IMPORTANCE OF SITE CONDITIONS AND CAPACITY ALLOCATION FOR CONSTRUCTION COST AND PERFORMANCE: A CASE STUDY

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"The best-laid schemes o' mice an' men gang aft agley." (Robert Burns, To a Mouse)

Abstract
Traditional construction thinking that an ‘optimal’ solution to the problem of shifting project schedules can be found via a time-cost tradeoff analysis does not take into account the influence of capacity allocation and site conditions on cost and performance. Specifically, the time-cost tradeoff can only account for the direct costs of compressing an activity's duration, not its capacity costs. Loosely restated, the time-cost tradeoff accounts for the costs of a change in an activity's duration but not the costs of a change of when in time the activity takes place (which will affect a firm's commitments to other projects and hence cause capacity costs). Similarly, moving an activity in time may place the activity in a different set of site conditions than those which were assumed when the activity's cost-time curve was generated. The cost-time curve of an activity may change as site conditions change, which can only be accounted for in the time-cost tradeoff optimization method by manually generating new cost-time curves for each instance of site conditions and solving anew (an exercise that quickly becomes too cumbersome to perform). This paper presents an in-depth case study of a £100 Million project highlighting the limited applicability of the time-cost tradeoff approach to real world situations and discusses the impact of site conditions and capacity allocations on cost and performance.

Keywords: time-cost tradeoff, capacity allocation, site conditions, supply chain management, construction scheduling

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INTRODUCTION

The Durand Centre project presented in this paper is a classic example of the problems of production in construction: a delay to one activity causing delay to subsequent activities. As Robert Burns reminds us, delays or similar changes in plan and schedule (e.g. accelerations; changes of scope, unexpected site conditions, and rework that affects schedule) are common occurrences on even the best run projects. The Durand project is a good example of this, as it was completed on time and within its contingent budget (and placed second in a national project manager competition). Despite this, a significant delay occurred in the erection of steel, requiring acceleration of following activities to meet promised completion dates. Acceleration proved difficult to coordinate as it involved multiple firms with differing abilities and demands on resources; firms' constraints had to be accommodated by the revised project schedule. Ultimately, acceleration cost £231,000. This problem of delay and its solution of acceleration forms the canonical example of this paper.

Analysis of the Durand Centre project suggests that acceleration could have been accomplished at a cost less than the actual cost. This is less interesting as a critique of Durand Centre project management than as a critique of existing approaches to managing changes in project schedule. Existing approaches (principally, the time-cost tradeoff problem (Antill and Woodhead 1990)) to managing changes such as delays attempt to construct optimal solutions by minimizing the total costs of acceleration of multiple activities while meeting schedule constraints. Unfortunately, these approaches are incapable of fully capturing the relevant costs of the subcontractors and suppliers of the Durand Centre project. In particular, both subcontractors and suppliers' costs are affected by their capacity commitments across multiple projects. Subcontractor costs on the Durand Centre were also affected by changes in site conditions. The time-cost tradeoff problem is incapable of considering the costs of capacity utilization or site conditions in anything but a static manner. On the Durand Centre, capacity utilization and site conditions changed dynamically as activities were accelerated, rendering the time-cost tradeoff (and more broadly, the assumptions about construction cost embodied by the time-cost tradeoff) a limited framework by which to assess and solve the problem of steel delay and acceleration.

The limitations of current approaches for resolving the problems of the Durand Centre forms the basis of investigation for our broader research program. This paper presents the details of the delay to steel on the Durand Centre project as well as details of the principal firms involved in the delay and subsequent acceleration. A critique of the time-cost tradeoff problem and related approaches to solving changes in project schedule is also presented. We conclude with three research questions which inquire about the generality of the cost factors relevant to firms on the Durand Centre project as well as the mechanisms by which capacity and site condition costs manifest themselves.

DURAND CENTRE CASE STUDY

This section presents the details of the Durand Centre project, in particular, the tasks associated with creation of the project schedule, the delay to steel and accelerations, and the particulars of the steel and concrete subcontractors who were principally affected by the delay and acceleration. Discussion focuses on firms' relevant production costs.

