PRODUCTION PRACTICES FOR HIGH RELIABILITY IN CONCRETE CONSTRUCTION

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ABSTRACT

This study examined the production control practices that a high-reliability supervisor used to accelerate the schedule and minimize waste during the construction of a 10-story cast-in-place concrete building. A "high-reliability" supervisor is one who has consistently exceptional performance in both productivity and safety. From a lean construction perspective, this case study is concerned with the production control practices that achieved an accelerated schedule, while minimizing waste and maintaining high levels of safety. The authors collected extensive data from the project including interviews with the supervisor and the work crew, and regular work observations over a period of eight weeks. The paper describes the project and project demands, the activities and work sequence. The findings highlight that in order to meet the aggressive milestones, the supervisor used several production control strategies that created a highly reliable work process. These strategies included: specializing in "product lines" (horizontal and vertical concrete elements), reducing product variety (the number of different concrete mix designs), standardizing the work process, emphasizing manpower reliability and predictability (e.g., minimizing absenteeism), reducing task complexity and time pressures (by simplifying and decoupling tasks), preventing errors, exploiting limited resources (in this case the crane), etc. As a result, the case findings identify specific production control practices that minimizing waste and reduce cycle time.

KEYWORDS

Production system design, production planning, time compression, safety, high-reliability supervisor.

INTRODUCTION

This case study analyzes the work organization and production practices of a high reliability field supervisor in a concrete construction firm. The work practices of the exceptional supervisor were observed and documented during the construction of a 10-story concrete frame for a commercial building with a very aggressive schedule. This project provided the opportunity to investigate how an exceptional supervisor organized and managed the work to reduce the schedule, while minimizing waste and maintaining high levels of safety.

This study is part of an on-going research effort that investigates work practices that result in both high production and high safety (Mitropoulos and Cupido 2009, Memarian and Mitropoulos 2010, Mitropoulos and Guillama 2010). To accomplish this, the research investigates the work practices of 'high-reliability' field supervisors

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and crews. The term High Reliability Organizations (HROs) has been used in organizational research to describe organizations such as aircraft carriers, nuclear power plants and wildland firefighting crews who function extremely reliably under very uncertain and hazardous environments. In the context of this research, 'high reliability crews' are defined as those construction crews and supervisors who consistently achieve very high levels of production and safety, even during challenging project conditions. From a lean construction perspective, this case study is concerned with the production control practices that achieved an accelerated schedule, while minimizing waste and maintaining high levels of safety.

BACKGROUND

Schedule pressures are considered an important factor that increases the likelihood of accidents. Hinze and Parker (1978) found that production pressures and crew competition are related to more injuries, and suggested that job practices are more important than safety policies in preventing accidents. The negative effects of schedule pressure include: working out of sequence, generating work defects, cutting corners, and losing the motivation to work (Nepal et al. 2006). Safety research has recognized that production pressures can create work overload (Karasek and Theorell 1990, Parker and Sprigg 1999). Excessive demands overwhelm the resources available to meet demands and harm job performance (Bakker et al. 2005, Brown et al. 2005). Furthermore, production pressures can arise from unclear or conflicting messages from management generate role ambiguity that in turn reduces work performance and weakens safety (Hemingway and Smith 1999).

Overtime is typically a consequence of production pressures and has been related to reduced productivity and increased accidents (Hanna et al. 2005). Shift work has also been found to have a significant effect on fatigue. Folkard and Tucker (2003) found strong evidence that both productivity and safety may be compromised at night. A review of the research on piece rates has found that in most situations, piece rates have a negative effect on safety (Johansson et al. 2010).

Schedule acceleration typically increases production cost, as indicated by the Time-Cost Trade-Off concept. This can be due to increased portion of non-productive time (e.g., due to congestion), reduced fruitfulness of the productive time (e.g., due to fatigue), and/or higher cost of labor (e.g., due to overtime rates). Howell et al. (2001) indicated that the Time-Cost Trade-off can be mitigated by increasing the reliability of the production process. Lean construction practices, and specifically the Last Planner System (LPS) emphasize reliability of workflow in order to reduce waste and increase speed. In the LPS system, the primary means for achieving reliability is securing the directives (design, submittals, and authorizations) and resources (material, equipment, manpower) for the work assignments.

The above discussion highlights the effect of schedule and work organization on safety. Based on a cognitive perspective, Mitropoulos and Cupido (2009) proposed that construction safety is considered an emergent property of the production system. From this perspective, the work practices and the team processes of the crew shape the task demands of the situations that the workers face, and the potential for errors and accidents (Mitropoulos and Guillama 2010). Along this research direction, this study investigates the production processes that high reliability supervisors use to achieve both high speed (accelerated project schedule) and safety.

