Interaction between subcycles - One key to improved methods.

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ABSTRACT: The relationship of one subcycle to another can be complex. Productivity suffers when the output of one subcycle delays a following step or when resources required for one subcycle are engaged in another subcycle. Isolating subcycles from immediate interaction with other subcycles is an important principle in the design and improvement of work methods. While interaction cannot be eliminated, the negative effect of immediate interactions can be reduced with careful provision of buffers and shared resources. Five cases demonstrate different aspects of this concept. A review of 31 performance improvement cases shows that reducing the immediacy of interactions between subcycles is an effective method used by supervisors to cope with the uncertainty. Reducing immediate interaction through the provision of buffers and/or shared resources will be the most effective technique for eliminating performance-reducing interactions until greater control is achieved over the rates of supply and use of resources. A process for the design and improvement of work methods based on these concepts is offered.

Introduction:

The relationship between the construction methods applied by crews and the systems that supply resources is intimate and immediate. The details of the methods used by the crew are constrained by the specific resources supplied and the rate which they are supplied. Work must slow or stop and workers are delayed when any resource is unavailable (Borcherding et al. 1980, Tucker et al. 1982, Chang and Borcherding 1986, Adrian 1987, Oglesby et al. 1989). Because of this relationship, changing the work method to increase the installation rate may have little lasting effect unless a backlog of resources is at hand or the rate of supply increases. The rates of resource supply and consumption are difficult to match because both rates are unsteady, not well controlled, and can only be estimated until initial cycles are completed (Bernhold 1989, Koskela 1992). Hence, continuous planning is required to adjust to the developing situation (Lemna et al. 1986, Shohet and Laufer 1991, Laufer et al. 1992).

Two strategies emerge in the face of this uncertainty. The first is to reduce uncertainty by gaining control over the rates of supply and use of resources. The second is to cope with uncertainty by reducing either the level of required performance or the immediacy of the interaction between supply and use subcycles .

The advantages of gaining control of supply and installation processes have been shown in other industries and are well documented in the automotive industry (Womack et al. 1990). In construction, as in other industries, this is not a simple matter because of at least two obstacles, both related to uncertainty. First, no single authority can assure or improve the rate of support system output. Since systems cut across commercial and/or contractual boundaries any number of people can slow or stop the process. Second, interactions between subcycles make it difficult to determine in advance the details of the work method and the precise rate of production.

This paper demonstrates that reducing the immediacy of interactions between subcycles is an effective strategy employed by supervisors to use available resources more efficiently. Drawn from the application of common sense, this concept provides practitioners and academics with one principle for designing and improving construction operations.

After defining terms, five case studies explore the relationship between uncertainty, reduced immediacy of interaction, and improved performance. Summary results are then reported for 31 studies in which an improvement in performance was documented. Based on these 31 cases, a process offered for the design and improvement of construction operations which formalizes the intuitive methods used by experienced supervisors and foremen.

Sources of Interaction:

Subcycles interact because they are linked by intermediate products and/or process requirements. These interactions cause resource and worker delays (Emery 1975, Perrow 1984, Brandlhuber 1991). Intermediate product linkages exist when the input for a following activity is provided by the output of a preceding activity, i.e., when a following activity and workers must wait until the preceding step(s) deliver the required products. Intermediate products produced by a preceding step and required for a following step include information and/or actual physical output. Depending on the circumstances, these intermediate products either must be processed immediately (as in the application of an epoxy coating), or may be stored in a surge pile or buffer (as in a rock quarry). In simulation terms, these buffers are called *queues* (Halpin and Woodhead 1976). Interaction between subcycles is reduced as buffers compensate for differences between the rate and/or sequence of supply subcycle output and the requirements of the using subcycle. While buffers do not eliminate the sequential relationship between subcycles, they do reduce the delays caused by the interaction and the related need for close coordination (Emery 1975).

Interaction also exists when resources are shared between two or more activities. Work cannot proceed on one cycle because it requires a resource -- such as a crane, ladder, work area, or worker -- currently employed in another operation.

Delays due to interaction from intermediate products or shared resources occur if all necessary resources are not on hand when required. Thus delays may develop from a failure of a previous cycle or supply system, from an adjacent or leading crew, or from variations in cycle time within the work process itself.

Degrees of Linkage:

The immediacy of these interactions can be described in terms of tight or loose linkages. *Tight linkage* means no slack exists between steps of an operation: one cycle immediately affects the following one(s) where no buffer or queue exists between cycles. The sequence of steps for lifting materials with a crane, for instance, is "hook, lift, unhook." The only step that can follow "hook" is "lift," and the only step that can follow "lift" is "unhook." The sequence repeats itself, of course, but no individual step can be repeated prior to completion of the previous step.

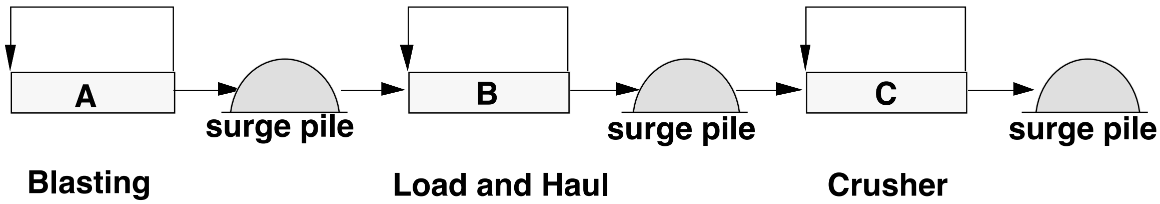


Figure 1

Loose linkage means the subcycles within a larger operation may proceed with little interaction -- for example, intermediate-product surge piles between two cycles in a rock quarry allow both cycles to proceed without interference up to the limits of the buffers (Bernhold 1989). In Fig. 1, loose linkage is maintained by a buffer between the blasting operation (A) which breaks rock from a wall, and the loading-and-hauling operation (B) which carries the rock to a crusher. Another surge pile at the crusher (C) buffers the intermittent arrival of trucks and the continuous operation of the rock crusher. While the trucks' average rate of delivery and the crusher's crushing rate will be the same over a long period, the surge pile allows trucks and crusher to operate continuously and independently by preventing interaction between operations.

