Shielding Production: An Essential Step in Production Control

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Abstract: Effective production control systems are structured around the assignment as the unit of analysis. The quality of work assignments to production units such as construction crews and engineering squads is the key to production control and a key factor determining production unit productivity. Research has revealed that the quality of assignments can be substantially improved by forming and selecting them to meet soundness, sequence, and size criteria. Making quality assignments shields production units from work flow uncertainty, enabling those units to improve their own productivity, and also to improve the productivity of the production units downstream. The associated reduction in task duration can shorten projects. Further reduction of project duration comes from reducing the buffers previously needed to accommodate flow uncertainty.

Preface

The approach to production management described in this paper can best be understood in terms of production control, which has until recently been developed and applied in manufacturing as distinct from construction. Production control consists of aggregate production planning, material coordination, work load control, work order release, and production unit control (Bertrand et al. 1990). The construction industry uses different terms and a different conceptual model. In construction, "planning" is the production of budgets, schedules, and other detailed specification of the steps to be followed and the constraints to be obeyed in the execution of the project. Once production begins, management devotes its efforts to "control", i.e., monitoring of performance against those specifications, with corrective action as needed to conform performance to them. In manufacturing, control is conceived as the progressively more detailed shaping of material and information flows, i.e., the physical production process. Perhaps influenced by the fact that most direct production work is performed by specialists under contract, project and construction managers conceive control as the enforcement of contractual commitments, even when the 'contract' exists in the form of a division of responsibilities between units of the same organization. Where manufacturing control is forward looking and acts directly on the production processes, construction control tracks results in order to identify which party is at fault.

The construction model of control is actually a model of project control, not production control. Direct control of production itself is conceived as occurring only within the production unit, and is not addressed by the disciplines of project or construction management. In other words, how the contractor, subcontractor, or department gets the job done is their own business and is irrelevant as long as they meet their "contractual" commitments. Construction can thus be said to have no theory of production control proper.

This way of thinking is problematic. First of all, it is assumed that sufficient coordination of "contractors" can be achieved solely by means of initial schedules and budgets; i.e., through defining, awarding, then enforcing commitments. Work order release is accomplished by mobilization notices or their equivalent, with no significant additional coordination required among the "contractors" as they execute those commitments. This story is plausible only to the extent that the various "contracts" or work scopes are independent, and only to the extent that those scopes do not change. No theory of production control is needed in a construction world that is stable and predictable. In fact, however, construction is highly uncertain. Stability and predictability are actually the consequences of production control, rather than arguments against the need for production control. Further, construction's objects are complex wholes such that the design and construction of their parts are necessarily interdependent one with another. This paper is a contribution to a much-needed theory of production control in construction.

Introduction

Construction production control systems can be usefully conceived and represented as consisting of three hierarchical levels, corresponding roughly to manufacturing's 1) aggregate production planning, 2) material coordination and workload capacity, and 3) work order release and production unit control. As shown in Figure 1, the construction project levels are:

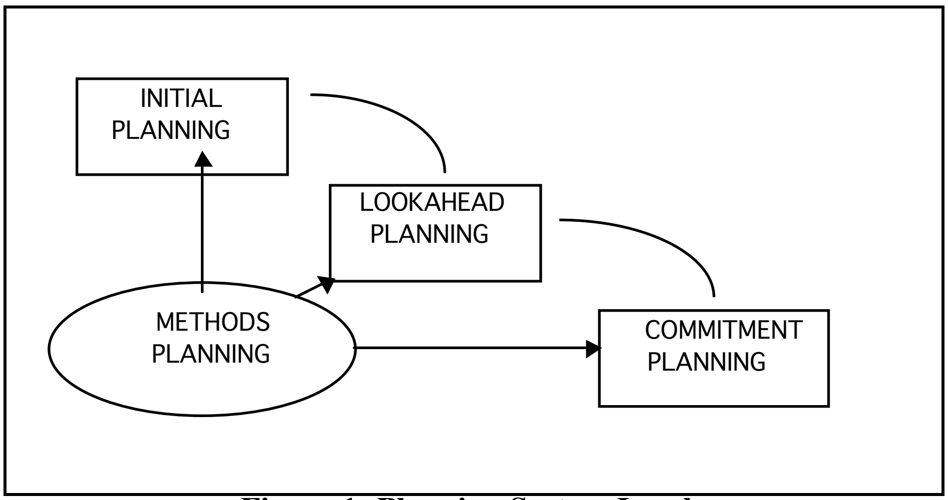

Figure 1: Planning System Levels

1) Initial Planning, which produces the project budget and schedule, and provides a coordinating map that "pushes" completions and deliveries onto the project, 2) Lookahead Planning, which details and adjusts budgets and schedules, "pulling" resources into play, 3) and Commitment Planning, which is a commitment to what will be done, after evaluating 'should' against 'can', based on actual receipt of resources and completion of prerequisites. Methods Planning, which decides how work is actually going to be done, is a component in each of the three levels, with progressively more detailed specification of methods from top to bottom. While all components are essential to an effective production control system, Commitment Planning is the starting point, and is the subject of this paper.

Influenced by the seminal work of Victor Sanvido (1984) on systems, Lauri Koskela (1992) on flows, and Alexander Laufer on construction project planning (Laufer and Howell1993), the authors have conducted research over the last five years on production control in both the engineering and construction phases of projects. Our experience with changing how organizations actually control production suggests that change begin with Commitment Planning. This strategy imitates that followed by Toyota in the implementation and development of their lean production system. Toyota chose to eliminate intermediate inventories on the factory floor in order to force defects and delivery problems to the surface. Their rule was (and is) to stop production rather than send bad product down the line.

Construction differs from manufacturing in many ways, but one way is in the primacy of directives as means of managing work flows and resources. The construction analog to stopping production rather than pass on bad product is to make only quality assignments. Committing to that principle exposes one to the risk of not using available productive capacity and to the risk of failing to meet scheduled dates, i.e., the consequences of 'stopping the production line'. However, it also reveals what management needs to know in order to truly control and improve production.

The focal point of the authors' research has been the production unit and the assignments that direct their work. The research has supported the claim that performance against Commitment Plans can be improved by improving the quality of assignments, and that production unit productivity also increases. Making only quality assignments shields production from work flow uncertainty, and is the first step in a process of implementing a production control system for construction.

