Behavior under Good Job Rhythm

Figure 8 depicts the impact of management capacity, materials and equipment on labor productivity. The variables labeled “Impact” indicate some type of constraint. Under ideal conditions these variables should have the value of one (1), which would indicate that labor has all of the required materials, equipment or management capacity required to complete the work. As shown in the Figure 8, Impact of Equipment Inadequacy falls below one when Work in Progress increases drastically in Week 4, but quickly returns to one as the necessary equipment is delivered to the worksite. Impact of Management Limits also drops below one and slowly rises back to one as more management personnel are assigned to the project. The Impact of Management Limits drops at a slower rate than that of Impact of Equipment Inadequacy as it takes time to perceive the inadequacy of management capacity. Similarly, Impact of Management Limits rises slower than Impact of Equipment Inadequacy because it takes more time to retain management capacity than it does to bring additional equipment to the worksite. Over Time Fraction begins to rise around Week 10 and approaches 1.25 (or 50 hours per week) for a short period of time towards the end of the project as management's willingness to hire additional labor drops and the pressure to hire more people to finish the project on time is translated into the use of overtime.

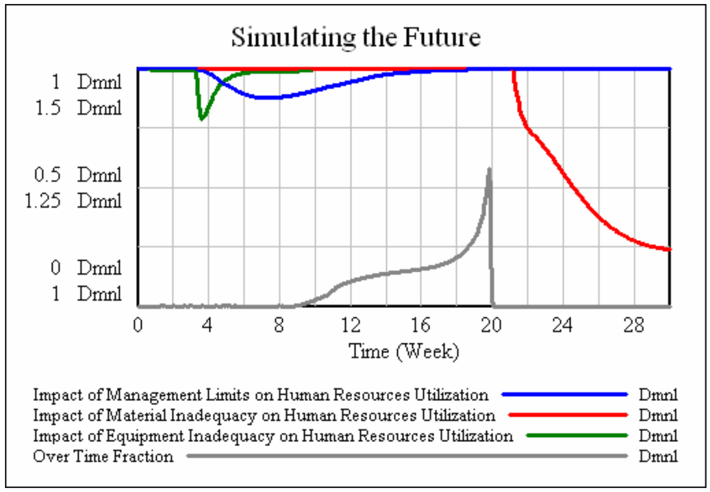

Figure 8: Model Behavior under Good Job Rhythm

Figure 9 shows the behavior of Real Productivity, New and Experienced Employees, and Cumulative Manhours used to complete the project. Real Productivity is measured as the ratio of Total Completion Rate (sum of the completion rates for Work in Progress, Rework in Progress, and RFIs Answered) and Human Resources Total. Real Productivity drops significantly around Week 3 when Work in Progress increases and new

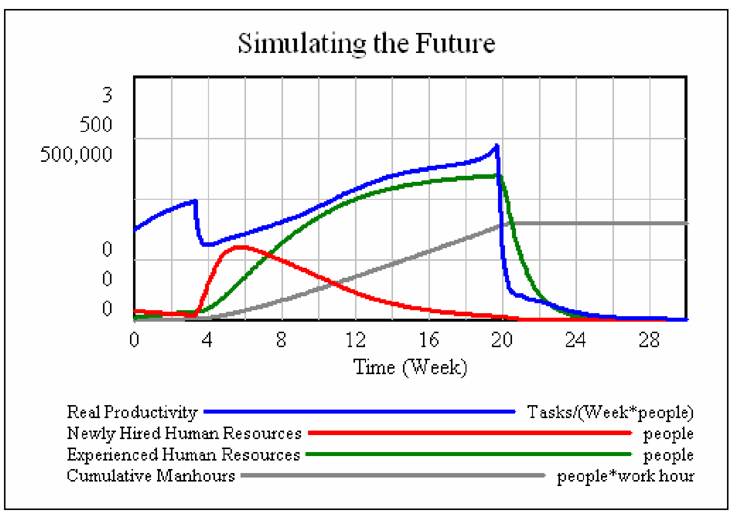

Figure 9: Model Behavior under Good Job Rhythm

employees are hired. The productivity of New Employees is lower than that for Experienced Employees and the hiring of a large number of new employees initially drives Real Productivity down. Real Productivity begins to rise as the new employees gain experience and become more productive. Real Productivity peaks toward the end of the project for two reasons. First, management stops hiring towards the end of the project and relies more on overtime to complete the project. The reduction in hiring results in a higher Average Productivity as the ratio of New Employees to Experienced Employees has changed in favor of Experienced Employees (the Experienced Employees have a higher productivity rate). In addition, the use of overtime increases productivity since more hours per day are being worked. The additional hours are being put in at the end of the project and the loss of productivity due to fatigue is less than the gain from working more hours per day. Cumulative Manhours increases steadily and levels off at about 200,000 manhours at the end of the project.