Tightly-linked processes may be quite productive when up and running because the work, workers and equipment are not delayed, work in process (WIP) inventories are low and through-put is high (Goldratt 1985). But tightly-linked processes are tricky to start and easily disrupted because the sequence is usually invariant and the interactions immediate. Failure or delay of a subcycle in a tightly-linked assembly process causes an immediate delay in "downstream" cycles, while "upstream" products pile up. For efficient operation, the intermediate products and process resources must be supplied to each subcycle in precise quantities and at the correct time; little slack is allowed, or the process must be redesigned to accommodate supply variations. Intermediate product-linked operations become less fragile if buffers are introduced to absorb the variation in cycle times -- essentially, reducing interaction by loosening the linkage between subcycles.

Tightly-linked operations can minimize both slack resources and intermediate-product inventory if the supply of requirements is reliable, that is, if variations in cycle times can be controlled and the subcycles synchronized and balanced to minimize delays. While tightly-linked operations are efficient when control and balance are achieved, actual cycle times in construction are difficult to predict and control with precision. Assembling the required combination of resources at the proper rate can be difficult when numerous sources of uncertainty and interaction exist. To avoid disruptive interactions in tightly-linked subcycles with fluctuating cycle times, either (1) control information must be collected and processed while work is in progress or (2) linkage must be loosened.

Before work begins, production rates are only estimates, so achieving a synchronized and balanced state requires that the subcycles essentially be freed from immediate interactions so that accurate cycle time data can be collected. Sufficient stockpiles of the resources must be available so the causes of variations within the operation can be identified. Thus the costs of achieving a synchronized and balanced state include: assuring a stable environment around the operation; insuring a steady supply of resources; collecting duration and variation information on subcycles; removing the causes of variations; providing the additional resources necessary to balance production; and eliminating defects from the subcycle products. While these costs are often relatively small compared to the cost of an unbalanced operation (particularly on equipment-paced operations typical of earth-moving), the balancing process may not occur due to the pressure for production and the limited authority of field supervisors and foremen (Oglesby et al. 1989).

Synchronization and balance are not required in loosely-linked operations. If the buffers are large enough to allow a subcycle to operate without immediate interaction from other subcycles, required products are available despite fluctuations. Likewise, providing more units of a previously-shared resource will loosen a tightly-linked operation. In both cases, previously interacting subcycles now have the freedom of multiple repetitions because the start of an iteration does not depend on the finish of a previous cycle.

Loosely-linked operations are flexible; that is, they can absorb the uncertainty caused by variations, short-term failures, or changes without destabilizing the larger operation. Delays within subcycles can be accommodated up to the length of time required to consume the intermediate buffer. While the productivity consequences of loosened linkage in uncertain situations are obvious, the change to loosely-linked operations can raise issues of quality, interface, and inventory control. The costs of looser product linkage include the materials stored in the buffers, the space occupied by the buffer, extra handling steps, and the potential for increased quality control or rework costs if errors in preceding steps are not immediately identified.

The following examples were drawn from 31 cases collected by the authors and their associates, or by students in productivity-improvement courses. These 31 cases were selected for review because significant details are available and because before-and-after performance can be measured. The cases chosen for presentation here are typical of the larger sample.

A word of caution: these cases are not unusual. All were recorded on profitable jobs. Like most construction operations recorded in detail, each contains significant opportunity for improvement. They reinforce Koskela's observation (1992): "In most activity flows in construction, it is more profitable to initiate process improvement activities than to automate parts of the present activity flow." At first it may appear that the operation "*should*" have been planned and resources provided so that workers could use the final, improved method from the start. This ignores the reality that supervisors, foremen and workers are seldom completely familiar with the specific job-site conditions of a given operation. This results both from the diffusion of responsibilty for the design of work methods and the uncertainty which remains up to the start of work.

The reader is also urged to avoid taking the "moralist" position that these sorts of things "should not happen." If uncertainty were extremely low, detailed plans could be developed well before operations began and there would be little to learn or improve. We suggest that those who hold this "moralist" position study closely the circumstances in which work methods are designed and employed.

Interaction Due to Intermediate Product Linkage:

<u>The cable-cutting case</u>

A cable-cutting operation consisted of five tightly-linked steps, as shown in Fig. 2.

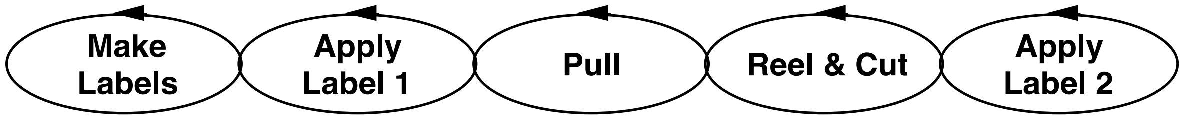


Figure 2

Since no buffers existed, every subcycle waited on the product of a preceding step. In the "Before" situation (Fig. 3a), worker A prepared and applied a label to each end of a cable. Worker B pulled, measured, rolled, and cut the cable. Instead of continuing to write labels, worker A warmed his hands and pen while waiting for worker B to finish cutting and rolling. The complete process for each cable required nine worker minutes.

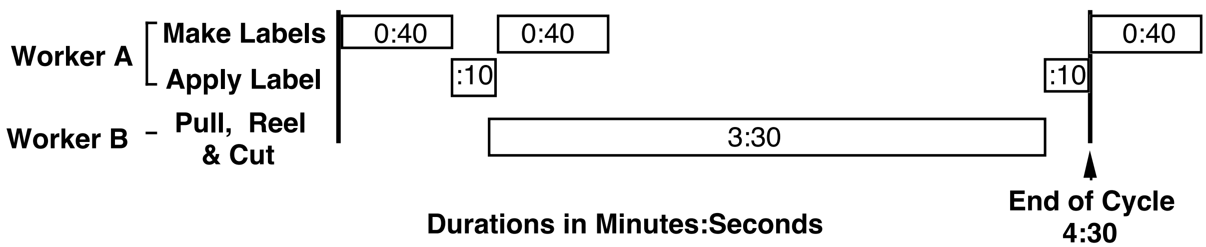


Figure 3

Worker delays caused by the interaction between the label preparation and the reel-and-cut subcycles were established when the operation began. They resulted in part from the physical location of the cable reels, the shape of the work area, the extremely cold weather, and the relationship of the cable-cutting operation to the cable-installation operation. It was impossible to judge the cable-cutting performance against a budget because cable-cutting costs were included in the estimate for cable installation. The contractor was making a profit on this project and, during a site tour, saw no particular problem with the operation. He commented that everyone looked busy.