Quality Requirements of Commitment Plans

Commitments by production units to specific activities and tasks are often made weekly. Weekly work plans are effective when they meet specific quality requirements for definition, soundness, sequence, size, and learning:

1) Definition: Are assignments specific enough that the right type and amount of materials can be collected, work can be coordinated with other trades, and it is possible to tell at the end of the week if the assignment was completed?

2) Soundness: Are all assignments sound, that is: Are all materials on hand? Is design complete? Is prerequisite work complete? Note: During the plan week, the foreman will have additional tasks to perform in order to make assignments ready to be executed, e.g., coordination with trades working in the same area, movement of materials to the point of installation, etc. However, the intent is to do whatever can be done to get the work ready before the week in which it is to be done.

3) Sequence: Are assignments selected from those that are sound in the constructability order needed by the production unit itself and in the order needed by customer processes? Are additional, lower priority assignments identified as workable backlog, i.e., additional quality tasks available in case assignments fail or productivity exceeds expectations?

4) Size: Are assignments sized to the productive capability of each crew or subcrew, while still being achievable within the plan period? Does the assignment produce work for the next production unit in the size and format required?

5) Learning: Are assignments that are not completed within the week tracked and reasons identified?

Quality assignments shield production from work flow uncertainty. Failure to make quality assignments exposes production units to non-productive delays looking or waiting for resources, to multiple stops and starts, and to inefficient construction sequences and the resulting rework. Even more destructive of productivity is failure to match workload and labor capacity, which is consistently possible only by managing work flow through matching resources with production tasks that are otherwise ready.

Assignments

The authors employ a method of graphically displaying systems that is called Work Mapping (Talley and Ballard 1986). In the graphic conventions of Work Mapping illustrated in Figure 2, processes have two kinds of inputs: 1) resources that are used completely or partially in the production of outputs, and 2) directives specifying desired input, process or output characteristics. Resources are the outputs of procurement processes. Directives are the outputs of planning processes.

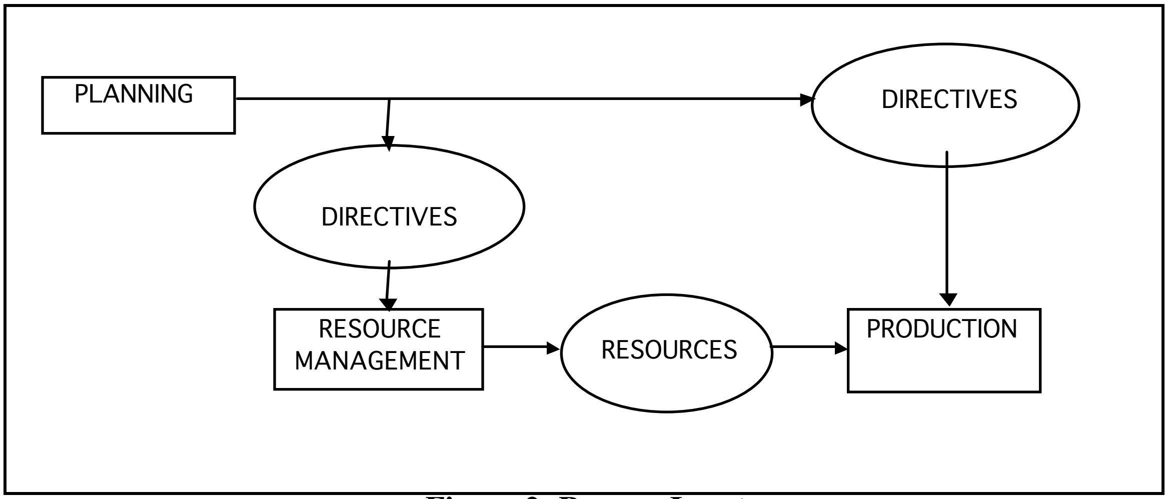

Figure 2: Process Inputs

The ultimate directive is an assignment to a production unit that shapes physical work. If design information is inadequate, materials are missing, or prerequisite work is incomplete, the assigned work will cost more, take more time or be done incorrectly, if at all. In such cases, the assignment does not meet quality requirements. Improving the quality of such directives is vital if performance is to be improved.

Work Flow Uncertainty

There are various types of uncertainty relevant to the management of production on construction projects. Howell et al. (1993) have discussed 1) uncertainty of project objectives and 2) uncertainty of the means for achieving those objectives. In addition, there is 3) uncertainty regarding work flow to production units within the project, and 4) uncertainty regarding the availability of labor and labor-related resources such as tools and equipment. Deliveries of information, drawings or materials may slip. Work that must be completed prior to beginning later work may not finish when scheduled or promised.

These various types of uncertainty are interdependent. Project objectives may change once the means required to achieve them are revealed. Late deliveries of resources or completed work can radically change the best available means, e.g., installation sequences, costs, or durations. Market or technologically driven changes in objectives can impact schedules and budgets (means). Uncertainty of labor and related resources is often greater when work flow uncertainty is high because trade contractors cannot be sure that there will be production work available to their crews, and consequently try to make the best bets in the circumstances. In this paper, we restrict our attention to work flow uncertainty, without exploring its interdependency with other types of uncertainty.

Consider a simplified model of the construction process, consisting of multiple production units, each represented by a box, linked together in customer/supplier relationships. Figure 3 shows an example, in which an engineer produces drawings, which a fabricator uses to fabricate pipe, which a contractor installs. When it is

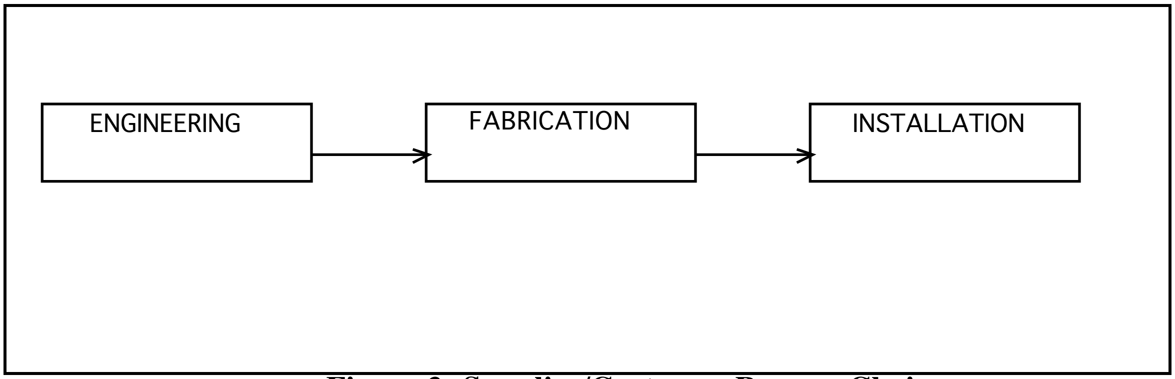

Figure 3: Supplier/Customer Process Chains

impossible to determine what and how much work will be available at a future time, it is impossible to arrange for the specific resources needed, and it is impractical to develop detailed methods and to make detailed preparations for doing what could be widely different types of work. Thus the certainty of work flow from one production unit to the next is a key to productivity.

