Delivery Time Reduction in Pulp and Paper Mill Construction Projects: A Dynamic Analysis of Alternatives

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Abstract

A system dynamics model was developed for a company looking to reduce delivery times in projects involving the engineering, procurement, and construction of complex equipment systems for pulp and paper mills. The model has some original features, particularly its portrayal of a critical path determined by the "gates" connecting sequential activities, which should be of general interest to project modelers. The model has helped the company identify practical ways to reduce delivery times by at least 30% and do so without driving up costs.

Background

The reduction of project delivery times has become a high priority for many companies who are looking for ways to become more competitive and to accomplish more with given resources. But delivery time reduction is not a simple task and may require sizable investments with uncertain payback periods. Simplistic attempts at project schedule compression may work to eliminate obvious areas of slack, but beyond that tend to reduce worker productivity and increase the amount of required revision and rework. Such side effects of attempted schedule compression drive up costs and may render compression ineffective if not counterproductive.

Companies must carefully consider the expected costs and benefits of alternative proposals for delivery time reduction and give the inevitable side effects their due. Conventional scheduling tools, such as the critical path method, can help in drawing out detailed schedule implications, but require input assumptions about activity durations, which in turn are directly related to assumptions about worker productivity and the need for rework. Only with an integrated dynamic model can one hope systematically to evaluate all of the important consequences which emerge and interact over the course of a project, and thereby get a realistic idea of what is likely to happen under the different alternatives.

A system dynamics model was recently developed for a company which manages the entire "EPC" cycle of engineering, procurement, and construction of large-scale equipment systems for pulp and paper mills. The model was developed so that the company might better assess the delivery time and cost consequences of streamlining or compressing their own activities, or those of their subcontractors and vendors, with the hope that key investments for change might lead to sizable delivery time reductions and rapid payback.

In developing the EPC project model we were able to draw on a long history of work in the area, including that of Roberts (1964, 1978), Cooper (1980, 1993), Abdel-Hamid (1989, 1991), Homer (1988), and Reichelt (1990). (See also Sterman (1992) for a general discussion of system dynamics project modeling.) Like previous models, ours portrays the flow of work from one project activity to another, distinguishes original basework from later rework, and represents workforce adjustments and variations in productivity. But the complex interdependency of EPC project activities has led to the introduction of model features which we believe to be both original and of general interest to project modelers.

Framework

An overview of the five-sector EPC model is presented in Figure 1. The "Workflows" sector includes twelve separate activities that characterize a typical EPC project for the company. Each activity involves a specified number of tasks that must be completed before they are passed on to the next activity. Some of these activities are performed by the company's own employees, some by subcontractors, and others by vendors of equipment and construction materials.

The "Workforces" sector portrays the changing sizes, workweeks, and schedule pressures of the design and construction workforces. These workforces report to the company's project management team, which, in turn, deals with the customer throughout the project. The "Project Management" sector tracks the various demands made on project management (PM), allows for changes to the size of the PM team and its workweek, and computes a ratio that expresses how well the PM team is keeping up with the demands placed upon it. When the PM ratio is less than 1, indicating some degree of inadequacy on the part of project management, all ongoing workflow activities may be hindered to some extent, and the quality of design work may suffer.

The sector entitled "Productivities, Fab Times, and Rework Need Fractions" contains constants and behavioral relationships which determine (1) productivity and quality of design, (2) productivity and quality of construction, and (3) duration times and quality for the various categories of vendor fabrication. In design and construction, productivity is computed as the minimum of a "potential" value and an upper limit implied by comparing work available with labor hours worked; if too little work is available relative to labor hours, actual productivity will be less than its potential. Potential productivity, in turn, represents the average skill of the workforce multiplied by effects of workforce size (productivity is reduced when the workforce grows large, due to problems of congestion and/or coordination), work pressure (an inverted-U curve with a point of optimal work pressure), hours per workweek (fatigue effect), project management ratio (productivity is reduced if the PM ratio is less than 1), and subcontractor fraction (subcontractors may increase coordination problems).

All of the factors affecting potential productivity in design and construction also affect the quality of those activities: A factor which reduces productivity will also reduce quality and, thereby, increase the need for later design revisions or construction rework.