Reducing the immediate interaction between label preparation and the remainder of the operation improved performance. The linkage was loosened as label preparation was shifted from a step in the work method to a resource supply process. As shown in the "After" situation (Fig. 3b), a "surge pile" of labels was prepared in an office by worker A ahead of the actual cable-related operations.

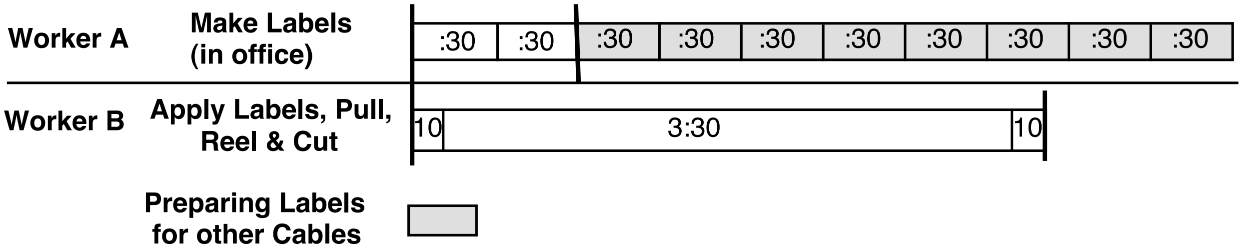


Figure 3 b

Worker B was then free to reel and cut as quickly as possible. While the cost of the change included the time for replanning and the provision of a work space and equipment for label preparation, the cost of the whole operation was cut nearly in half to 4.83 worker minutes per cable. Fig. 4 shows the resulting operation.

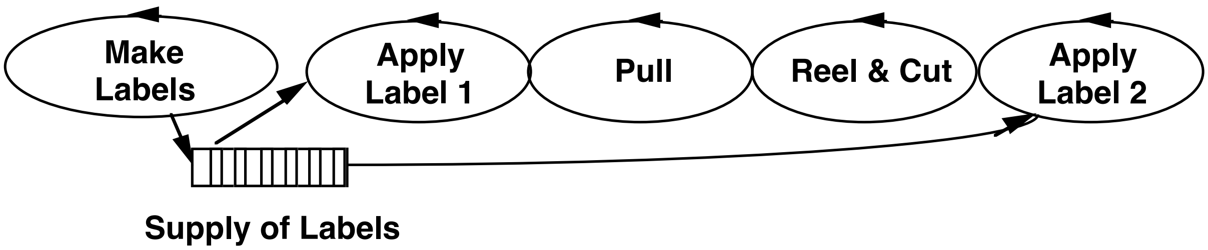


Figure 4

This new process also affected the crews which were installing cables. They were now required to order needed cables 24 hours in advance. In return for the effort required to increase planning lead time, the installation crews were able to draw from a stockpile of cables on hand. The result was fewer delays waiting for materials.

Interaction Due to Shared Resources:

Interaction due to shared resources can be more complex, since product linkages are often involved as well. Three examples show the effect of reducing shared resource related interaction.

Placing Concrete with Buckets

Placing concrete with a crane and bucket is a classic productivity study. In an operation using a crane and one bucket, the steps are: fill, lift, place, and lower-and-spot the bucket. Typical durations for the operation are shown in Fig. 5a. The problem is that the same resources -- the bucket and crane -- are required for all steps in the operation; thus all steps are tightly linked. The crane remains idle while the bucket is filled.

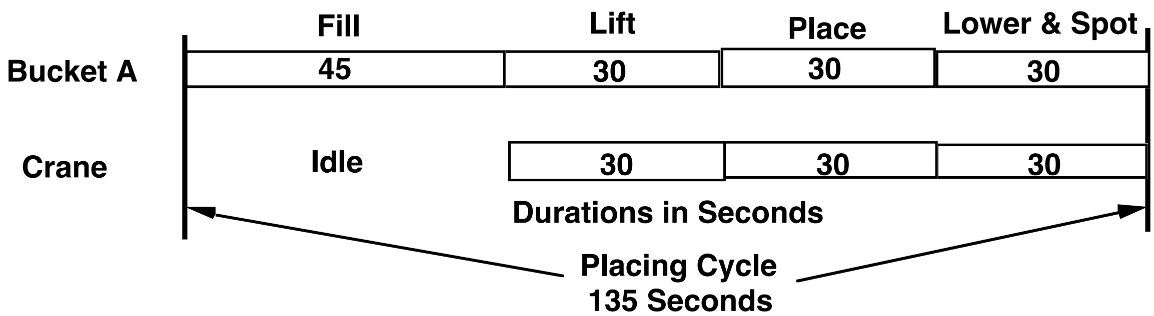


Figure 5 a

Here the problem is not so much uncertainty as it is the ability to acquire additional resources. The simple solution is to add another bucket. Provision of a second bucket loosens the relationship between cycles since the fill cycle can now proceed independent of the crane. In essence, the delay in the crane cycle has been reduced by the provision of a less-expensive slack resource. Switching concrete trucks without interrupting the placing operation is easier with the extra bucket. In this case, provision of an additional bucket resulted in a savings of about 24%

(Fig. 5b). In the same vein, the solution can be further developed by providing room for two concrete trucks.