Strategies for Managing in Conditions of Work Flow Uncertainty

Since current approaches to construction project management do not provide a conceptual basis or practical tools for controlling production, it is hardly surprising to find that flexibility was the most common strategy for managing production (as opposed to controlling it in the manufacturing sense) in the face of high work flow uncertainty (Howell and Ballard 1995, 1996). The flexibility strategy consists of mobilizing resources sufficient to do whatever work happens to come through. Redundant resources, multiple stops and starts of operations best performed as a whole, inefficient sequencing of tasks, and inability to do detailed advance planning render this approach very expensive. When this strategy is practiced by a production unit, it also passes on the work flow uncertainty to its customer processes, thus multiplying the uncertainty and the expense. However, the flexibility strategy is relatively easy to carry out, and the increased cost can be at least partially offset by blaming others for failing to keep their commitments. It may appear to be the only alternative for participants interdependent with others in the production process, but organizationally independent and uncoordinated.

Shielding Production: The First Building Block in a Comprehensive Approach to Production Control

Shielding production is an alternative strategy in conditions of work flow uncertainty. Shielding is accomplished by making quality assignments, thereby increasing the reliability of Commitment Plans such as weekly work plans. Figure 4 illustrates a production control strategy for improving plan reliability, and so fighting back against uncertainty by making only quality assignments.

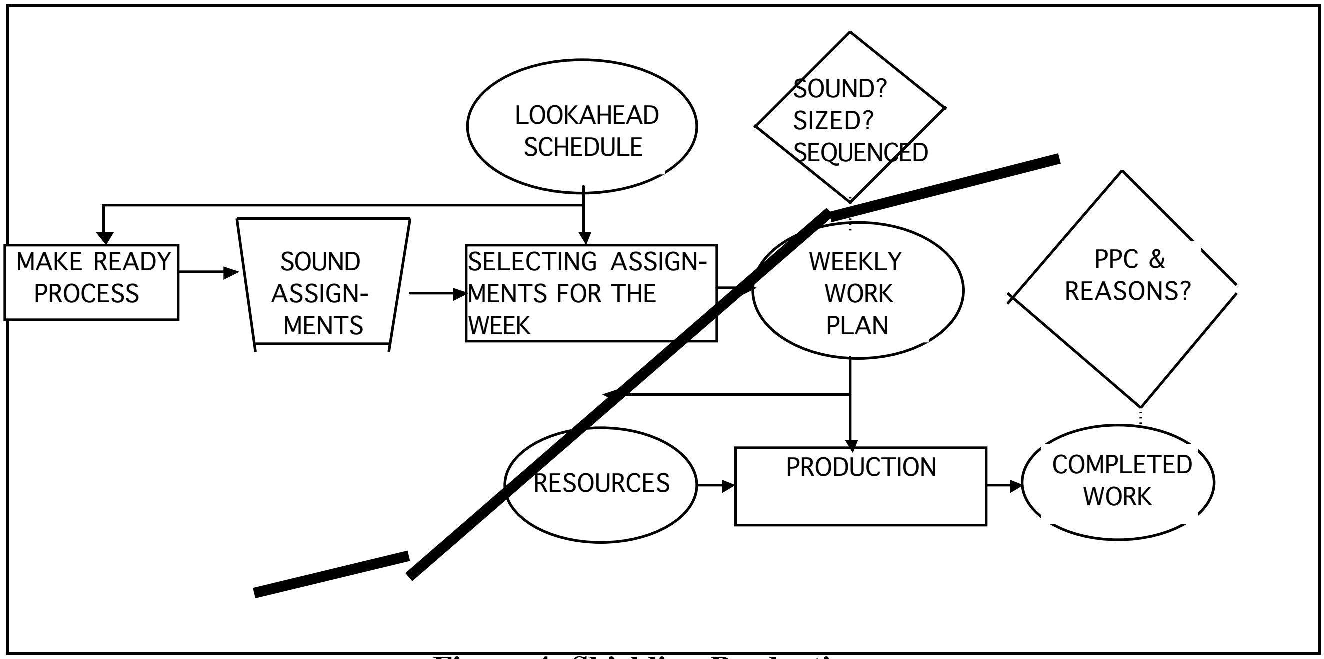

Figure 4: Shielding Production

The shielding process begins with an initial screening of scheduled activities carried out in the formation of a lookahead schedule, which drives a make-ready process that matches resources with opportunities so that production throughput is maximized. Its output is a buffer of sound assignments, from which to select assignments each plan period. This produces a near term Commitment Plan, which is most often a weekly work plan in construction. Weekly work plans are inspected for soundness, sizing, and sequence before being approved for production. After resources have been consumed by production processes, resulting in completed work, Percent Plan Complete (PPC), calculated by dividing the number of completed assignments by the total number of assignments each week) is calculated and reasons are identified and acted on for failures to complete assignments. This is a strategy that improves productivity at the production unit using the buffer. In addition, it increases the certainty of work flow to customer processes, allowing them to improve their productivity, and ultimately allowing a recovery of the schedule time spent accumulating the buffer and potentially even an absolute reduction in duration of flow through the entire chain of processes (Ballard and Howell 1995).