2. The Impact of a Delay in Access

In the Base Run access to the worksite is granted around Week 3 when planning is complete. In this run, we look at a scenario where access is delayed from Week 3 to Week 10.

Figure 10 shows the behavior of the model under the "Delayed Access" scenario. Every thing is held constant with the exception of access which is not granted until Week 10 instead of Week 3 used in the Base Run. Just like the Base Run, Project Scope To be Planned (the blue line in Figure 10) illustrates that all the planning is complete by Week 3 since access does not influence planning. Planned tasks are waiting to move to the Work in Progress stock as soon as access is provided. Work in Progress (the red line in Figure 10) begins with 1,000 tasks and this

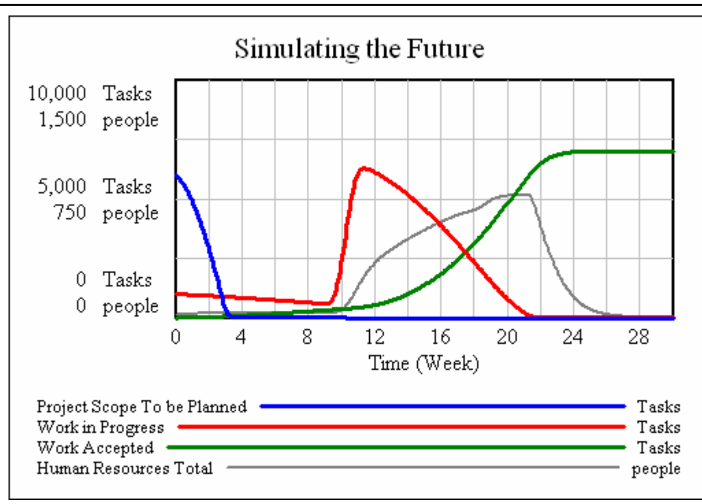

Figure 10: Model Behavior under Delayed Access

slowly decreases as tasks are completed, but the Work in Progress grows to over 6,000 when access is suddenly granted at Week 10, yielding a significant amount of work available.

Human Resources Total (the gray line in Figure 10) begins to rise after Week 10 in response to a drastic change in the Work in Progress stock. Project Completion Time has remained at 20 weeks, indicating that the tasks must be completed in 10 weeks, which is 7 weeks less than the Base Run. Such a significant decline in the Time Left to Complete suggests that the project managers must quickly hire labor to compensate for the time lost due to delayed access. Human Resource Total increases to 800 people, which exceeds a two-fold increase when compared to the Base Run. Human Resources Total begins to decline just before Week 22 when Work in Progress is complete. Work Accepted (the green line in Figure 10) rises slowly in the beginning, but the rate increases after Week 10 and levels off before Week 24 when the project is complete.

Figure 11 shows the behavior of impacts of management capacity, material and equipment on labor. Impact of Management Limits and Impact of Equipment Inadequacy behave in a similar way as in the Base Run. However, under this scenario, towards the end of the project overtime is utilized more than the Base Run due to the accelerated efforts to recover the delay in granting access. Furthermore, towards the end of the project, managers' willingness to hire additional labor is rather low and, therefore, the only way to increase manhours is through the use of overtime.