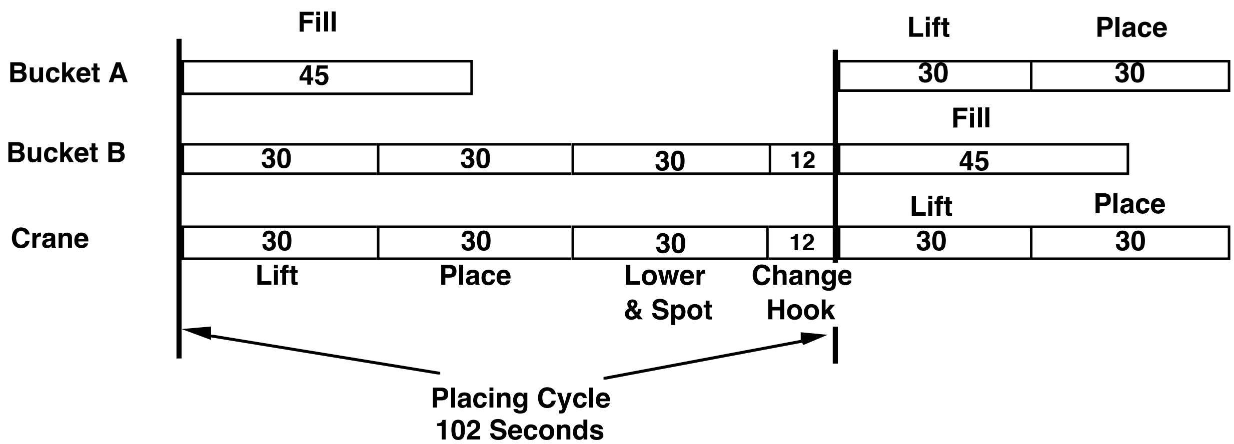


Figure 5 b

Both the concrete supplier and the placing and finishing crews had to work more quickly, since they were linked to the studied operation. The concrete supplier reacted favorably to the reduction in on-site time for each truck, but the placing crew was less enthusiastic about the change -- they initially lacked sufficient tools and workers to handle the concrete at the higher delivery rate.

<u>Pipe-rack Loading</u>

The initial work method was straightforward. Pipe sections brought to the work site on a trailer were lifted to a scaffold by a small hydraulic crane. The pipe was then aligned and tacked in place before being pulled forward to a weld-out station. The need to share the crane with other operations outside the building that contained the pipe-rack was a major source of uncertainty. As a result pipe was often unavailable (Fig. 6).

When the case was recorded, the crew had a several-week history of completing just four 12 m (40 ft.) sections per 10-hour day -- an average of one section of pipe every 2.5 hours.

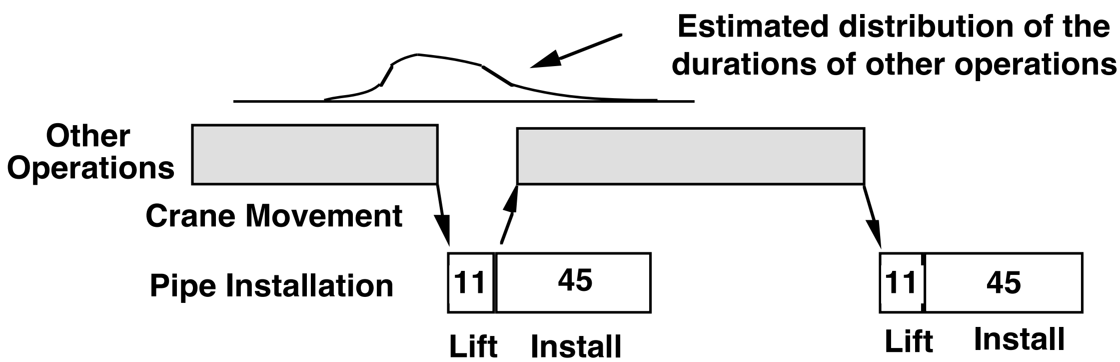


Figure 6

The steps in the operation required only .75 hours once a crew had a piece of pipe at the work level, which meant the crew waited on average about 1.75 hours for the crane to return and deliver pipe (Fig. 7a). Uncertainty as to the availability of the crane (due to the requirements of other operations and an occasional blocked entrance to the work area) made it difficult to maintain production inside the building. Likewise, supervisors of other operations could not predict the return of the crane since the building exit was often blocked by crews doing other work.

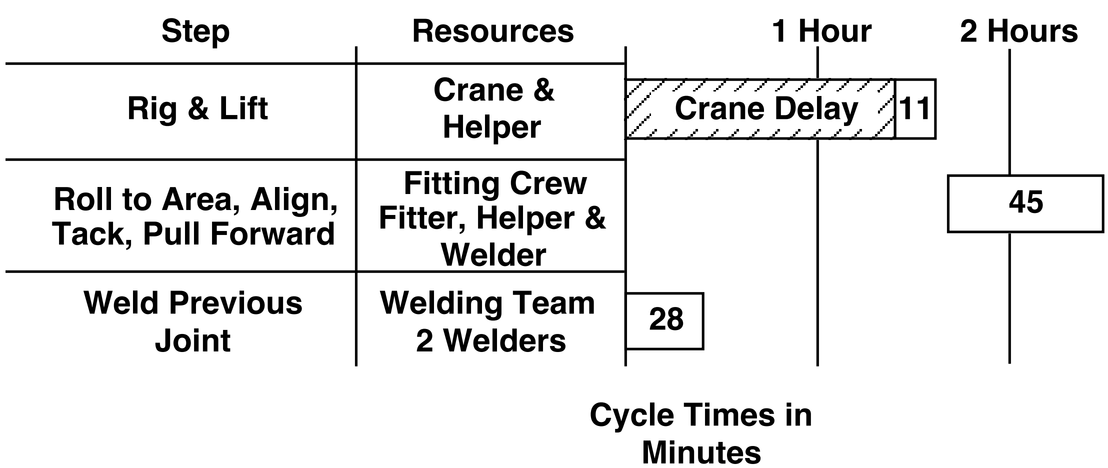


Figure 7 a

Two solutions were apparent, both of which loosened the linkage between the pipe-rack loading and the other operations. The first was to provide a crane for the sole use of the pipe-rack installation crew. The piping superintendent inside the building liked this idea because it offered him an additional resource to support other building-related operations. This solution was rejected as expensive and risky, however, because it contained the seeds of the original problem: shared resources in a highly-uncertain environment.