Commitment Planning Procedure

Figure 5 shows the sequence of actions taken by the foreman in the production and use of weekly work plans, the most common form of Commitment Plans in construction. By the end of each week, every foreman prepares the next week's work by doing the following:

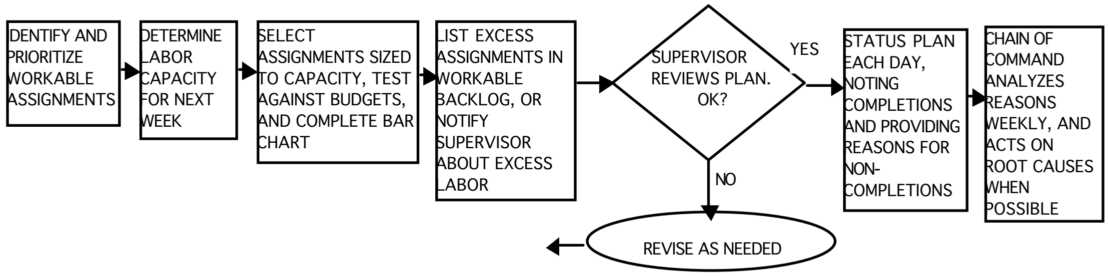

Figure 5: Foreman Weekly Work Planning Procedure

a) Identify the assignments that are sound and the relative priority of those assignments, using information provided by his/her supervisor, and from the foreman's own knowledge of field conditions and what is happening next week.

b) Determine the manpower expected to be available next week, taking vacations and other planned absences into account.

c) Make sound assignments to crews and subcrews, in order of priority, completing a bar chart planning sheet, until all crew members have assignments for the entire week, or until the foreman runs out of sound assignments.

The foreman sizes assignments to his/her expectations of crew and subcrew capabilities by identifying the steps involved in the work, crewing the work accordingly, and estimating durations. Where possible and appropriate, sizing is tested against target costs provided by the foreman's supervisor. Work methods and production rates are optimized within practical limits through detailed planning and analysis of the first operations of each type (Cf. Methods Planning in Figure 1; also Ballard and Howell 1994b).

Assignments are specified with sufficient detail so that it can be determined if they were completed at the end of the week. This may be accomplished by quantifying, referencing drawings to be completely installed, or some other unambiguous means such as saying "all toilets on the 2nd floor of Building A".

d) If work is left over after crews are fully loaded, the foreman lists that work on the planning sheet as workable backlog.

e) If manpower is left over, the foreman notifies his/her supervisor and asks for instructions.

f) Once the plan is completed, the foreman asks his/her supervisor to examine it. Once the plan is signed off, the foreman's responsibility is simply to complete planned assignments, while doing quality work and working safely. Responsibility for sequencing and sizing belongs to the supervisor. Foremen are evaluated on their ability to complete planned work only to the extent that obstacles and constraints lie within their control.

Note that craft supervisors must work closely with foremen in the production of weekly work plans, especially in order to communicate information regarding soundness (other craft activity, expected deliveries, etc.), priority sequencing, and sizing. These supervisors check weekly work plans for conformance to quality requirements of definition, soundness, sequence, and size, and then take the initiative in learn and act on reasons why planned work does not get done, when those reasons are outside the control of the foreman.

During the week, each foreman:

g) Statuses his/her plan each day, marking whether or not assignments were completed as planned, and providing a reason why planned work was not done. Reasons are discussed with the supervisor in order to get closer to root causes, so that action can be taken to prevent future occurrences.

h) Each week, project management/supervisors chart the total PPC for the project and reasons why planned work was not done. The goal is to continuously increase PPC up to 100% by eliminating reasons.

Figure 6 shows a weekly work plan for a foreman and crew working on a 1995 refinery expansion project in Venezuela. Assignments are expressed in terms of the specific items that are to be installed and so are satisfactorily <u>defined</u>. Workable backlog is listed on the plan, indicating that prioritizing and <u>sequencing</u> have been done. The crewing of each activity by means of the bar chart indicates that an attempt was made to <u>size</u> the work to fit the crew. (In this case, only the planned allocation of labor is shown. Other forms show both the planned and actual labor allocation.) Lastly, the foreman has noted which assignments were completed and has provided reasons for failing to complete assignments, some of which indicate that the assignments were not <u>sound</u>. For example, two assignments could not be completed because of missing material. By acting on these reasons, the foreman and the contractor for which he worked <u>learned</u> how to make better assignments, thus improving craft productivity and the reliability of Commitment Planning (Ballard et al. 1996).

CONTRACTOR: Formiconi

WEEKLY WORK LIST

FOREMAN: Vera

Week Ending: 11/1/95

		T	F	S	S	M	T	W	COMMENTS
1	28386F1 - 02 & 03	4	4	-	-				OK
2	3035YF1 - 93	4	4	-	-				changed priorities
3	2838YF1 - 04	4	4	-	-				OK
4	0349YF2 - 03	4	4	-	-				prereq. work not done
5	0349YF2 - 07					4		2	missing material
6	0349YF2 - 08					4		2	prereq. work not done
7	1501-D1 -21, -22, -23					4		2	OK
8	supports 201G1 - 6 & -7					4		2	OK
9	12305YD1-03,-02,-01						4	2	missing material
10	0658D1-02						4	2	OK
11	605D1-02,-04						4	2	changed priorities
12	607D1-01						4	2	OK
13									
14									
15									
									PPC=6/12=50%

WORKABLE BACKLOG

1 supports 204G1-2, -3
2 0907 YH1
3 0906 YH1
4 0921 F3 -01
5 0921 F3 -02
6 0921 F3 -03
7 support 203
8

Figure 6: Weekly Work Plan

PPC and Performance Improvement

Figure 7 shows the improvement in PPC of a contractor on the same Venezuelan project over a period of several months. PPC increased from approximately 65% to 85% as a result of improving the quality of assignments (Ballard et al. 1996).