Previous studies of high reliability foremen in framing and masonry (Mitropoulos and Cupido 2009, Memarian and Mitropoulos 2010) found that the production practices of such foremen were shaped by a clear ‘guiding principle,’ which is a strong focus on avoiding errors and rework. These foremen used a set of strategies that support this principle, including actions to prevent disruptions, controlling the production pressures, mitigating the physical and cognitive task demands for the workers, matching skills with task demands, and carefully preparing and coordinating the high demand tasks.

METHODOLOGY

This study used the case study approach, which involves an in-depth examination of the production practices. The selection of the supervisor was a critical concern, as the goal was to investigate the practices of a high reliability supervisor in concrete work. After contacting several contractors, a large concrete contractor who operates in several states agreed to participate in the study and to provide access to data and jobsites. To identify any ‘high reliability’ field supervisors, the management provided assessment and data on the productivity and safety performance of the company’s supervisors. The production performance of field supervisors was assessed over the previous 3 years. The supervisor selected for the study was assessed as performing project with the highest degree of difficulty and having exceptional production and quality performance. Over the previous 3 years he had 1 first aid incident.

Data were collected over a period of 2-months, and included interviews and direct observations. Interviews with the supervisor focused on the organization and sequencing of the work, the selection of work methods, the management of resources, the production goals and pressures, the safety practices, etc. The authors also conducted extensive close observations in order to understand the details of the operation and to cross-examine the data from interviews.

PROJECT DESCRIPTION

The project in this case study was a 10-story office building, with a cast-in-place (CIP) concrete frame and post-tensioned concrete slab. Each floor was about 27,000 Square Feet (SF). The floor layout was typical with minor changes at the second and ninth floors. On each floor there were 28 columns and the elevator shaft. Columns were of two different sizes (24"× 24" and 28"×28") and their dimensions did not change from the first to the last floor. The slab around the elevator shaft was the area that required the highest level of accuracy.

According to the concrete crew superintendent, the design complexity of the project was low and the deck forms were easy to set up. The repetitive layout created a repetitive work process. The main challenge was the very aggressive schedule. The schedule for the CIP concrete frame was to 10 weeks (one floor per week). Furthermore, construction was performed during the summer when the high temperature is consistently above 110 °F. This was another concern in terms of safety risk and productivity loss. The jobsite was congested and different trades were working very close to each other.

WORK ORGANIZATION

The concrete supervisor divided the concrete work into two major operations: horizontal (deck) and vertical (walls and columns) concrete work, and assigned a specialized crew to each operation. To shorten the schedule, a night crew was also used that continued the work of the deck and vertical crews, as needed. The contractor for the reinforcing steel was a subcontractor to the concrete contractor. Overall, three crews were working in parallel during the day time (horizontal, vertical and rebar crews) and the night crew was working from 8 p.m. to 6 a.m. Each floor was divided into two halves, and the deck and vertical crews were working on different halves in parallel. A concrete placing crew poured and finished the concrete slabs. The vertical crew poured the columns and walls themselves.

The work schedule was 6 days a week (Monday through Saturday), 10 hours a day. The supervisor established a standardized repetitive work process. For each section A (the first half of the slab) the deck was poured on Thursdays at 9:00 p.m., and the walls and columns on Friday on at 1:00 p.m. The deck for section B was poured on Mondays at 9:00 p.m. (section B), and the walls and columns on Tuesday at 1:00 p.m.

CONCRETE DECK OPERATION

The concrete deck crew consisted of 18-20 members including one superintendent, one foreman, two leadmen carpenters, 10-12 carpenters, one grader, and three laborers. The supervisor who planned the entire operation was also in charge of the concrete deck operation. On this project, the Elevated Aluminum Tables system was used for the deck formwork. Tables were adjustable to be used at different heights and had folding wings to cover perimeter of the column. The concrete deck crew performed the following activities for each half of slab, as figure 1 shows:

Section A	Monday	Tuesday	Wednesday	Thursday (night)
Section B	Thursday	Friday	Saturday	Monday (night)