The other solution, which was adopted, was to extend the scaffold to allow a full day's supply of pipe to be lifted in one crane visit. Thus the process was replanned to eliminate delays arising from crane availability.

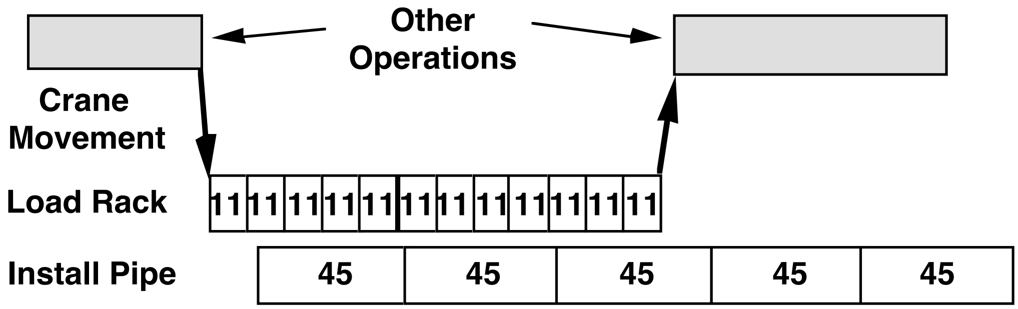


Figure 7 b

The result was a 66% reduction in the time required to install a pipe section (Fig. 7b). The successful plan loosened but did not completely sever the linkage. The supervisor's attention shifted from trying to find a crane for each piece of pipe to managing the relationship between the surge pile and the crane. The crew reported significantly increased morale; in particular, the welding crews were able to concentrate on welding rather than merely trying to look busy. The details of the impact of this change on other operations is not recorded but the greater flexibility in the crane time allowed other supervisors to better coordinate their own operations.

Pier Cap Handrails

Lowering and lifting 6 meter (20 foot) sections of pier cap handrails required a crane and a two-worker crew. At the time of the study, 65 pier caps remained uncompleted. Moving the forms between pier caps required lowering and lifting 12 sections of handrails. The lowering operation required the crane to (a) move into position, (b) attach to the handrail, (c) hold while 12 bolts were removed, and (d) lower the section. Raising the handrails simply reversed the operation.

The raising or lowering subcycle is linked to other operations (as in the pipe rack loading case) by the need for a crane, since the handrail could not safely be dropped outward by hand. Dropping the rail inward was prevented by the design of the connection between the form and the rail (Fig. 8a).

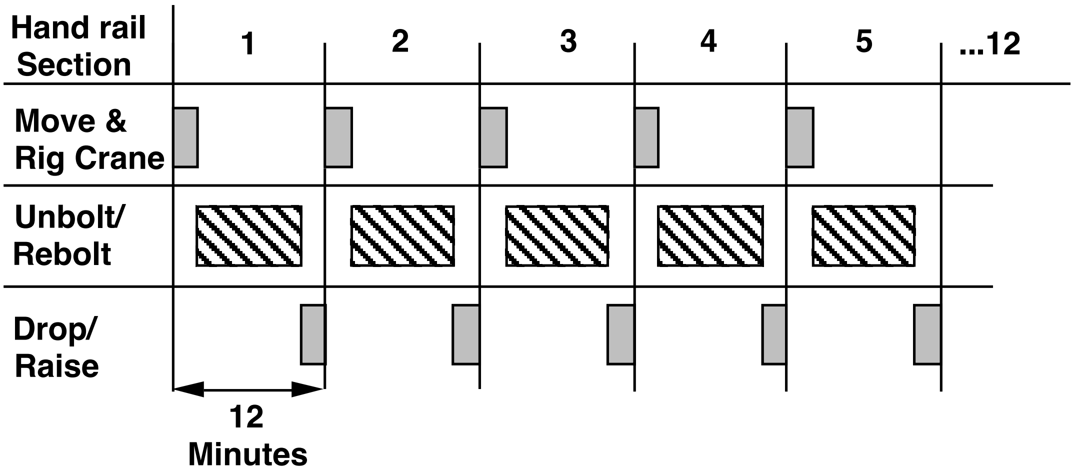


Figure 8 a

The exact timing of the handrail operation depended on the availability of the small hydraulic crane. If the crane happened to be free after the concrete was placed but before the forms were moved, two workers had to be pulled from another operation to lower the rails. More frequently, the crane was removed from another operation so the rails could be lowered just prior to moving the forms. In either case, other operations were disrupted by the handrail operation. As in the cable-cutting case, the estimate for this project was not at a level of detail which allowed budget control of the handrail operation. The labor cost was developed from the methods study. Two workers using a crane raised or lowered each section of handrail in 12 minutes. They completed the work on a pier cap in 2.4 hours. The labor cost counting the crane operator was .6 worker hours per section. The solution was to eliminate the need for a crane by allowing the rail to be dropped inward, which required redesigning the connection between the handrail and the form (Fig. 8b).

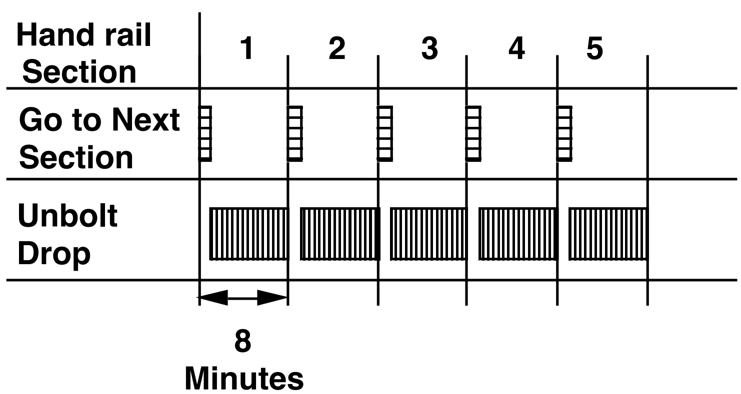


Figure 8 b

As a result, the handrail could now be both lowered and raised by two workers without a crane. Since the redesigned connection now required the installation or removal of only six bolts, the duration of the operation was further reduced. The workers raised or lowered one section of railing in eight minutes (about .27 worker minutes per section). They only needed 96 minutes to raise or lower the twelve sections required for each pier cap. The cost of the design and installation of the new connection was less than $500. The savings over the remaining work amounted to more than $25,000, which included the savings from the eliminated crane. Similar changes in the relationship between the steps required to form a pier cap cut the total forming cost by more than half.