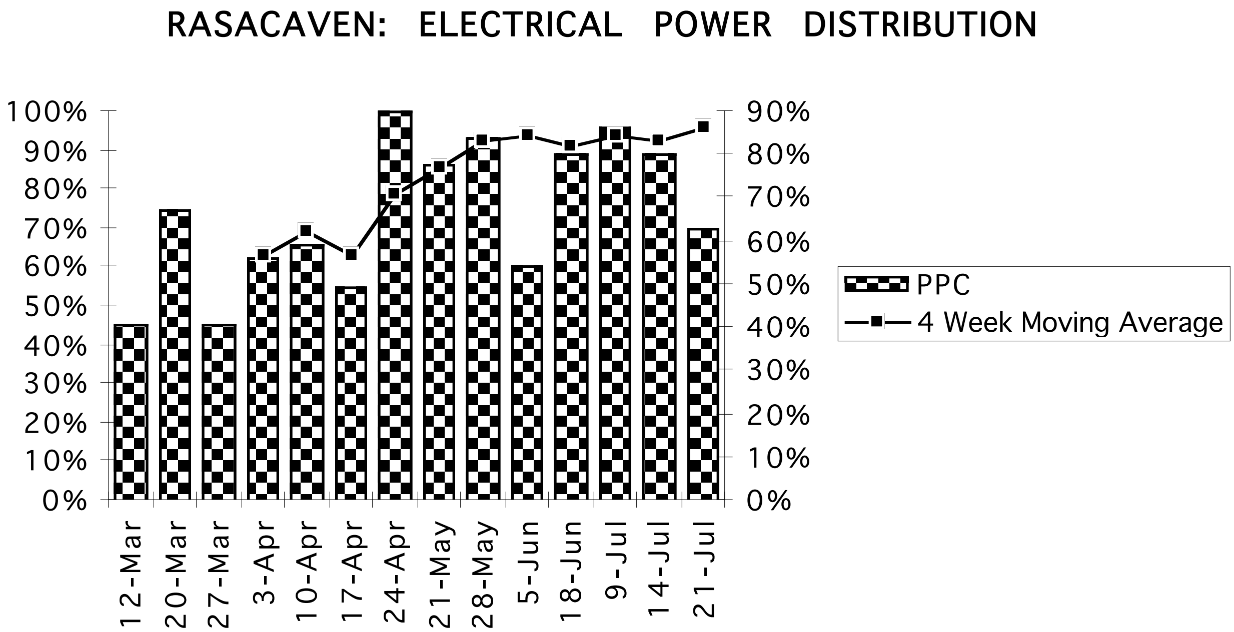

Figure 7: Improving PPC

Figure 8 shows a typical reasons chart, graphically displaying why weekly assignments

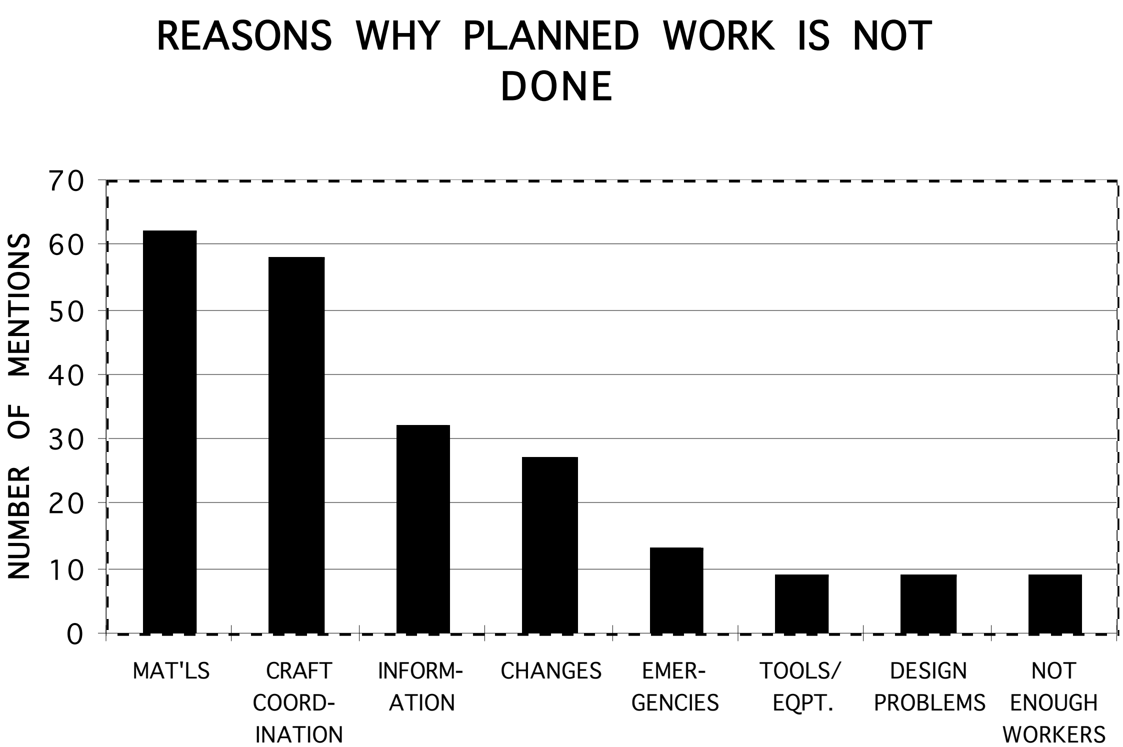

Figure 8: Reasons Chart

were not completed. Many of these reasons are within the control of the contractor. Consider insufficient or incorrect materials: Why were foremen allowed to select assignments for which the correct type and amount of materials had not been previously acquired and reserved for that use?

As shown in Figure 9, reasons for not completing assignments can be divided into plan quality failures resulting from quality defects in the assignments themselves, and into execution failures resulting from other causes. Unexpected absences and even equipment breakdowns may be considered execution failures, whereas missing tools or materials are definitely plan quality failures. The distinction between these two categories is obviously not firmly defined, since one may choose to change the types of reasons that the production control system is designed to eliminate. Indeed, the distinction between plan quality failures and execution failures is useful insofar as it focuses management attention on preventing what can practically be prevented.