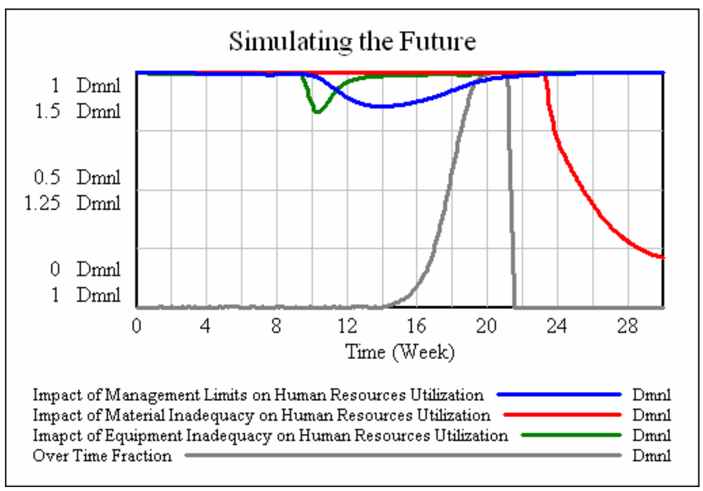

Figure 11: Model Behavior under Delayed Access

Figure 12 shows the behavior of Real Productivity, New and Experienced Employees, and Cumulative Manhours under the "Delayed Access" scenario. Real Productivity behaves in a similar manner as in the Base Run with one exception - it dramatically decreases around Week 10 as Work in Progress spikes. Under this scenario, Real Productivity falls more significantly than in the Base Run because of aggressive hiring, indicated by the sharp increase in Human Resources Total. Real Productivity begins to rise as new employees gain experience and more tasks are completed. Around Week 18 Real Productivity begins to fall again due to the impact of overtime on fatigue and therefore Completion Rate. This decline suggests that the productivity gained by overtime is less than the fatigue-induced productivity losses. Real Productivity continues to decline after Week 22, but this is the result of completing the tasks and there remains no task to complete.

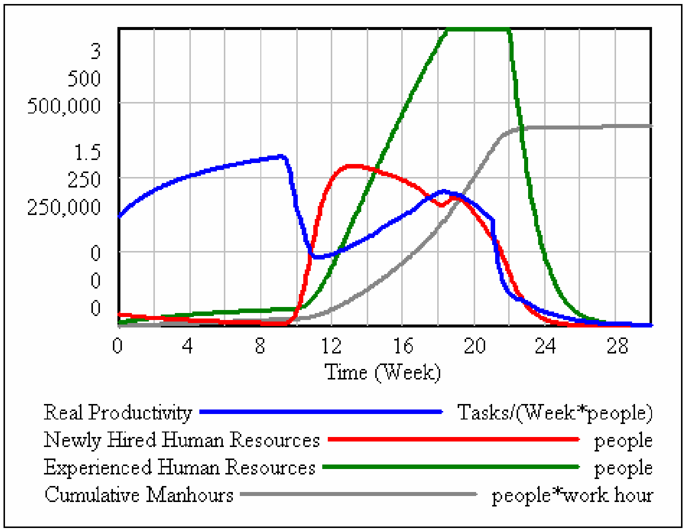

Figure 12: Model Behavior under Delayed Access

The number of New Employees rises slightly above 250 people and begins to decline as they gain experience and move the stock of Experienced Employees. Around Week 18, when productivity falls, the number of New Employees increases to compensate for the loss in productivity due primarily to fatigue. The number of Experienced Employees increases after Week 10 and levels off around Week 18 at about 500 people. It begins to decline at Week 22 when the tasks in the Work in Progress stock are completed and the project managers lay off human resources.

Cumulative Manhours increases steadily and levels off at about 330,000 manhours at the end of the project in the "Delayed Access" scenario. Figure 13 compares Cumulative Manhours between the Base Run and the Delayed Access scenario. In the beginning, Cumulative

Manhours rises slower in the Delayed Access scenario than in the Base Run because of delay in access to the work site. However, it exceeds the Base Run around Week 18 and levels off at 130,000 manhours more than the manhours in Base Run. This is due to the loss in productivity.

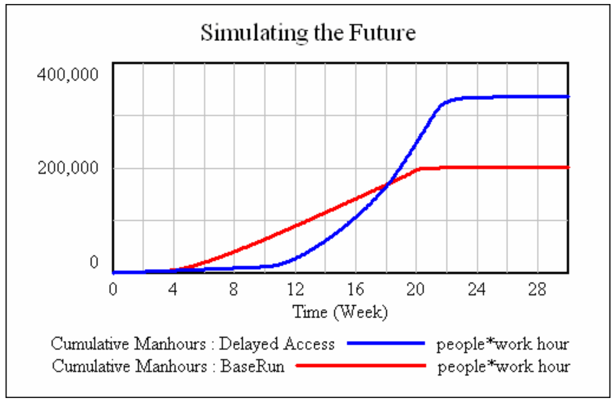

Figure 13: Cumulative Manhours Comparisons

The loss of productivity goes through two vicious cycles. First, in this Delayed Access scenario, overtime is used more to complete the project faster, which causes fatigue and leads to further loss in productivity. To compensate such a loss, even more overtime is used and that causes additional fatigue and additional loss in productivity. The second vicious cycle has to do with diseconomy of scale. In an effort to complete the project on time in the presence of a delay to access, project managers need to hire additional labor to accelerate the completion rate and finish on time. However, when Human Resources Total rises significantly above the expected level established at the start of the project, productivity declines and project managers may feel pressured to hire more even more labor to compensate for the loss in productivity. These two vicious cycles are the reasons for the drastic loss in productivity and the significant increase in Cumulative Manhours in the Delayed Access scenario.