It is worth noting that, unlike the other cases presented here, this improvement involved a redesign of the pieces being handled to eliminate the need for shared resources.

Combination of Intermediate Product and Shared Resources:

Light Fixture Assembly and Installation

A light-fixture installation project provides examples of both product and shared-resource interactions. The job consisted of assembling and installing 314 light fixtures (Fig. 9) in a ceiling grid (Howell 1990).

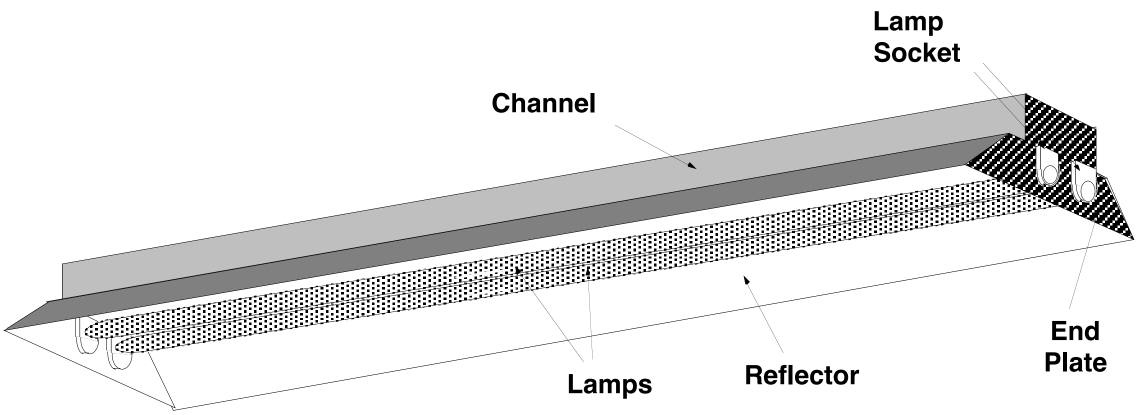


Figure 9

The data for this study were collected from interviews with the estimator and supervisor prior to the operation's start and by videotape during the operation. Minute-by-minute records were kept for the installation of more than half of the fixtures. The analyst recorded data on the operation itself, the amount of time spent on planning and replanning the operation, and changes in staffing and resources.

Neither the supervisor nor the crew was familiar with the particular fixture required for the installation. The contractor's estimate and supervisor's work plan called for one journeyman and one apprentice using one movable scissor-lift to complete the installation in 16 days. The estimate was based on a planned production rate of 2.5 fixtures per hour for the two-person crew, or 48 worker-minutes per fixture. The budget unit price of $8.36 per fixture was based on wages of $13.40 per hour for the journeyman and $6.00 per hour for the apprentice (not including fringes), and $1.50 per hour for the equipment.

The crew spent the morning of the first day learning to assemble and install the fixture. When the operation began, the apprentice assembled one fixture at a time and carried it to the journeyman, who installed and completed it. The four steps required to assemble and install one light fixture are shown in Fig. 10.

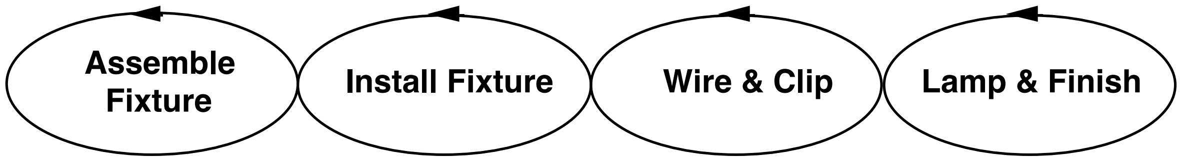
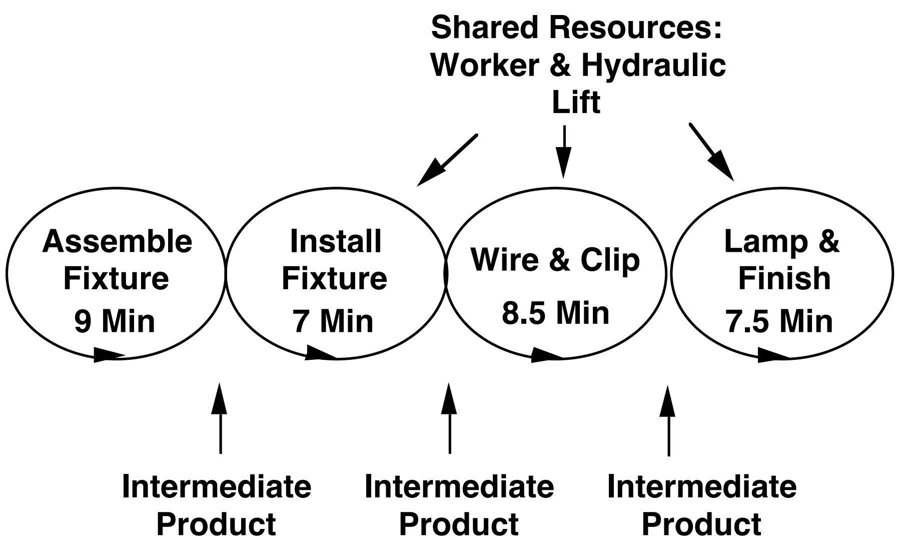


Figure 10

In essence, one fixture at a time was assembled, installed, and finished. The primary factor shaping the initial method was the supervisor's and lead worker's concern that any problems in the installation sequence be completely understood. Average times for each step and the nature of the linkage between steps are shown in Fig. 11a. Note the differences in the durations of the subcycles. The operation was performed from assembly through completion in 42 worker-minutes at a cost of $7.32 -- using less time and money than the original 48-minute, $8.36-cost estimate. An average of 10 worker minutes, 25% of the total time budgeted, were lost to delays from one worker or the other in the process. The need to learn how to assemble and install the particular fixture led to both intermediate and shared-resource interaction between the subcycles of the operation.