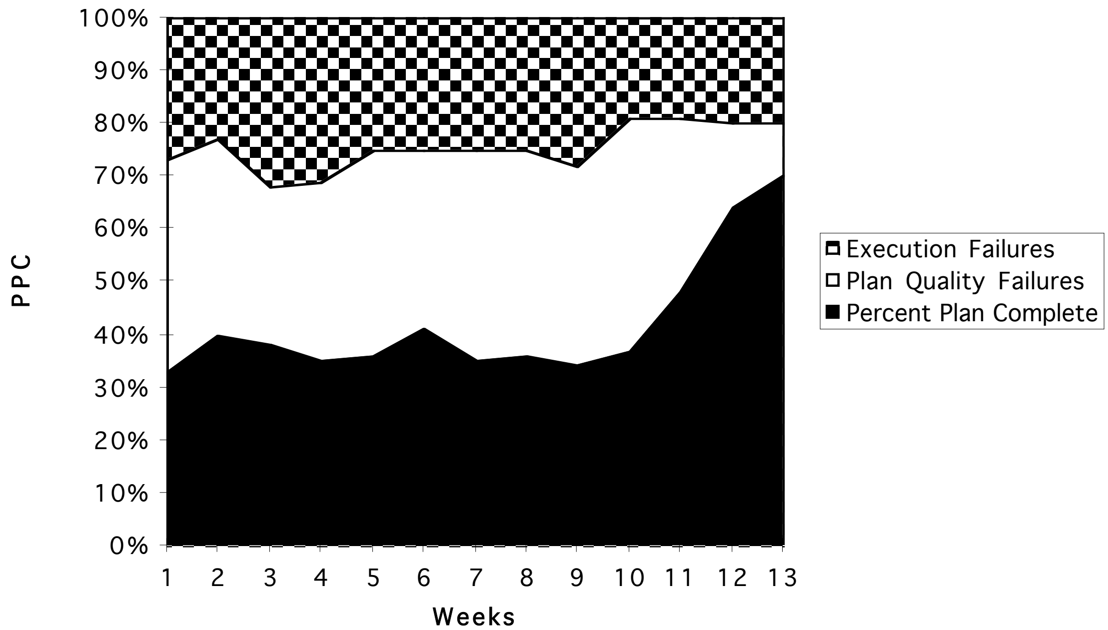

Figure 9: Plan Quality Failures

Improving the quality of directives effectively shields production from flow uncertainty, immediately improving productivity in the work groups responding to the directives, and increasing the lead time and reliability of information needed by ‘customer’ production processes for better planning and performing their work. Figure 10 shows the difference in productivity, measured in terms of performance factor[3] , between pipefitter crews on a refinery project that averaged completing less than half their weekly assignments

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[3] Performance factors are an indirect measure of productivity, calculated as a ratio of actual to expected productivity, measured either by dividing earned labor hours by actual, as in this case, or vice versa.

and crews that averaged completing more than half. The crews with higher PPC have 30 points better PF, shown as the difference between 1.15 and .85 in Figure 10.

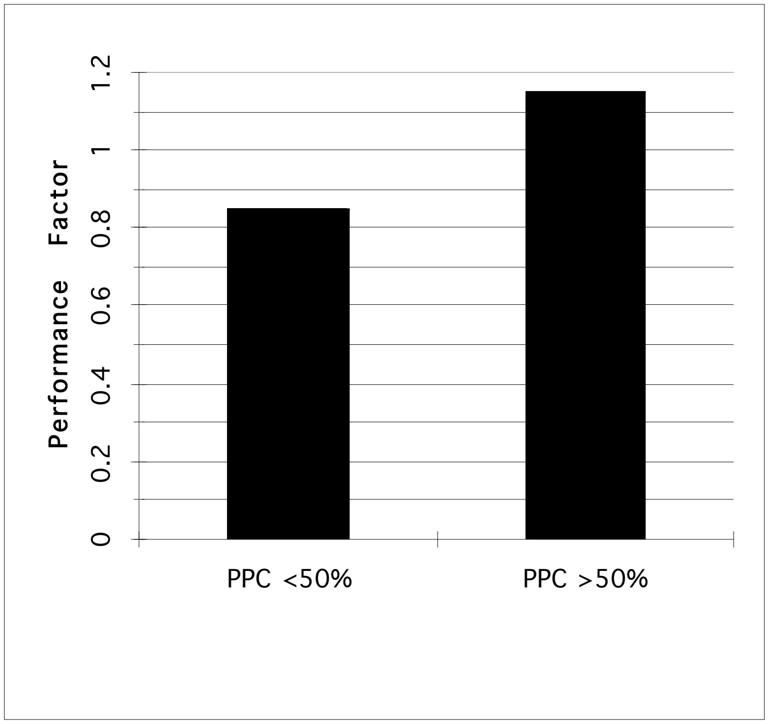

Figure 10: PPC and Productivity

Defensive Reactions

The recommendations above may seem to some to describe standard industry practice, but research does not support that view (Howell and Ballard 1995, 1996; Ballard et al. 1996). In fact, it is by far the exception rather than the rule to find construction contractors who make quality assignments, and even rarer to find engineering firms or departments that do so. Many more-or-less consciously pursue a strategy of flexibility, attempting to be prepared for whatever work may become available. Some make weekly assignments, but few observe the quality requirements of soundness, sizing, and sequencing. None track PPC and reasons in an effort to improve the performance of the production control system.

Those whose practice is inconsistent with the production control model and procedures advocated here often struggle against that fact. Three refuges are so popular as to warrant comment.

1) Shielding is unnecessary.

Some claim that shielding is unnecessary, arguing that work flow is sufficiently reliable that production unit weekly assignments can be derived directly from the master schedule, and can be safely left in the hands of field supervision. Research data thus far collected contradict that claim. Many engineering and construction contractors do not define assignments sufficiently to determine if they were completed or not. Where measurement is possible, prior to implementing the shielding rules we have described, contractors have consistently been found to complete less than 60% of assignments and sometimes as little as 35%. For construction crews, the largest categories of reasons for failure are missing materials and failure to complete prerequisite work (Ballard and Howell 1994a, Ballard et al. 1996, Howell and Ballard 1995). Admittedly, most of the research data has been developed on industrial projects (refineries, pulp and paper mills, chemical plants, water treatment plants), with some significant amount also from commercial building construction (hospitals, high rise office buildings, condominium developments). Since the research has not covered all types of construction, it is a future research task to determine if work flow uncertainty varies with different types of construction, e.g., tunneling, dams, bridges, highways, single family residential, etc.

2) Shielding is impossible.

Another refuge is the claim that shielding is impossible, that work cannot wait while quality assignments are produced. On its positive face, this is actually the argument for flexibility, rooted in the belief that no alternative strategy is consistent with meeting project end dates. We can only point to the companies and projects that have installed planning that shields and have been able to meet end dates while improving productivity and lowering their costs (Ballard and Howell 1994a, 1994b, Ballard et al. 1996). It is obvious that there are situations on schedule-driven projects where it is impossible to avoid sacrificing productivity to schedule. However, we suggest that the relationship between schedule and productivity needs to be reexamined. Productivity is often sacrificed for the sake of schedule, but much less often are schedule benefits actually realized. The flexibility strategy demands early starts. From the standpoint of the strategy of plan reliability, the relevant question is "How long can we wait?" Going slow to go fast may be a paradoxical idea for the construction industry, but it is an idea whose time has come. (Remember that data shows that 30% less labor is needed when planning reliability is above 50%.)