Overview of Durand Centre Project

The Durand Centre is a shopping mall constructed on an existing site in southwest London, UK. Project cost was £100 million. Construction on an existing site posed difficult problems. Limited access to site and little on-site storage required careful coordination of site activities to minimize conflicts and to ensure a smooth work flow towards completion. Construction was accomplished in two phases: demolition and construction of temporary facilities to provide access to adjacent stores (Phase I), and construction of the new shopping mall (Phase II). The overall on-site construction schedule was limited to five years. In the paper, ‘Durand,’ ‘Lion,’ ‘Stone,’ ‘Boulder,’ ‘Seaview,’ and ‘Empire’ are used to mask the names of the firms involved. Any relation to real firms of the same name is coincidental. All dates, contract values, and prices have been modified but are representative.

The Durand Centre site was developed by Durand Real Estate, a division of Lion Ventures, plc. Both phases were let to Stone Builders. Stone was involved in the construction process as a management contractor since 1987 with the award of Phase I; Phase II was substantially complete in 1992 when the Centre opened for trading.

The contracting structure for the Durand Centre follows the typical model for building construction in the United Kingdom. The owner held three contracts; one with a design team, the second with a management contractor, and the third with a quantity surveyor. All physical work was subcontracted. Stone coordinated the activities of the subcontractors and held their contracts. Stone was responsible for completing project scope within Lion’s overall schedule. Penalty for late delivery was £50,000 a week.

Subcontracts were awarded through pre-selection and bidding. Stone assembled a short list of subcontractors deemed competent for each work package, e.g., foundation work, steel frame, mechanical equipment, etc. Firms on the short list were invited to bid on the work package. Selection was by low bid, although technical differences between bids did justify selection of higher price bids in a few cases. To a certain extent, bidding was contingent on the ability to meet Stone off-site and on-site schedules. Subcontracts were typically lump sum or bill of quantities. Lump sum contracts could also include a schedule of prices per unit installed for variation. Subcontracts included a clause for liquidated damages, passing the risk for late delivery to subcontractors.

Appointment as contractor for Phase II approximately one year before Phase II construction began gave Stone Builders time to plan in an otherwise tight construction schedule. To take advantage of this breathing room, Stone sought to finalize design quickly and scope clearly defined work packages. This removed some uncertainty in the planning and scheduling process. Specifically, early scoping of work packages allowed early tender and award of subcontracts. This gave Stone some assurance that subcontractors would be able to fulfill their commitments within the allotted time and ensure that lead times-the time to finalize design and manufacture and transport materials to site-it the constraints of the on-site construction schedule. Confirmation of lead times and time required for on-site construction from subcontractors allowed creation of realistic construction schedules. Further, Stone encouraged off-site pre-fabrication techniques to minimize the time subcontractors would need to be on site. To ensure that subcontractors and suppliers would meet schedules, Stone set up an elaborate off-site progress tracking program. Thus Stone was able to formulate a plan of construction that fit the tight overall schedule constraint by giving subcontractors enough time to fabricate materials for installation on site.

Chronologically, management tasks began with scoping work packages. After packages were well scoped, a detailed construction schedule for on-site activities was created that reflected lead times for off-site fabrication. At this time, no subcontracts had been awarded, so off-site lead times were not known with certainty. However, Stone personnel have enough experience to know approximate lead times, and many lead time allowances were generous. Stone was able to reasonably estimate the time to complete on-site activities, leaving a little contingency in the schedule for overruns on each activity. The provision of float reflects a philosophy of containing delays at the source and not allowing delays to propagate.

After creation of the schedule, a procurement program was designed to reflect time for bidding, review, and award as well as fabrication. Appointed subcontractors with significant off-site fabrication tasks were given schedules for completion of that work. Typically, the subcontractor rejected this schedule as unfeasible or uneconomic. A revised schedule for off-site fabrication was then agreed upon by both Stone and the subcontractor. The revised program was highly detailed and gave specific start and finish dates for the activities involved. This program was called a *marker program* and was used to monitor progress. Stone personnel responsible for packages telephoned and visited subcontractor sites periodically to monitor progress and check quality, using the marker programs as reporting devices. A similar procedure was used to design marker programs for on-site activities. Stone and subcontractors would agree upon a construction sequence, and a detailed program would be created, used for planning and monitoring. On-site marker programs included handover dates for completion of work to allow following trades to start.

Introduction to main subcontractors

Seaview Steelwork is a £30 million a year contractor specializing in erection of structural steel for buildings. It buys steel pieces and performs detail design and fabrication on its primary location in central/northern England. From its central factory, Seaview ships finished steel to construction sites for erection by crews it hires locally. Thus, Seaview is responsible for the supply of steel after it is rolled through installation on site. For the Durand Centre, Seaview was awarded the job on a lump sum price of approximately £6 million pounds for 5,500 tons of steel work and 49,000 square meters of metal decking with associated shear studs and edge trim. This price included a design change made after award, adding 1,000 pieces to the roof frame.