Vendor fabrication activities are modeled in a simpler fashion than are design and construction activities, since (1) vendor workforces are not amenable to direct manipulation by the EPC company and (2) vendor costs are typically determined via fixed-price contracts before the project begins. But the model does identify two factors which may inflate fabrication duration times: (1) purchase order revisions (which may hinder or reverse progress), and (2) a low PM ratio (which may take the pressure off of vendors or cause them to stall for lack of sufficient support). Like duration times, the quality of fabrication may be hurt by excessive purchase order revisions, leading to defects which are passed along to construction if they are not first caught by quality assurance (QA).

The "Labor Costs" sector accumulates the burdened wages and salaries of the design and construction workforces and the PM team. Vendor costs are negotiated through fixed-price contracts and so are not treated as a variable item in the model.

The sequencing and interdependence of the various workflow activities is portrayed in Figure 2. The clock on an EPC project starts with a handshake, signifying agreement upon contractual terms and conditions, and ends with the first full production run known as Start-Up. The first phase of work is Process and Equipment (P&E) Design, which produces detailed plant layouts and drawings for processing vessels, major equipment, and minor equipment. Once P&E Design progresses far enough, Construction Design may begin, which produces detailed drawings for foundations and other construction materials. As designs are completed, Purchasing becomes involved in identifying potential vendors, evaluating their bids, and issuing purchase orders (PO's). Vendors then proceed to fabricate in their shops according to the PO's (and any PO revisions that may follow) and ship the completed equipment and materials to the construction site. The first stage of Construction may then occur, which is to lay foundations for the large processing vessels; then, as vessel components arrive to the site, a specialized team of vendors may initiate the erection of vessels. The multiple building phases of construction continue until the system is largely completed, at which time two types of testing or Check-Out are performed: Functionality Check-Out and Operational Check-Out. Start-Up occurs toward the end of Operational Check-Out, but the processes of final correction and tuning of the installed system continue to occur even after Start-Up has been performed.

The model contains a variety of unique "gate functions", indicated by the arrows in Figure 2, which determine how many tasks are available to perform in a particular activity at a particular time. The model portrays both "external" gates (found throughout the project), in which one activity is logically preceded by another, and "internal" gates (found in design and construction), in which the multiple stages within an activity may be viewed as an expanding sequence of branches. In design and construction, the number and types of tasks available are limited during the earliest stages of the activity and then increase--the internal gate opening--as a greater variety of work becomes possible.

When combined with activity durations, the gate functions determine the project's critical path. For example, construction can only proceed to a certain point based on the extent to which necessary equipment and construction materials have been received and vessels erected. Since the fabrication and erection of vessels are long lead time activities, vessels may lie on the project's critical path, meaning that construction may be delayed at some point (or made less productive) due to the absence of complete vessels.

Clearly, only two ways exist to remove an activity like vessel erection from the critical path: Initiate the activity earlier, or reduce its duration. Initiating the activity earlier will typically require that preceding activities, such as design or purchasing, be themselves compressed. Reducing a particular activity's duration may involve implementing measures both simple and complex, both inexpensive and costly. For example, the company feels that vendor contracts have traditionally contained a certain amount of slack time, which means it should be possible to achieve some inexpensive (if not cost-free) reduction of vessel-related lead times by simply requiring shorter lead time bids from prospective vendors. But more radical reduction of vessel lead times will probably require some form of vendor partnering, a venture which involves both risks and tangible costs for the company.

Figure 3 presents a generic view of how tasks flow within the activities of design and construction, and how workforce size is adjusted as an activity progresses. The logic of workforce-sizing is similar to that found in previous project models, but with one important difference: The indicated workforce size is determined not only by a comparison of total remaining tasks with remaining schedule, but also by examining the number of tasks currently available to perform (based on the gate functions and the detection of rework needs). It is possible, when critical path items are delayed, for there to be too few tasks available to justify a workforce as large as the schedule alone might suggest; for example, a construction crew may have to be temporarily downsized if critical materials arrive late.

Results

Before testing alternative strategies for delivery time reduction, the model was calibrated and validated against a wide range of data collected on one of the company's recently completed EPC projects. The model successfully reproduces historical data on all of the project's activities, covering workforces and labor hours, overtime and rework rates, purchase order volumes and PO revision rates, vendor shipments, and the progress of vessel erection and construction.