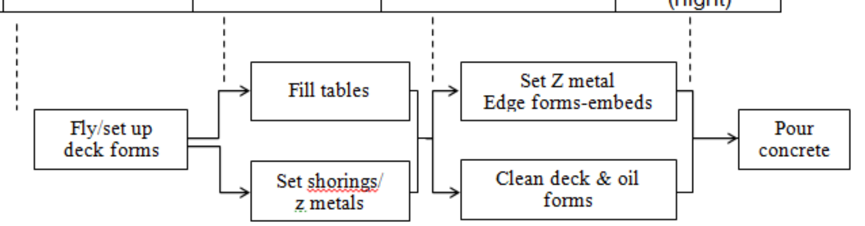

Figure 1: Deck crew's activities

- **Set up deck forms.** When a deck was stripped, the crane would lift the tables to the next level and place them at the correct position. Once the tables were set up, a grader would start grading (leveling) them.
- **Fill tables.** After the tables were set, two carpenters would fill the gap between the table wings and columns using 2×4 and plywood.
- **Install "Z metal".** Z shaped plates were used to form the sides of deep concrete beams. Z metal is easy to install (nailed down) and either carpenters or laborers can install it.
- **Set edge forms.** Plywood and 2×4 were used to form the edge of the slab.
- **Install steel embeds.** There were 250 pieces of embed for each half a floor.
- **Set shoring.** The quick-pop adjustable aluminum shores were installed at every six feet.

- **Clean the deck and oil the forms.** This tedious task was the last task before concrete placement.
- **Pour concrete.** A concrete placing crew poured concrete.
- **Strip & fly tables.** When the concrete was adequately cured, the crew striped the edge forms and removed the shoring. Then the tables were stripped and rigged to the next floor.

VERTICAL CONCRETE OPERATION

The vertical concrete crew consisted of 9 members—1 field supervisor, 1 carpenter foreman, 5 carpenters, and 2 apprentices. The supervisor was in charge of management tasks and the foreman was closely monitoring the crew's performance and participating in the wall form setting activity. The carpenters' tasks included installing embeds, installing rebar chairs, setting and plumbing wall and column formworks. Apprentices mainly performed support tasks including cleaning and oiling forms and ties, housekeeping, material handling, etc. The vertical work crew performed the following activities for each half of slab in a three-day work cycle, as figure 2 shows:

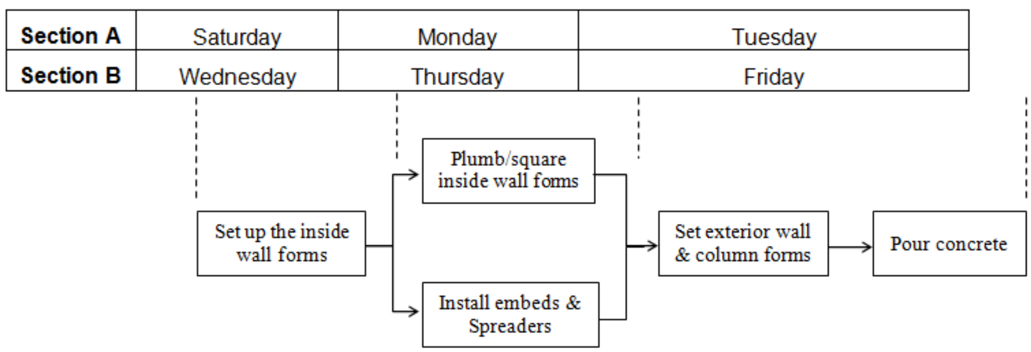

Figure 2: Vertical work crew's activities

- **Install embeds and spreaders.** Embeds are steel plates installed in the walls before pouring. Spreaders (rebar chairs) are accessories installed on the rebar cage to maintain the clearance between form and rebar.
- **Prepare the forms & ties.** This activity was to clean and oil the wall panels and column forms.
- **Set the inside wall forms.** The wall forms were formed by inside and outside formworks. To raise the inside forms, the crew used rails that were set up on the sides of the wall.
- **Set the outside wall forms.** Using the crane, the crew set up the outside wall and column forms.
- **Plumb and square inner core walls**. This activity was to check the accuracy and alignment of formworks.
- **Set the column forms.** This activity was to fly, set, and plum-square column forms.
- **Pour walls and columns.** The whole crew participated in this activity which would take about four hours.

NIGHT SHIFT

The night crew consisted of six members including the night superintendent. The night crew performed activities for both day crews including raising interior core wall forms, stripping wall and column forms, lowering tables, installing Z metal and edge forms, and help for pouring deck concrete. To facilitate the night crews' work, the day crews made the following work preparations: (1) set up lights at proper spots, (2) get the generator ready, (3) make sure the crew has all the materials needed, and (4) provide a clear description of what have been done during the day shift and what have been left to be done by the night crew.