3. Can An Aggressive Overtime Policy Solve the Problem?

One might believe that one way to prevent the loss in productivity when there is a delay in granting access might be to use overtime aggressively and early in the project so headcount would not increase as much. Figure 14 compares the behavior of Human Resources, Work Accepted, and Cumulative Manhours under three scenarios: Base Run; Delayed Access; and Delayed Access with Aggressive Overtime.

Figure 14: Comparative Graphs of Major System Performance

Human Resources under the "Delayed Access with Aggressive Overtime" scenario (the blue line in Figure 14) levels off slightly below 500 people from Week 14 to Week 18. The use of overtime provides the manhours needed to complete the project. Around Week 18, however, additional hiring is needed because of the loss in productivity due to excessive use of overtime. Hiring new employees continues until the number of human resources approaches reaches the physical space limit constraint set in the model. Work Accepted experiences a sluggish growth and does not reach 7,000 tasks before Week 30, which is the end of the simulation time.

Under this scenario, Cumulative Manhours exceeds 400,000 in Week 22 when less that 60 percent of the project is complete. In sum, in the presence of a delay in access, although aggressive use of overtime may appear to be advantageous in the short run, the productivity losses in long run are much greater. The project may be completed much later time and be significantly more expensive than contemplated.

4. Can A No-Overtime Policy Solve the Problem?

One might believe that one way to prevent the loss of productivity when there is a delay in access might be to prohibit the use of overtime. Figure 15 depicts the behavior of Human Resources, Work Accepted, and Cumulative Manhours under four scenarios: BaseRun; Delayed Access; Delayed Access with Aggressive Overtime; and Delayed Access with No Overtime.

Figure 15: Comparative Analysis of Major System Performance

Human Resources under the "Delayed Access with No Overtime" scenario (the blue line in Figure 15) reaches its threshold value, limited by the space limit constraint, earlier than other scenarios and for a longer period of time. The reason is that hiring is the only way to increase needed manhours. The Work Accepted curve finishes later than the BaseRun and Delayed Access scenarios. Cumulative Manhours accrue later than and in excess of the Delayed Access scenario, where overtime is moderately used late in the project. There is no loss of productivity due to the use of overtime, however, the additional hiring leads to productivity losses due to diseconomy of scale.

In summary, in the presence of a delay in access, moderate use of overtime is slightly more advantageous that no overtime. Moderate use of overtime leads to a faster completion of overtime and less cost.

CONCLUSIONS

In business, profitability is threatened by unexpected cost increases, revenue shortfalls and time demands. The construction industry is no exception. Completing a project where cost can be impacted by a wide range of variables, unyielding schedule pressure and the constant threat of unexpected impacts significantly challenge the capacity and capability of managers and owners. The industry functions on a large network of suppliers, specialty manufacturers and subcontractors. Orchestrating such a network for a given project can at times become a daunting and frustrating task. The reality of this effort becomes a dynamic interplay between many discrete activities, resources and time. The impacts, which arise during a projects life cycle, can significantly impact the project cost. Managers subsequently react to these impacts and, at times, make decisions that ultimately affect project cost and time without fully understanding the ramifications of those decisions on profitability and performance. Casual relationships between the impact event and cost can become difficult to identify and defend. The current tools available to management lack the robust capability to fully demonstrate the logical interrelationships, which affect project performance, time, cost and quality.

The Capital Project Management Model (CPMM) is a system dynamics model developed to link the interrelationships between significant contributing resources and simulate the effects of change events on project performance. These performance metrics include time and labor productivity. The simulation provides quantifiable measures of the impact of change in contrast to current empirical estimates. The model specifically allows an examination of various model attributes to measure the relative influences on driving labor productivity. Furthermore, the model offers decision makers insight into a number of leverage points, which can offer an awareness to more effectively implement decision making policy guidance.

One of the more significant results of the simulation, typically not adequately considered in the construction arena, suggests that "management capacity" is a crucial factor influencing productivity and delay. Strained or insufficient management limits the capability to adequately orchestrate the required resources. This imbalance can lead to inefficient use of resources without a corresponding increase in performance. For instance, underutilization of labor can be attributed to ineffective management through inadequate planning, coordination, labor, equipment and materials. As the projects fall behind schedule, management typically elects to employ additional manhours through any combination of overtime and hiring as a means to recover lost time. However, the model suggests that acceleration efforts can fall into vicious cycles and negatively influence productivity. These cycles can greatly erode costs and ultimately profitability. The impact from fatigue, diseconomy of scale with respect to crew size, inefficient deployment and planning and resource limitations also contribute to negatively influence productivity.

The CPMM offers a robust tool that greatly improves management's capacity to effectuate policy and decision making in an effort to efficiently manage the many project performance challenges that arise during the project life cycle. Cause and effect relationships can be more effectively demonstrated and accountability identified.

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