The model was designed to test strategic alternatives encompassing every phase of the EPC cycle. Some alternatives may be implemented almost immediately, including changes in the use of overtime, changes in allowable workforce ceilings or construction shift ceilings, and the removal of perceived schedule slack in vessel fabrication contracts. Other alternatives would likely require two to three years to implement and some dollar investment as well, including vendor partnering, engineering automation, and construction modularization. The testing of these strategies was supplemented by a sensitivity analysis that focused on key vulnerabilities that can inflate delivery time and costs, including the possibility of inadequate pre-sales engineering, unanticipated scope changes, difficult customer relations, and inexperienced workforces.

Graphical results from three typical strategy simulations--entitled "Baseline", "Feasible Today", and "Future"--are presented in Figures 4 through 7. (Increments of time are expressed in "time units" at the company's request.) Figure 4 shows the progress of construction in percentage terms; Figure 5 shows total cumulative labor hours across all company and subcontractor workforces; Figure 6 shows the combined engineering workforce, including P&E Design, Construction Design, and Project Management; and Figure 7 shows the construction workforce.

The baseline run assumes a standard set of conditions and achieves a project delivery time of 80 time units which is the traditional standard for the company. Of particular interest in this simulation is the slowdown in construction progress that occurs around time unit 65 and the temporary downsizing of the construction workforce that results. The slowdown occurs because some of the major vessels which lie on the critical path are still being erected, making it impossible to move on to certain construction tasks in the vicinity of the vessels.

The Feasible Today run assumes only certain easily implemented improvements that take vessels off of the critical path and allow for more rapid work in construction; in this simulation, a delivery time of 70 time units is achieved without any increase in costs over the baseline run. The Future run goes several steps further, by introducing certain longer-term improvements; in this run, a delivery time of 55 time units is achieved and actually at lower cost. The lower cost of the Future run is largely attributable to improvements which reduce the required engineering workforce (see Figure 6) as well as the number of design revisions and the need for rework throughout the project. Other key improvements also allow for earlier vendor deliveries and, consequently, much more rapid progress in construction.

In general, the model suggests that a small number of leverage points exist allowing for significant delivery time reduction without increased costs. The model also identifies policies for schedule compression that initially looked promising but now appear either (1) insufficiently effective relative to their cost of implementation or (2) counterproductive from a cost or schedule standpoint. For example, simple increases in workforce or workweek ceilings may lead to lower productivity and quality of work and thereby end up doing more harm than good.

Conclusion

The company feels confident that the dynamic model does a good job of representing their typical EPC projects and allows them to do strategic analysis with greater precision and understanding of the problem as a whole. The model has been used to demonstrate that project delivery times can be reduced by at least 30% over the next few years, and has been used by management to justify certain investments the value of which was formerly questioned. Confidence in the model was much enhanced by the inclusion of realistic gate functions, a feature not seen in previous project models, and one that embraces and extends the notion of a critical path in complex construction projects.