Seaview buys most of its steel from Empire Steel, which rolls sections of different sizes on an eight to ten week cycle with a four month "look ahead" schedule for its rolling programs. Steel must be ordered in a minimum quantity, e.g. five tons, in each section size. Payment to Empire Steel is due 30 days following the month of delivery. If pieces of steel are needed on short notice, they can be purchased from third-party suppliers that hold stocks of rolled sections. This is two to three times more expensive than ordering pieces from Empire Steel. Seaview holds steel in inventory at its central site from delivery by Empire Steel until shipment to the construction site (or lay down yard near the site). This inventory is typically 10-12 weeks worth of steel, which includes raw pieces from Empire Steel and milled pieces completed by Seaview. If steel has been fabricated for a particular site, it will generally be paid for by the client (contractor/owner). Nominally, the production process from receipt of order and design information until the steel is ready for delivery to site takes 16 weeks.

Fabrication is performed at Seaview's home yard along a single milling line. Scheduling on this line is done by subdividing each job into 100 ton phases based on the erection schedule. A batch of a single section size from each phase is run through the milling line; batches range from five to twenty-five tons. There are 60 direct workers and 40 indirect workers on the milling line with a full day shift and a small second shift that can be expanded in busy periods. Seaview tries to run the milling line at 'over-capacity', bidding for jobs to keep a backlog of orders. Seaview aims to work on four to five construction jobs concurrently. To maintain performance at the job-site, Seaview tries to have one large job (such as the Durand Centre) and several smaller jobs to fit around the requirements of the larger job.

Boulder, a construction company with approximately £50 million of business each year and specializing in concrete construction, won the Phase II concrete package for the Durand job; this package consisted of floor slabs and retention of a historical facade. This was won on a lump sum bid, priced at £1.336 million, of which approximately £217,000 was earmarked for work on the facade. Boulder was particularly keen on winning the job as it had worked on Phase I of the project and had an experienced crew coming off another project at the time the concrete portion of the Durand project was due to begin. As a specialist in concrete construction, Boulder primarily carries out works on site; it contracts with other companies to bend rebar for jobs and to supply concrete and lumber.

On receipt of a letter of intent from a prime contractor to subcontract with Boulder, Boulder prepares orders for rebar and designs concrete mixtures for approval. Usually there is a three week lead time for bending of reinforcing steel; it is possible to order rebar with a one week lead time for an additional fee. Once given the go-ahead to proceed on site, Boulder orders steel, necessary formwork, and arranges a pour schedule with the site and batch plants. Boulder likes two weeks advance notice before being given the go-ahead to proceed on site. It can accommodate this short notice period as it knows it has the contract and knows at the time of contract approximately when workers will be needed on site. Should the schedule be delayed after rebar has been ordered, Boulder may tell the supplier to postpone production. There may be a fee for this; however, the rebar supplier can often substitute other orders or may waive the fee as Boulder is a good customer. It also has its own yards to store materials. Boulder asks for payment for materials stored in its yard if they are designated for a specific site and if they are expensive (more than several hundred pounds).

Once on a job, Boulder tries to maintain a constant size work force. It tries to do this to smooth out production and maintain good relations with workers; Boulder does not want a reputation as a hire-and-fire contractor. If there are substantial delays on site, Boulder will lay off workers to avoid paying for idle workers. It will also see if other Boulder sites need extra workers for a short period. Or, should a site need extra workers, it may call other sites to see if a few workers can be spared. In this way Boulder shares resources across jobs.

On the Durand job, the concrete package was well scoped and design was complete prior to tender. At the tender stage, the construction program was well advanced and Boulder knew the plan of construction, planned schedule, and the constraints of the site.

Scheduling of steel and concrete for Durand Centre, phase II

Many activities in the Phase II schedule overlapped to some extent as work finished on one area of the site could be continued in other areas while new trades started work in the completed area. Phase II was split into six areas for construction purposes; these areas roughly corresponded to expansion joints in the building. On the critical path, steelwork was to follow an erection sequence of area 1 › 2/3 › 6 › 4/5. This included erection of steel, placement of metal decking for floors, shear studs, and edge trim. After metal decking was complete in an area, concrete was poured to create a composite metal deck. Safety considerations required a complete metal deck between concrete workers and steel workers. The erection sequence was planned to open up whole floors for following work as quickly as possible as some trades can perform more efficiently working with an entire floor than a section. Thus the logic was to erect the steel quickly and sequence following activities away from the Phase I site. Handovers (one trade releasing an area to a following trade) were to be made according to marker programs.