3) We are already shielding.

Some are so persuaded by the proposal that they cannot believe they are not already doing it. To them, we suggest that they make sure. If it is so important, it is important enough to examine actual practice, evaluate weekly work plans and lookaheads against quality requirements, and measure PPC and identify reasons.

Conclusion and Suggestions for Future Research

Work flow uncertainty is made worse by flexibility strategies that sacrifice productivity for the sake of schedule. Progress itself is often slowed rather than accelerated as a result of the longer durations and greater labor time required to perform tasks when done piecemeal and out-of-sequence. A superior alternative is to shield production units from uncertainty by making sound assignments. Shielding improves the productivity of the production unit that is shielded and improves the productivity of customer processes, resulting in lower project costs and shorter durations.

Making only sound assignments forces quality and delivery problems to the surface, analogous to operating a factory production line without inventory buffers, and forbidding bad product to be passed down the line. In this way, manufacturing's theory of production control has been successfully adapted for construction, and the first step toward successful control has been demonstrated.

Once production units are shielded from work flow uncertainty, time and energy are released for improving downstream performance, specifically for detailed design of work methods with high involvement of direct workers and line supervisors. Such initiatives have achieved substantial improvements in productivity and schedule (Ballard et al. 1996). However, even greater improvements can be achieved, building on the research results thus far produced.

Projects are a complex and dynamic network of production units in customer/supplier relationships. To the extent that all production units practice shielding and consequently become more reliable at keeping their near-term commitments, each unit will need to maintain smaller buffers, thus shrinking total project duration and improving overall productivity and cost. It may be said that shielding eliminates the additions to flow uncertainty that resulted from project management itself. In addition, the learning that shielding promotes also leads to reduced flow uncertainty by identifying and attacking its root causes. This allows further reduction in the size of buffers and consequently further reductions in project duration (Huovila et al. 1994).

A further stage of improvement can be reached by increasing the visibility of work flow. Indeed, the lookahead and weekly work plans of supplier processes can be reliable guides for customer planning when flow is more predictable. With such a truly integrated production control system, unavoidable delays and changes can be accommodated with minimum impact on the total project (Ballard and Howell 1995).

Preliminary data indicate that not only productivity increases with PPC, but also that the range of variation of productivity decreases. One of the primary obstacles to detailed production control in construction has been the wide range of productivity within and across crews (Bennett 1985). If plan reliability can be shown to both enhance the mean and reduce the range of production unit productivity, many good things become possible, including reducing buffer sizes.

Further, the implications for greater certainty of work flow are not considered in current approaches to project and contract management, so new thinking will be required in those areas. Construction project management must incorporate an appropriate theory and model of production control in order to increase predictability of performance and to improve performance capability.

In addition to confirming and extending our findings regarding the improvement of production unit productivity through improving the quality of assignments, future research should be devoted to testing the following hypotheses: 1) Improving plan reliability as measured by PPC reduces productivity variation of production units, 2) Work flow uncertainty is sufficiently high that shielding is necessary in all types of construction, 3) Measurement of production control system performance at each hierarchical level provides the information needed for identification and action on root causes of uncertainty, leading to reduced uncertainty and to reduced schedule buffers and project durations, and 4) When all production units within supplier/customer networks practice shielding, total productivity of the network increases and its duration decreases.

Inquiry should be systematically pursued in the area of production controls in general, examining the interdependency of work flow and labor productivity, and looking to manufacturing to absorb and extend/modify its lessons to construction (Melles and Wamelink 1993).

Appendix: Summary of Research by the Authors on Production Management in Construction

The initial research was carried out privately on pulp and paper projects for a single engineer/construct contractor, beginning in 1992. In parallel, work was done with the Navy Public Works Center-San Francisco Bay prior to the decision to close that base (Kartam 1995). These early research efforts sharpened the focus of inquiry and substantiated the problems being addressed. Initial measurements showed high work flow uncertainty, ineffective production unit planning, and high percentages of non-productive time.

The next phase of research was on a greenfields refinery project, focused on designing and implementing a production unit control system for pipefitter crews. This 1993-4 project provided the first data confirming an increase in plan reliability after conforming planning processes to produce quality assignments, and also confirming a corresponding increase in productivity. It was also the first successful integration of materials coordination into the production control system (Ballard et al. 1994).

In 1994, an effort to replicate production control system redesign with yet a third engineer/construct contractor failed for lack of management support. This experience sharpened understanding of the pressure for production and the associated flexibility strategy. It was on this project that a superintendent argued for manning to the schedule regardless of its achievability, as a means of putting pressure on the engineering and procurement departments of his own company. In addition, quality characteristics of assignments were sharpened and clarified. Initial measurements of PPC were below 50%. Rudimentary screening improved PPC to 70%. No data on productivity was collected.

Research for the Construction Industry Institute began in 1993 (Howell and Ballard 1996). Data was collected showing that large buffers of pipe were necessary, though not sufficient, for good schedule and cost performance of industrial projects. These buffers were found to be sized without regard to the anticipated degree of work flow uncertainty on the project. In addition, buffers were found to be the result of political pulling and shoving between interdependent parties, and rarely to be either sized or located for optimum impact and least cost of the project as a whole.

In 1995, the plan reliability strategy was implemented on a major refinery expansion project in Venezuela (Ballard et al. 1996), resulting in productivity improvement across the board of 28%. Perhaps even more important, there was a direct confrontation between the flexibility and plan reliability strategies. Prior to redesigning the production control system, the project had intended to increase peak manning by 80% in order to hold schedule in conditions of low productivity. This project also sharpened the distinction between managing contracts and managing production, and led the researchers to realize that project management is currently conceived and practiced largely without regard to the flow of work across production units, but rather is concerned with the enforcement of contractual and quasi-contractual obligations of each production unit alone.

Work continued with the original engineer/construct contractor throughout these years, with major successes achieved. The first success involved site management of work flow through a structured lookahead process. Subsequently, the scope of redesign was extended to embrace the entire engineer-procure-construct team, in an effort to extend work flow management upstream, while continuing shielding of site construction crews. Lastly, shielding itself was applied to engineering squads, an initiative still underway. Engineering was found to lack explicit assignment and make-ready processes, and to experience even greater work flow uncertainty than construction.