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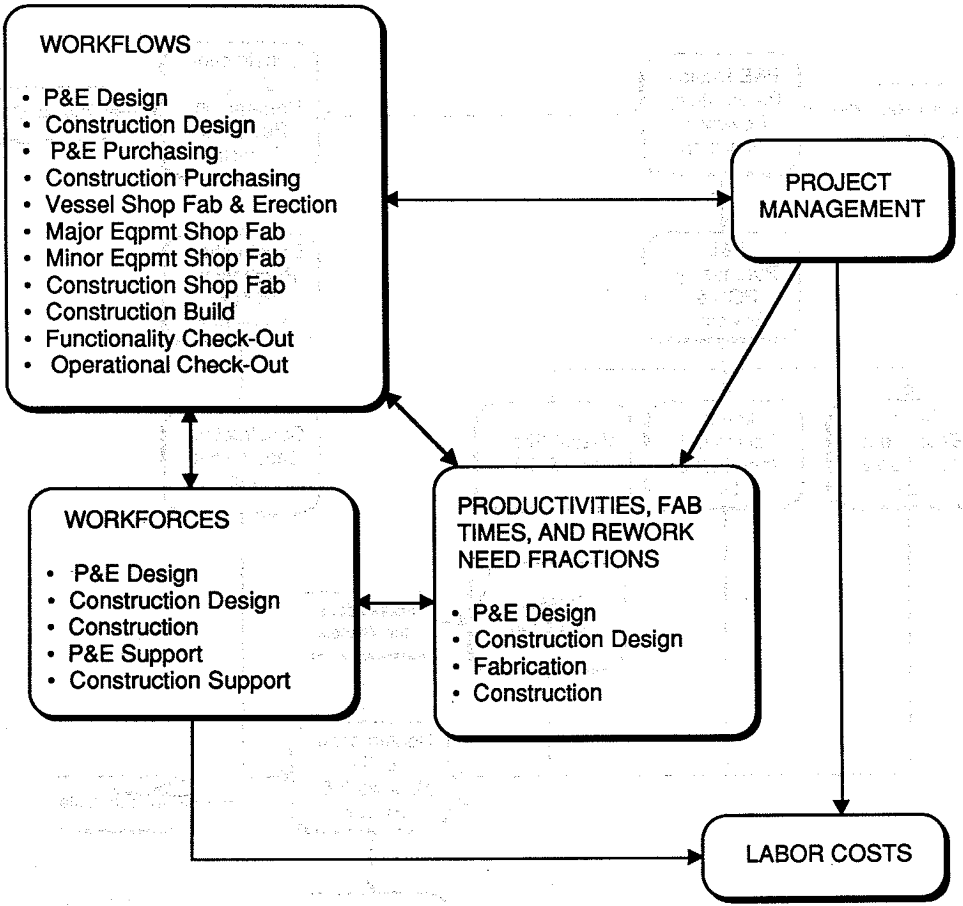