Problem with steel supply and response

Erection of the structural steel framework on site initially went well, then fell behind. Steel erection was delayed due to a number of factors, although the primary delay was due to late fabrication of steel for area six. A brief history of the erection program is drawn from Stone's monthly reports to Lion Ventures:

28.4. Handover to Seaview made on time. No problems anticipated.

26.5. Area 1 handed over to Boulder. Area 2/3 steel commenced one week ahead.

23.6. Unseasonable weather (rains and high winds) caused loss of 100 crane hours. Seaview is in possession of areas 2-5. Area 6 handover to Seaview on 24 June.

28.7. Weather conditions have improved, but are less than ideal for deck stud welding. Boulder is currently on-schedule, but delays on the steelwork may cause follow-on delays. Area 2/3 is expected to be handed over on time, but areas 4/5/6 are three weeks behind program. Weekend and night shifts have been introduced for steel fabrication and weekend working for erection on site. Delay to following activities in area 6 is now inevitable.

29.8. While weather conditions have improved, a fire on the ground level at the end of July disrupted works and requires replacement of some existing beams. Boulder reports delays to floor slab construction due to late and incomplete steelwork handovers and due to the fire. There has been no improvement in the rate of steel erection; handovers in areas 2/3 and 4/5 have not been achieved on program. The first floor section of area 6 is six weeks late and the whole of area six is expected to be five weeks late. Seaview's failure to complete sections of work and to give accurate revised dates for handover means the delay will be extended to following trades.

22.9. Steel erection has improved markedly in the last two weeks. Seaview have given firm dates for a handover of area 6, six weeks late. Boulder and other affected trades have increased resources on the job to bring the overall program back on schedule. Costs for this acceleration of program are under negotiation with each subcontractor.

27.10. Main structural steelwork is complete, as well as the floor slabs. Overall project delay is two weeks, and subcontractors affected by the delays are accelerating their programs.

After a good start, Seaview's erection progress slowed at first due to inclement weather, then because of late fabrication. The real problems were in area 6 with Seaview handing over that area six weeks late. It was this late delivery that overlapped with planned start dates for the floor slabs and other trades. The extent of the delay to area 6 was not reported by Seaview and was not foreseen by Stone. This can be seen in the varying estimates of delay given in the reports. Boulder did not always know of delays until handover dates were not met. Further, Seaview had difficulty promising revised completion dates for the steel, leading to further uncertainty.

Stone decided that it did not wish to allow the delay to propagate throughout the project and requested that subcontractors submit an estimate of costs for acceleration of their programs to put the project back on schedule. This required careful re-negotiation and re-scheduling of marker programs, complicated by uncertainty about Seaview's completion dates. Several iterations of re-scheduling were performed, and in some cases subcontractors proceeded with accelerated programs before agreeing on a price and final schedule. Table 1 lists the subcontractors affected, lead time between award and scheduled start on site, value of the package, and agreed upon price to accelerate the program. All affected packages were fully scoped at the time of award, with no special requirements for design coordination, making acceleration of works primarily a function of increasing resources on site.

Table 1 Packages affected by delay of steel.

Subcontractor	Lead Time	Package Value	Price to Accelerate Program
Floor Slabs	20 weeks	£1,119,000	£146,000
Fire Protection	16 weeks	528,000	34,800
Blockwork	26 weeks	1,327,000	19,500
Screed	21 weeks	653,000	0
Cladding	45 weeks	500,000	0
Inverted Roofing	14 weeks	371,000	30,700

Analysis of steel delay and accelerations

Cost to accelerate by six weeks the packages affected by steel delays totaled £231,000. This is a large sum of money, although reasonably small compared to the £100 million contract value. As the steel erection was on the critical path, a delay of six weeks could have been very costly: six weeks delay in project delivery multiplied by liquidated damages of £50,000 per week equals £300,000. Add to this an allowance for claims from subcontractors for alterations in schedule, and it is easy to see that Stone made a good decision to make up the delay. However, Stone's decision to accelerate the program was based on a cost analysis that compared the price of acceleration to the price of letting the delay propagate, which can be considered a worst case. This begs the obvious question: Could the acceleration have been accomplished at a lower cost? Although there was some iteration on revised marker programs, Stone did not carry out any search of alternatives to the basic acceleration program; iteration of marker programs was done at a micro-level.