The improvement was developed at the end of the first day. The supervisor discussed the operation with the crew and reorganized the work, adding resources and workers.



The method was shifted from completing one fixture at a time in a tightly-linked mode to four independent loosely-linked operations (Fig. 11b). The change from completing each fixture individually to completing each step independently required two more workers and scissor-lifts.

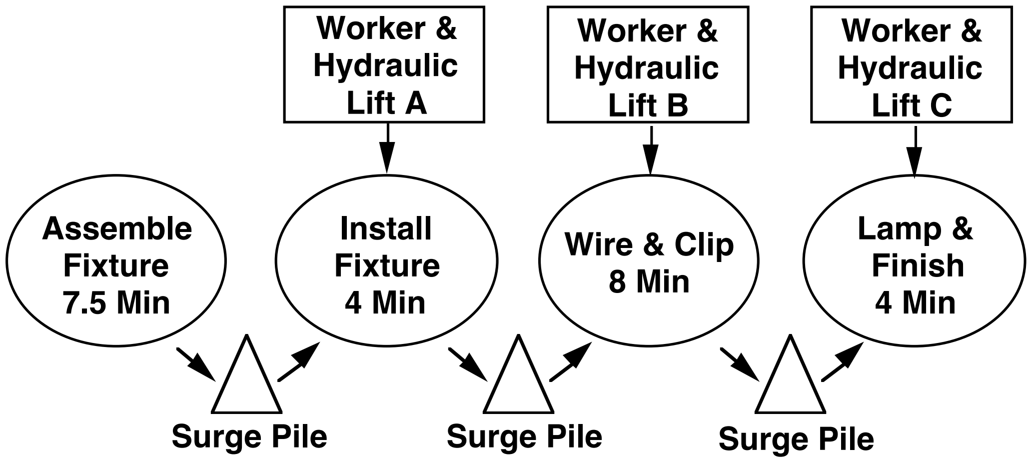


Figure 11b

One journeyman used a scissor-lift to install fixtures in the grid. To speed this installation, the crew improvised a temporary rack on the side of the scissor-lift to carry pieces for 16 fixtures, thus reducing the loading frequency (and increasing the buffer of fixtures on the scissor-lift). Another journeyman completed the wiring on a newly-assigned lift, which was also modified to increase the parts-carrying capacity so that 20 fixtures could be completed without restocking. A third journeyman used a similarly-modified lift to install the lamps and reflectors. Thus the work changes allowed each step to proceed independently of the others once the initial buffers were established. The apprentice and one journeyman prepared the initial buffers of assembled fixtures while the other two journeymen modified the scissor-lifts.

Subcycle durations are significantly different from those recorded in the original method (Figs. 11a and 11b). Worker delays waiting for other subcycles dropped 75% to 2.5 minutes per fixture. Given the difference in durations between the initial operation and the operation with reduced interaction, efforts to improve the original situation by balancing the operation would have been ineffective (Table 1).

Table 1. Results of Fixture Installation Changes

	Original Method	Revised Method	Time Saved	Source of Savings: Improved Dexterity	Source of Savings: Loosened Linkage	Notes on Savings
Assemble & Carry	9.0	7.5		1.5		Organized assembly process
Install in grid	7.0	4.0		1.0	2.0	Increased storage on lift
Pull and clip wires	8.5	8.0		.5		
Finish	7.5	4.0		1.5	2.0	Increase storage on lift
Total Work Time	32.0	23.5	Within Cycles	4.5	4.0	
Between Cycle Delay	10	2.5	Between Cycles		7.5	Improved Dexterity & Loosed Linkage
Total Installation	42	26.0	Total Saved	4.5	11.5	
Daily Production	23	74	% of Total	28%	72%	

(All Times in worker minutes)

The addition of buffers and resources clarified the amount of time required for each step. Although unfamiliar with "line of balance" scheduling techniques, the supervisors shifted workers between tasks throughout the remainder of the operation to assure that the buffers between tasks were sufficient to allow for the different subcycle durations.

As a result of this solution, the time required to assemble and install a fixture dropped from 42 worker-minutes to 26 worker-minutes. The production rate soared to more than nine fixtures per crew-hour. The hourly crew cost for three journeymen and an apprentice (based on the rates shown above) was $46.20 per hour for labor and $4.50 per hour for equipment. The resulting unit cost dropped to $5.50 per fixture -- a savings of $2.86 per fixture (35% below the original estimate that suggests that estimates should include allowance for significant interaction-caused delays). The operation was completed in four days after the changes -- a total of six work days for the operation, instead of the budgeted 16. The time distribution for each step of the operation is shown in Table 1.

While a reduction of about 4.5 worker-minutes resulted from improved worker dexterity (or learning curve effects), reducing delays within and between steps of the operation itself saved a total of 11.5 worker-minutes between steps. Thus individual learning provided 28% of the improvement while 72% related directly to changing the nature and degree of linkage. Here, as in other cases, had all of the resources required for the final method been assigned to the site on the first day, significant losses would have accrued while the crew worked out the details of assembly and installation. The improvement was a process of reducing both product and resource interaction.

In each of the five cases presented above, performance improved when the number of between-subcycle interactions was reduced. The durations of the subcycles themselves show relatively little change; rather, the design of the work process itself was altered.