Figure 1. Model Overview

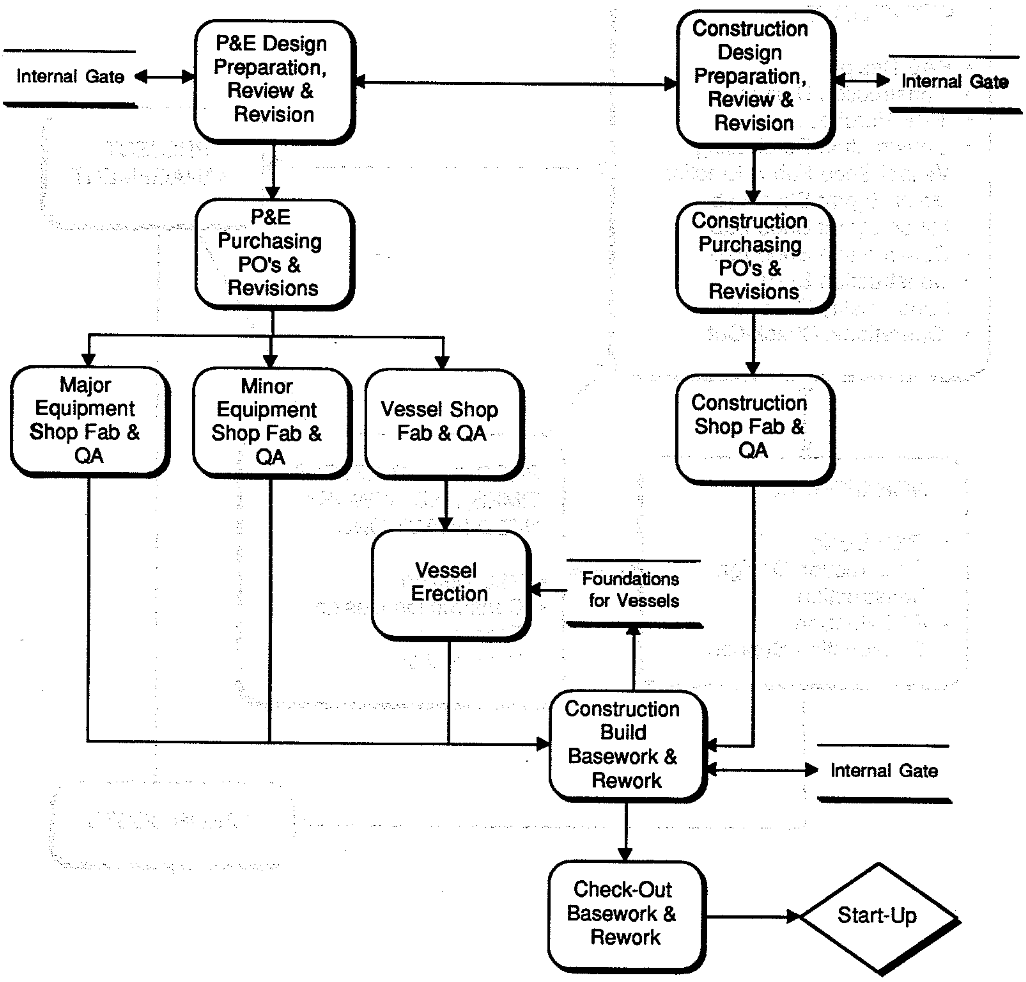

Figure 2. Activities Sequence and Gates

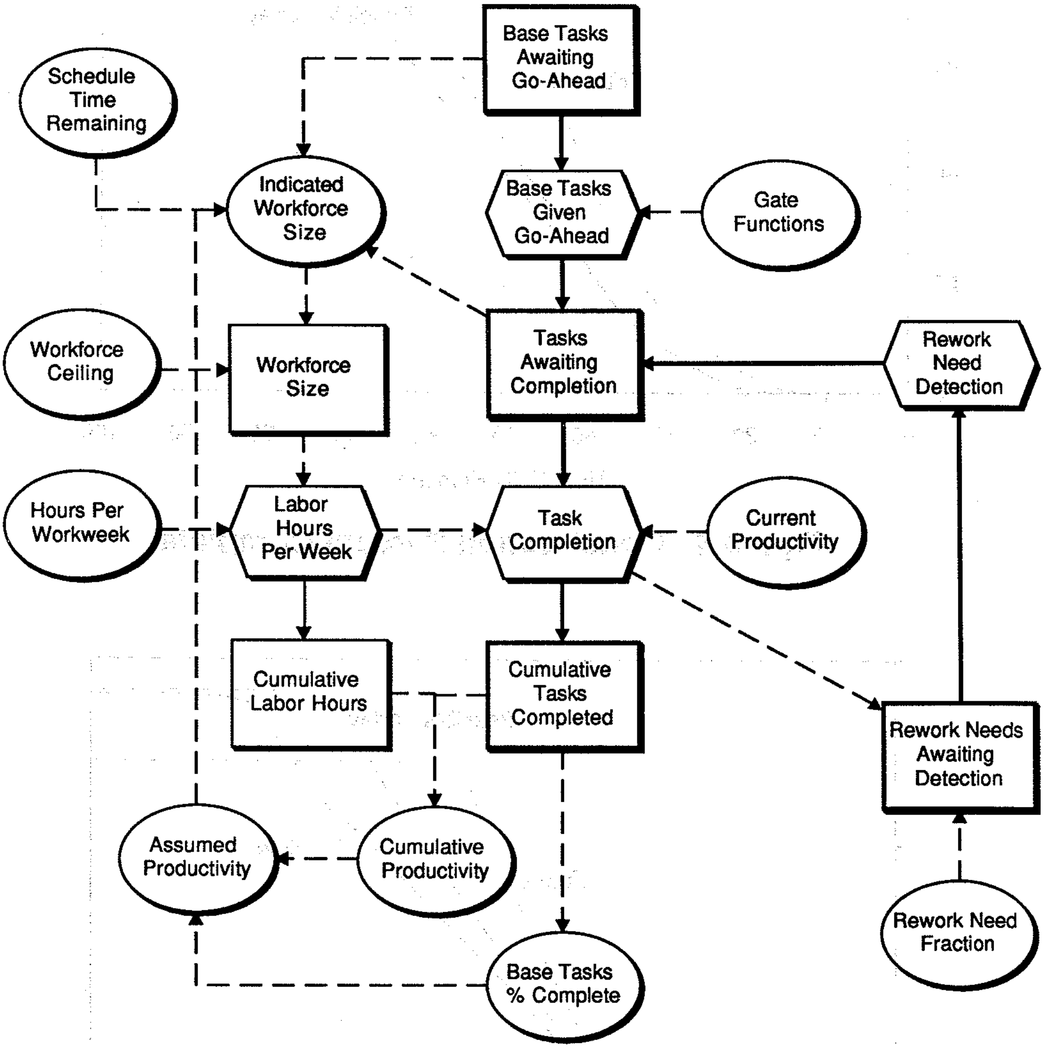