When queried about the possibility of alternative, lower cost accelerations, Stone's planning manager stated that, "basically, there is no way we could have reduced the cost of the delay through lowering the amount we paid subcontractors to accelerate their programs. Once Stone has contracted with these subs, we're locked into a contract with them and they can charge us what they want, within limits. The only way we could have reduced the cost is if we hadn't already contracted with a sub and were putting the package out to bid. In the case of the steel, all our packages were subcontracted with long lead times (Table 1), so we couldn't have reduced the cost of the delay to us. Besides, if we had known of the problem that far in advance, we would have acted with Seaview to rectify the situation." Stone's perception of the problem is primarily contractual; once locked into a contract with a subcontractor, the subcontractor can charge for changes in schedule beyond its actual costs. As Stone did not know actual costs incurred by subcontractors it was subject to opportunistic behavior by its subcontractors. This problem is not unique within the construction industry, and the belief held by Stone's planning manager is reasonable in this context. With this view, there is no value to advance information about the delay of steel, backdating to the point that packages went out to bid. Furthermore, under this contractual opportunism viewpoint, there is no value to searching for alternatives as subcontractors will charge the same amount.

Whatever the merit of Stone's planning manager's view of contractual opportunism by subcontractors, the details of the Durand case suggest that it is incomplete. Both the screed and cladding subcontractors charged nothing for the changes in their on-site schedules. The screed subcontractor allowed for overtime in its bid and could make up the delay at no additional cost, and the cladding subcontractor anticipated delays in its own material supply and was happy to negotiate a later start date. If all subcontractors are opportunistic, why did they charge nothing for their acceleration? Further, the project manager at Boulder made it clear when interviewed that the prices quoted were for accelerations initiated by Stone: "We are not and do not wish to have a reputation as a subcontractor that aggressively seeks additions to contract over the bid price." Boulder submitted two proposals to Stone for review: one for £146,000 to accelerate the schedule by three weeks (finishing three as opposed to six weeks late) and a second for £81,000 that reflects the normal cost of overrun (Boulder had already started on site when the delay occurred, and would incur fixed costs of about £13-14 thousand per week if they finished six weeks late with no attempt at acceleration). A Boulder staff member commented that "Stone got Boulder to start too early on site. If we started 2-3 weeks later the job would have been a lot smoother, and we still would have finished on time for the original price." Essentially, the job was broken into too many small pieces, preventing Boulder from organizing its pours efficiently.

With this knowledge, it is possible to construct an alternate acceleration of lower cost than that adopted by Stone: Let Boulder finish its work six weeks late and accelerate the following subcontractors at a lower cost. This would save £146,000 - £81,000 = £65,000; if the following subcontractors could accelerate their programs for less than £65,000, a lower cost alternative is found. As two subcontractors charged nothing for schedule changes and the remaining trades are labor intensive and hence don't require the provision of extra capital equipment, it is plausible that a lower cost alternative was possible.

This proposed alternative postpones making up the delay by pushing back all the acceleration to firms following Seaview and Boulder (steel and concrete). Another possibility is have Seaview make up as much of the delay as possible, limiting the impact on Boulder and leaving little or no acceleration to be accomplished by trades following Boulder. This is seen to be uneconomic or infeasible for two reasons: First, if it was possible, Stone would have acted with Seaview to accomplish it. Seaview was clearly unable to comply or made a choice that it would rather take the contractual risk of being liable for the cost of the delay than take action to make up the delay. While there are many possibilities for Seaview being unable to accelerate its works, a second reason that its making up the delay is infeasible or uneconomic is its utilization of the milling line at 'over-capacity'. There may simply have been no spare capacity to make up the delay (indeed, running at over-capacity may cause delays); provision of extra capacity via an extra shift or overtime may have been prohibitively expensive.