Other cases

Of the 31 cases reviewed for this paper, 27 demonstrated changes in the immediacy of interaction related to degree of linkage. Nine cases required the relaxing of both product and resource linkages, while eight involved loosening only product linkages and another eight involved loosening only resource linkages. Only two of the 27 showed a shift toward tighter linkage: one required tightening associated with the discovery of a quality-control problem in the intermediate products; on the other, tighter linkage resulted from eliminating an extra intermediate surge pile which caused double-handling of materials.

Of the four cases where improvement was not related to linkage, the change occurred either as the result of reducing material handling or from using an improved tool for an existing subcycle. It should be noted that unneeded workers were assigned to six operations; the presence of these workers is not included in the case presentations. The cost of these six operations was reduced both by transferring workers and by redesigning the method. These six over-staffed operations highlight the need for both careful assignment of workers and careful review to assure that all are actually required.

In the light-fixture case, as in 27 of the 31 cases reviewed, the primary source of improvement was *delay reduction associated with reducing the immediacy of interaction by loosening linkage*. In many cases the loosened linkage occurred within an operation, as with the fixture installation, while in other cases the looser linkage developed between "support" systems and the work of the crew. In all cases studied, active intervention by a supervisor was required to loosen the linkage. Frequently the approval for extra resources had to come from a higher level, up to the home office. For example, in the fixture-installation case, the superintendent requested and the company's general superintendent approved extra scissor-lifts and additional people.

Given the benefits of minimizing immediate interactions, why are subcycles tightly linked when operations begin? According to seven senior craft supervisors who reviewed the five cases, subcycles are tightly linked because of the need to completely understand the details of the installation and to respond to pressure for production. They report the pressure comes from two sources. The first is the need to make space available for following trades (tightly linking this operation with those that follow). The second is the need to provide visible (if premature) progress for the owner or general contractor. The reviewing supervisors considered this pressure for production to be ill-advised, as it sacrifices high production and productivity for small, short-term gains.

When asked why linkage is not loosened more frequently, the same supervisors gave four reasons. First, few operations appear to have a significant enough number of iterations to make the effort worthwhile. Second, the necessary materials for the surge piles and additional resources were not available in large enough quantities, or there was insufficient room for the storage of intermediate products. Third, some complained they lacked the authority to move resources, such as cranes, to the site soon enough. Fourth, and perhaps most interesting, the superintendents lacked the time to replan and improve operations because they were busy solving start-up problems on other operations. These observations invite further investigation.

Conclusions:

Two conclusions are drawn.

1) Assuring that subcycles do not interact is one key principle for the design and improvement of construction operations. The cases discussed here show that resources can be used more efficiently when immediate interactions between subcycles are kept to a minimum through the provision of buffers and/or by changing the required amount or supply of shared resources. Until greater control is achieved in rates of supply and use of resources, creating buffers and monitoring shared resources are the most effective techniques to reduce performance-limiting interactions.

2) Changes in work methods have implications for support-system performance and vice-versa. Three important factors identified by the cases discussed here affect the process of designing and improving work methods and support systems. First, the information needed for optimizing operations by synchronizing balancing subcycles is not available to supervisors when the details of work methods are determined. Second, the pressure for starting operations and achieving short-term progress leaves little time to review operations. Third, supervisors may lack (a) access to the resources needed either to provide buffers or reduce dependence on shared resources, and/or (b) the authority to alter support-system performance.

Recommendations:

The design and improvement of construction operations should be understood as a continuous process which extends from the earliest engineering design of the project to the last cycle. Since (by the very nature of construction operations) interaction between operations and subcycles cannot be eliminated, immediate interactions that reduce performance should be kept to a minimum. Managers and supervisors must work to eliminate immediate interactions through careful consideration of the relationship between uncertainty and linkage. They must encourage, support, and formalize a planning and replanning process that takes advantage of both the information available before starting and the information which emerges as work progresses.

Once an operation is underway, isolating subcycles by establishing buffers and eliminating shared resources is the first step to performance improvement in uncertain and/or unbalanced situations. The information needed to balance and synchronize an operation is often only available when one subcycle's operation is not affected by events in other subcycles. Immediate interactions must be eliminated either through the provision of buffers and/or shared resources or through achieving greater control of the rate of supply and use of resources.

Multi-cycle operations should be carefully designed and planned both (a) to minimize initial uncertainty -- that is, "will the crew know how to do the task?" and "what are the planned rates of supply and use of resources," and (b) to minimize potential interaction-related delays by isolating subcycles. If available information is insufficient for accurately estimating subcycle durations and/or if there is little confidence in the projected rates of resource supply, slack resources should be provided to loosen the relationship between operations. When the assembly process is unfamiliar to the crew, a few tightly-linked cycles may be completed to identify and resolve issues of quality and dimension. Steps should then be taken to reduce immediate interactions.

In any case, sequences should be examined to identify the relationships between subcycles and to determine whether savings will accrue from looser linkage. Quality control practice and "inspection" points must be carefully identified when buffers are established, since a following step may no longer perform an immediate -- if informal -- quality control function. Finding the unimpeded cycle time and the actual resource demand is difficult when cycles interact because workers may be delayed by or may pace themselves in relation to the flow of available products or resources.

Performance may be optimized by returning to tighter linkage once an operation is synchronized and balanced. Optimization requires avoiding delay-causing interactions, minimizing inventory in buffers, and maximizing the use of shared resources, such as cranes. The improvement objective is to increase the rate of through-put without allowing interactions to delay any part of the process (Goldratt 1985). Achieving this level of improvement means either the major sources of uncertainty are controlled or supervisors are constantly adjusting the operation to the circumstances. In conditions of even moderate uncertainty, low-delay operations with minimum surge piles or redundant resources will require significant control information and close supervision.

Operations can be continuously improved by moving from a tight-but-unbalanced state to loose-and-unbalanced to tightening-and-balanced. The work method will be reorganized with each step in the improvement process and new demands made on the related supply systems. Each step, in turn, provides information for future improvements. With little opportunity to study and improve operations, senior managers should consider expanding the planning process to include the use of supervisory quality circles and staff planning assistants (Laufer et al.1992) as these additional planning modes assist foremen in collecting data, finding solutions, and obtaining the authority to acquire needed resources.

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