Figure 3. Task-Flow and Workforce-Sizing Logic

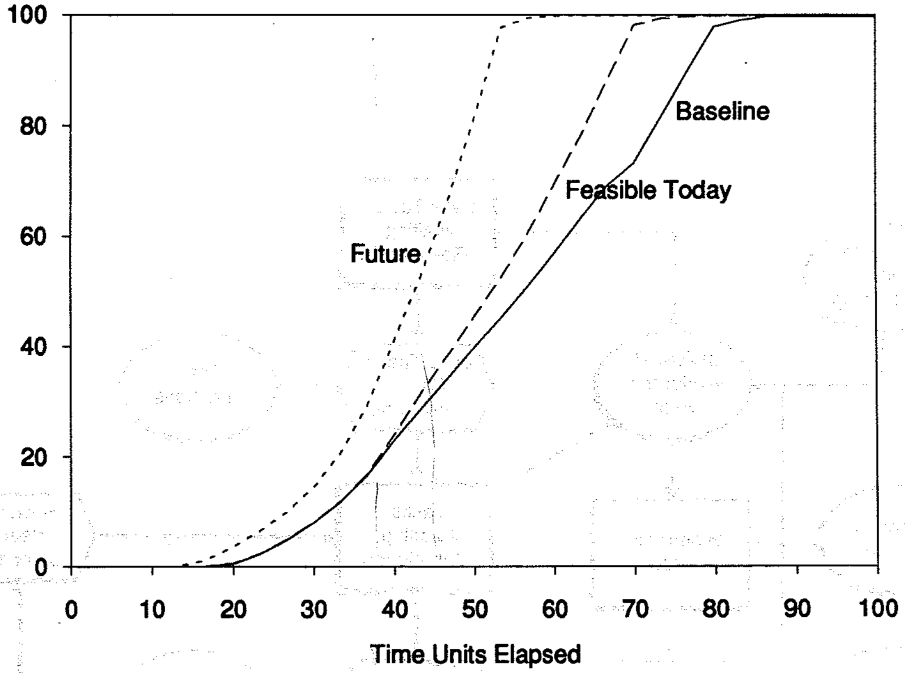

Figure 4. Construction Percent Complete

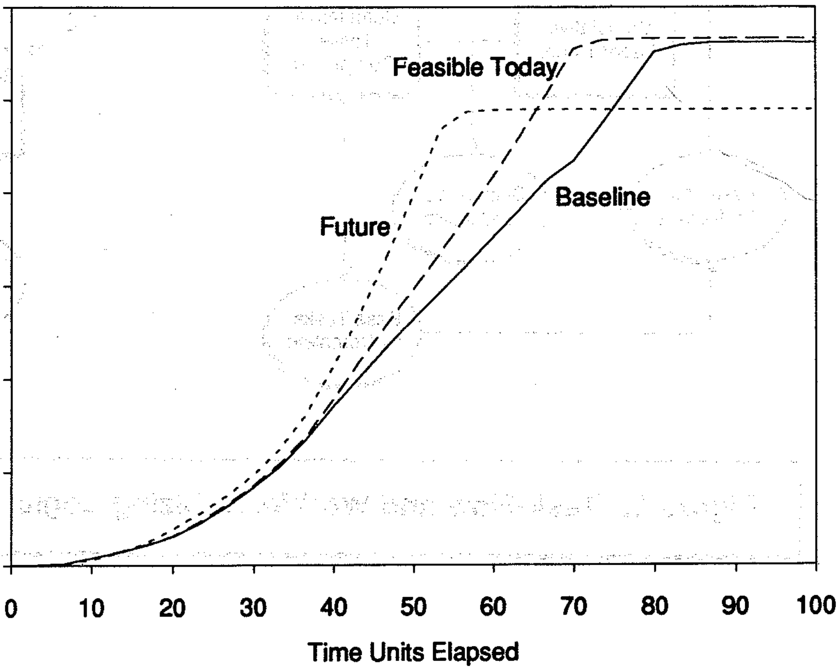

Figure 5. Total Labor Hours, Cumulative