In 1995-96, the production control system of a speciality contractor (waterproofing and roofing) was restructured in accordance with the findings of previous research, resulting in substantial improvements in gross profit margin. This experience expanded the focus of the researchers from single projects to multiple projects, and exposed them to the peculiar planning difficulties of subcontractors. Success at making only sound assignments to the subcontractor's crews has been limited by the effectiveness of their clients' planning systems, which routinely fail to ensure that prior work is completed before demanding that a subsequent activity start, and which routinely fail to provide sufficient lead time to properly prepare for efficient execution.

Also in 1995-6, research was done for the National Electrical Contractors Association (Howell and Ballard 1995), which confirmed previous findings of highly uncertain work flow, unstructured assignment formation and selection processes, and dedication to strategies of flexibility (known to some as "just-in-case"). The second phase of that research is devoted to redesign of electrical contractor production control, and measurement of both PPC and productivity. It is scheduled for completion in 1997.

In 1996, a diagnostic evaluation was performed on the production control system of a chemical plant construction project. The principal findings were that productivity was being sacrificed for the sake of schedule, but that the gains in schedule were not being realized. Productivity, especially in piping, was poor, but the project was on its earnings plan. That was achieved by working around missing materials, e.g., by hanging pipe spools on temporary hangers. Analysis suggested that the physical percent complete was inflated. Not only was work counted as complete that would require additional labor hours in the future, but work was installed out-of-sequence so that future activity durations would be extended. In addition, there would be negative impact on trades such as electrical that follow piping. This was important because it revealed that flexibility strategies, which admittedly increase production costs, may also be ineffective in terms of maintaining end dates. It was also important because of the strength and experience of both the owner's and the contractor's management team. The problems on the project were not a result of errors or mistakes in applying the best of current project management theory and techniques, but rather their direct result.

Currently the authors are working with a major mechanical contractor, restructuring the entire production control system, from multiproject resource planning to weekly work planning and methods design. Among the objectives are detailed specification of the lookahead process and linkage of lookahead plans to internal and external organizations responsible for making assignments ready, such as project management (design clarifications, major equipment expediting), fabrication shops, the coordination department that produces installation drawings, other trade contractors, the general contractor, commodity suppliers, etc.

Most of the research has been carried out in conjunction with consulting assignments. Consequently, data has been collected and experiments conducted largely as members of project construction management teams. In very few cases has data been collected by means of questionnaire surveys, and in no case has survey data or data collected by other means been accepted without rigorous scrutiny. Generally, the research has proceeded through changing something about how production is controlled, then measuring the results of those changes on plan reliability (PPC) and productivity.

In addition to research carried out by the researchers, others have done related research under their influence. Kartam (1995) did research for his Ph.D. partly on the construction of a water purification plant, and helped the contractor achieve significant performance improvements. Cruz (1996), a Master's student at the Catholic University of Chile, applied the researchers' production control ideas to a Chilean contractor and helped that company cut activity durations in half, while improving productivity by more than 70%.

References

Ballard, G. and Howell, G. (1994a). "Implementing Lean Construction: Stabilizing Work Flow." *Proceedings of the 2nd Annual Meeting of the International Group for Lean Construction*, Santiago, Chile. (Available in *Lean Construction*, A.A. Balkema Publishers, Rotterdam, Netherlands, 1997.)

Ballard, G. and Howell, G. (1994b). "Implementing Lean Construction: Improving Performance Behind the Shield." *Proceedings of the 2nd Annual Meeting of the International Group for Lean Construction*, Santiago, Chile. (Available in *Lean Construction*, A.A. Balkema Publishers, Rotterdam, Netherlands, 1997.)

Ballard, G. and Howell, G. (1995). “Toward Construction JIT.” *Proceedings of the 1995 ARCOM Conference,* Association of Researchers in Construction Management, Sheffield, England.

Ballard, G., Howell, G., and Casten, M. (1996). “PARC: A Case Study.” *Proceedings of the 4th Annual Conference on Lean Construction*, Birmingham, England. (available at http://www.vtt.fi/rte/lean/)

Ballard, G., Howell, G., and Kartam, S. (1994). “Redesigning Job Site Planning Systems.” Conference on Computing in Civil Engineering, ASCE, Washington, D.C.

Bennett, J. (1985). *Construction Project Management*. Butterworths, London, England**.**

Bertrand, J. W. M., Wortmann, J. C., and Wijngaard, J. (1990). *Production Control: A Structural and Design Oriented Approach*. Elsevier, Amsterdam, The Netherlands.

Cruz, J. C. (1996). "Diagnosis, evaluation and improvement of planning systems." Master’s thesis, Catolica Universidad de Chile at Santiago, Chile.

Howell, G. and Ballard, G. (1995). “Improving Performance in Electrical Construction: An Implementation Strategy and Planning System Audit.” Prepared for the National Electrical Contractors Association, 1995.

Howell, G. and Ballard, G. (1995). “Managing Uncertainty in the Piping Function.” Construction Industry Institute, University of Texas, Austin, TX., November, 1995.

Howell, G., Laufer, A., and Ballard, G. (1993). “Uncertainty and Project Objectives.” *Project Appraisal Journal*, 8, pp. 37-43. Guildford, England.

Huovila, P., Koskela, L., and Lautanala, M. (1994). "Fast or Concurrent-The Art of Getting Construction Improved." *Proceedings, 2nd Annual Conference on Lean Construction*, Santiago, Chile. (Available in *Lean Construction*, A.A. Balkema Publishers, Rotterdam, Netherlands, 1997.)

Kartam, S. (1995). “Reengineering Construction Planning Systems.” Ph.D. Dissertation, Department of Civil Engineering, University of California at Berkeley, CA.

Koskela, L. (1992). “Application of the New Production Philosophy to Construction”. *Technical Report No. 72*, Center for Integrated Facility Engineering, Stanford University, Stanford, CA.

Laufer, A. and Howell, G. (1993). “Construction Planning: Revising the Paradigm.” *Project Management Journal*, 24 (3).

Melles, B. and Wamelink, J. W. F. (1993). *Production Control in Construction*. Delft University Press, Delft, The Netherlands.

Sanvido, V.E. (1984). “Designing productivity management and control systems for construction projects.” Ph.D. Dissertation, Department of Civil Engineering, Stanford University, Stanford, CA.

Talley, J. and Ballard, G. (1986). Unpublished papers. Described in Kartam (1995).