LIMITATIONS OF CURRENT APPROACHES TO RESOLVING DELAYS AND ACCELERATIONS

The time-cost tradeoff problem

It is useful to view the delay and subsequent acceleration of the Durand Centre project from the perspective of formal construction approaches to such problems. The principal construction approach to planning and analysis of schedule changes such as those of the Durand Centre project is the time-cost tradeoff approach (Antill and Woodhead 1990; Fondahl 1991), which is a methodology for representing and optimizing project costs over time. The classic time cost-tradeoff for an activity is shown in Figure 1. The time-cost tradeoff assumes that costs are either the direct costs of materials, labor and equipment associated with project activities, or the indirect costs of supervision, site expenses, interest, and penalty payments. Direct costs are associated with each activity while indirect costs are associated with the project as an entity and are assumed to vary linearly over time (Antill and Woodhead 1990).

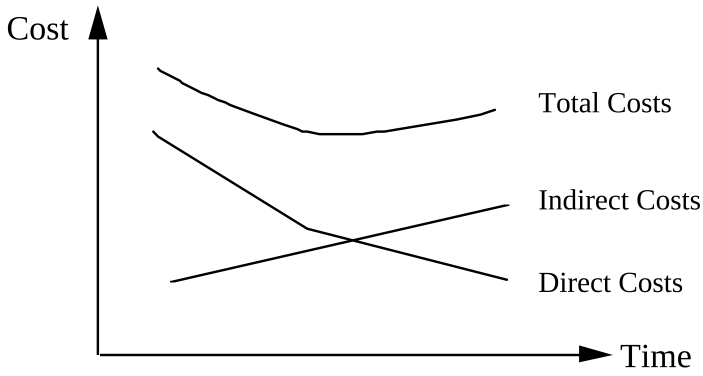

Figure 1 The time-cost tradeoff for a project activity.

It is assumed that direct costs for an activity increase as duration is decreased. This increase is due to overtime and uneconomical working conditions leading to lowered productivity. Direct cost curves must be independently derived for each activity. When such curves are prepared, they are associated with a critical-path network for the project. Optimization of project costs is performed over the set of all activities' time-cost curves and project indirect costs; this multi-activity optimization is called the time-cost tradeoff problem. For example, to find an optimal acceleration of activities on the Durand project, a direct cost curve would be manually generated for each activity. Then, starting with activities on the critical path, duration would be shortened for activities with the shallowest cost slope to find an optimal (least cost) compression of project activities. There is some complexity here as shortening one activity along a critical path can generate other critical paths, but such complexity can be resolved. Time-cost tradeoff problems are notoriously difficult to solve for large networks. Current research is investigating new solution techniques using genetic algorithms to solve time-cost tradeoff problems in a computationally efficient manner (Liu 1996).

Site conditions and the time-cost tradeoff

Although the time-cost tradeoff can be optimally resolved, the assumptions under which it operates do not match the details of the Durand case. The key assumption of the time-cost tradeoff is that the direct cost curves are independent for each activity. However, on the Durand project Boulder noted that it could not organize its pours efficiently as the project was broken into too many small pieces. More generally, the specifics of the site conditions affected Boulder’s costs; the time-cost tradeoff method has no explicit way to account for this. Let us consider an example. Concrete work on a project is broken into two pours of equal size. Each has a direct cost-time curve and can be accelerated (Figure 2).

Now suppose that as other activities are accelerated, the work released to the concrete subcontractor varies in size such that A grows larger than B (Figure 3). The only solution within the time-cost tradeoff methodology is to generate and price each possible instance of the schedule (e.g. a new schedule exists for each combination of pour sizes for A and B). In general, as activities are accelerated or otherwise moved in time in relation to other activities, they will be subject to different site conditions (or will create new conditions for other activities). Within the time-cost tradeoff methodology, the only way to assess the affects of these varying site conditions is to manually enumerate each possible instance of site conditions, generate direct cost curves, and solve the time-cost tradeoff for each enumeration. For a project of any size, this quickly becomes too cumbersome to perform.

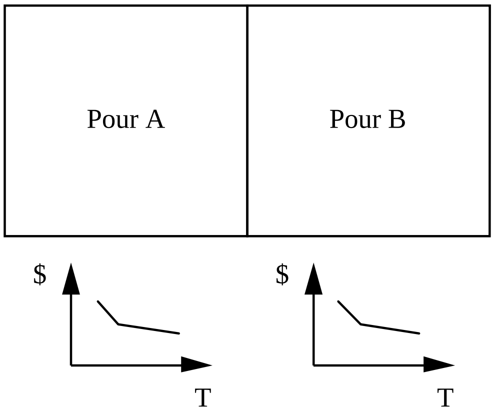

Figure 2 Two concrete pours.