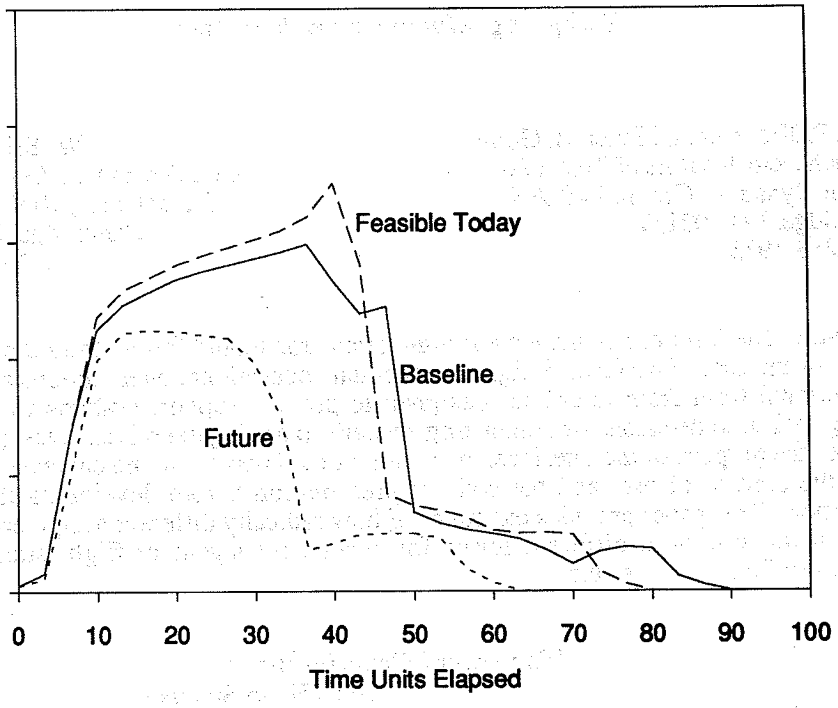

Figure 6. Combined Engineering Workforce

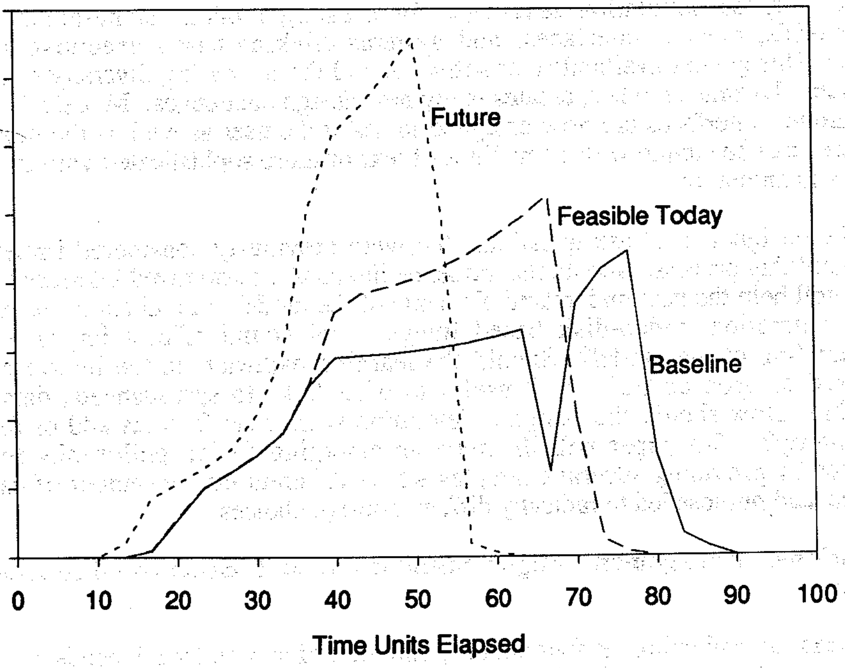

Figure 7. Construction Workforce