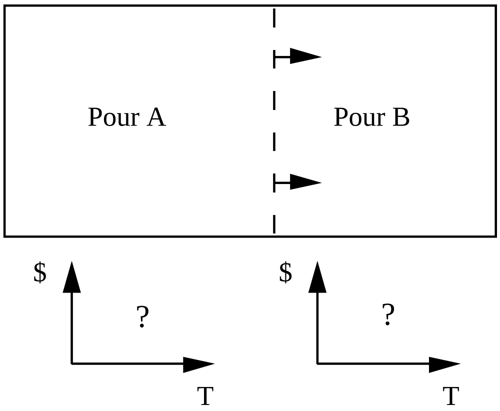

Figure 3 Work area of pours varies due to varying site conditions (not shown).

Research performed by Thabet and Beliveau (1994) suggests a methodology to assess the impact of work area on activity productivity. As work area drops below some minimum level, they assume productivity falls; this drop is scaled by a [0,1] function of work area shortage. Although not empirically calibrated, Thabet and Beliveau demonstrate a scheduling methodology using this work area modifier. However, their research is limited only to the impact of work area on productivity, leaving out other influences of site conditions such as those through shared site resources (Fondahl 1991; Howell et al. 1993) or through site access conditions (Riley and Sanvido 1995).

Capacity utilization and the time-cost tradeoff

Having Seaview make up its delay as quickly as possible on the Durand Centre project was rejected because Seaview's capacity utilization made such acceleration infeasible or uneconomic. Capacity commitments also affect Boulder, which has a resource policy of maintaining a constant work force by absorbing the cost of keeping workers idle in slow periods or by shifting workers among projects to keep them busy. Boulder also shifts workers between sites to manage busy periods. If a project requires more workers to meet a due date Boulder may shift them from other sites. This, of course, is contingent on the needs of the other sites. Boulder's resource allocation across sites affects the direct cost-time curve of a particular site. For example, it is clearly less expensive for Boulder to transfer idle workers to a project than it is to transfer workers which are fully engaged on a project. More generally, individual firms such as Boulder have a finite amount of resources or capacity; utilization of this capacity will vary over time (Figure 4). This affects production on projects:

> *"A general contractor may manage a construction project but he must do that through the array of subcontractors who control the resources. There may be anything from 6-60 subcontractors and each is trying to allocate and level his resources across say 6-12 projects simultaneously. The general contractor cannot dictate to his subcontractors the resource levels they should employ or*

utilize on a particular project. Such action would usurp the individual entrepreneurial contractual role of both the general and subcontractor. The general contractor may try to persuade the subcontractors to produce work at a desired speed, but it is each subcontractor with his perceptions of his overall resources and current projects, who will decide the volume of resources he allocates to each specific project." (Birrell 1980, p. 394)

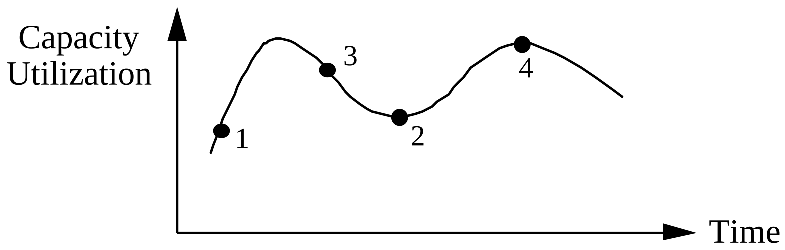

Figure 4 A firm's capacity utilization over time.

Subcontractor resource allocation at a particular instance in time affects the direct time-cost curves of a particular project activity. This is a poorly understood phenomenon, but as capacity allocation varies over time, so will a subcontractor's direct cost-time curve (Figure 5; direct cost curves refer to capacity utilization 1-4 on Figure 4). Moreover, an activity moved in time may place a firm in a different level of capacity utilization than it desires; for example, Boulder was happy to get the Durand Centre project in part because it had an experienced crew coming off another project at the start of its work on the Durand Centre. If its work had been moved forward in time, the experienced crew would still be attached to the other project and Boulder's costs would be different. The time-cost tradeoff approach does not take this into account; there is no link between resources and cost-time curves. When accelerating activities - hence, changing when in time multiple activities take place - the time-cost tradeoff problem (Antill and Woodhead 1990) does not consider resource availability and is incapable of accounting for the costs of capacity utilization as shown in Figure 5. This shortcoming is also true of Thabet and Beliveau's (1994) methodology, which assumes resource quantities are fixed and hence does not include capacity related costs and behaviors such as Boulder's behavior of shifting workers between jobs.

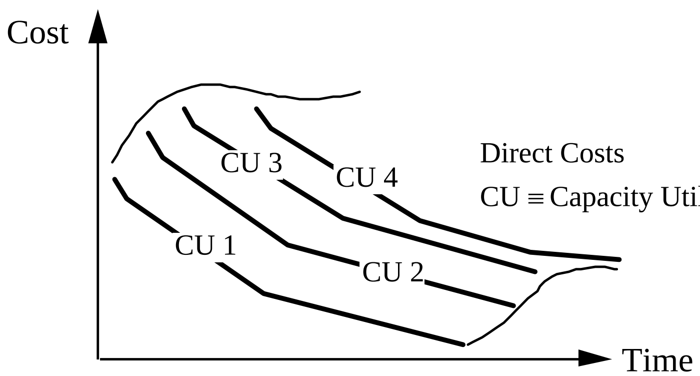

Figure 5 Direct cost curves for an activity may vary over time as a function of a firm's capacity utilization.

The time-cost tradeoff also has difficulty representing Seaview's costs of capacity utilization. Given Seaview's policy of maintaining its single milling line at "over-capacity," its acceleration costs will be a function of its current capacity utilization just as for on-site subcontractors such as Boulder. Thus if Seaview's production activities are modeled as activities within a network, then the time-cost tradeoff has the same problems of representation as summarized in figures 4 and 5. Often, however, suppliers such as Seaview are not modeled as project activities but are considered to require adequate lead time; if given enough lead time, the supplier can smooth its capacity without incurring capacity costs as in Figure 5. This is the assumption behind Shtub's (1988) work, which integrates material lead times into a project activity network and time-cost tradeoff model. This may be true for long enough lead times, but lead times give little information about the nature of a supplier's capacity utilization or capabilities. For example, the nominal lead time for steel on the Durand project was 16 weeks and the actual lead time was 48 weeks; nonetheless, steel was still late.

Similarly, lead times give little indication of a supplier's ability to accelerate its work. Within Shtub's methodology, there is a fixed expediting expense for accelerating the delivery of materials. This does not correspond to the details of the Durand Centre. For example, Seaview's milling plant obtained its materials from Empire Steel, which cycles through a fixed eight-week rolling schedule. Ability to accelerate is partially a function of materials needed and where these materials are on Empire Steel's rolling schedule. Alternately, Seaview could obtain the materials from a stock yard, which is an immediate source but comes with a higher price. Thus the price to expedite will be a function of when in time the materials are needed on site, and when in time materials are needed will be a function of activity acceleration. This leads to the same problem of accommodating changes in site conditions within the time-cost tradeoff framework; an expediting price would have to be manually set for every combination of capacity utilization. And as for site conditions, enumeration of the possibilities quickly becomes too cumbersome to carry out.

CONCLUSIONS

Both on-site subcontractors and off-site suppliers must make decisions about the allocation of capacity across projects; the interaction between the needs of a single project and those of a firm trying to effectively utilize its capacity across projects is poorly understood. This interaction is complicated for on-site subcontractors by the influence of varying site conditions on their work.

From the specifics of the Durand Centre project, three limitations in current approaches to adjusting to changes in schedule are apparent. First, there is only limited understanding (through Thabet and Beliveau's (1994) model) of the interaction between site conditions and an activity's cost-time curve. Second, other than Birrell's (1980) recognition of the interaction between site production and firms' multi-project resource or capacity allocation, there is little understanding in the construction literature of the affects of resource allocation on site production capabilities and cost. Third, the influence of suppliers' capacity allocation on cost is poorly understood, but is a more complicated scenario than Shtub's (1988) utilization of a single price for expediting materials delivery. These limitations lead us to pose three questions:

1) Does capacity utilization affect the costs of firms (both on site and off site) involved on a project when there are changes in project schedule?
2) Do site conditions influence the direct cost-time curves of firms working on site?
3) What are the mechanisms by which capacity/site conditions affect cost?

The purpose of questions one and two are to generalize the importance of capacity and site conditions for project production beyond the specifics of the Durand case. The third question is more open-ended; the purpose is to deepen our understanding beyond the importance of capacity and site conditions to develop more specific models and tools to improve production management and project performance.

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