REBAR CREW

Rebar work was sub-contracted to another crew. Their work included making wall and column rebar cages, setting and fixing slab rebar, and fixing post-tension cables. The rebar crew was sharing the crane with concrete crews during the day shift. This crew had its own supervisor who was coordinating their work with the concrete crew supervisors.

PRODUCTION PRACTICES

The supervisor developed the work plan for the entire operation, and was in charge of the deck crew. This was the crew with the greatest workload and production pressure. This section examines the work practices of the deck crew supervisor in order to meet the aggressive schedule

STANDARDIZED WORK CYCLES

The work cycle for each floor was the same and everybody in the crew knew when to do what. The crew had a clear work plan which specified when, where, who, and how to do the work. The supervisors of deck and vertical work crews established a timetable specifying what time each task had to be finished. Close coordination between crew supervisors of concrete, rebar, and night crews helped them update their work plan and help each other recover from any potential problems.

METHOD SELECTION

To meet the schedule requirements, the management and the supervisor selected to use Elevated Aluminum tables for the deck formwork, Z metals for the beam side forms, quick-pop aluminum shoring to support deck formwork, and Logik forms for the vertical forms. These components were delivered to the jobsite preassembled and concrete crews were to a large extent installers. The shared characteristic of these methods was that they transferred several assembly activities from the jobsite to the shop. These methods reduced the need for measurement, cutting, and assembling wood material on site, thus reducing the time, the potential for errors and rework. When the contractor faced some cost-speed trade-offs, they decided in favor of speed.

CREW SIZE, SELECTION AND POLICIES

The critical concern of the supervisor was to meet the timetable, not to maximize productivity. As a result he sized the crew to reliably meet the goals, rather than to increase productivity at the risk of missing a milestone. The size of the crew increased from the original estimate to account for the requirements of the work plan and for reduced productivity due to heat. The deck foreman was another resource “buffer,” as he was not only assigning the work, but also helping where needed. The crew members had clear instructions not to stop their work to help someone with a production problem, but to bring these problems to the foreman.

Crew members were selected based on two key criteria: (1) Capability, and (2) Reliability. As the supervisor explained, he selected workers who (1) Know what they are doing, and do not need much instruction, (2) Know the sequence of the work,

(3) "Stay ahead of their task" and prepare for the work some steps ahead without telling them. Absenteeism was a major concern as it would create problems at meeting the milestones. The supervisor had a zero tolerance policy on absenteeism, which he explained at the time of hiring. The supervisor considered unjustified absenteeism as "*steeling other workers' time, which is not fair.*" As a result, he had just two occasions when a worker was absent over the life of project. The supervisor would not tolerate unprofessional behaviors and lack of personal tools in his crew.

Specialization was used for the tasks that required high accuracy: (1) The most skilled carpenters were assigned to the areas where higher accuracy of the edge form was required. (2) The leadman with strong construction engineering background was assigned to perform the slab and embeds layout. To prevent errors and omissions in important activities (layout, embeds, etc.) the supervisor established extensive checking requirements. Task rotation was another important element of the work organization, as the supervisor wanted to rotate the carpenters doing the heavier tasks. Furthermore, half the crew had Wednesday off—this was the crew members who were doing the heavier work on Monday and Thursday.

TASK SIMPLIFICATION / STANDARDIZATION

The deck supervisor found several opportunities to simplify and decouple activities. (1) He designed the configuration of the aluminum tables for ease of installation. As the supervisor explained he considered not only the number of tables, but the overall difficulty for moving them. For example, he would use two smaller tables instead of a large one, if that would make the work overall easier. (2) The tables were numbered so that the crew knew exactly where each table should be located. (3) The crew pre-marked the aluminum table legs at the appropriate heights to speed up installation and minimize potential mistakes. (4) The workers setting the tables used rubber mallets that deliver a softer blow and reduce the workers' discomfort. (5) The carpenters used screws for the edge forms instead of nails. The screws can be removed easier with less damage to the form. (6) While the dimensions of columns remained the same along all floors, the concrete mix design was different. To reduce the complexity of wall / column pours, the vertical crew reduced the number of concrete mixes from four to two. This modification was made after the engineers' approval.

CRITICAL RESOURCES

With the overlapping of the work activities, three crews were working at different areas of the deck every day. There was one tower-crane on the job, and all crews were dependent on that crane for their heavy lifts. This made the crane the bottleneck resource. In order to provide sufficient access to the crane and avoid conflicts, the crew supervisors developed a detailed crane schedule. Each crew was the primary user of the crane during their "busy" days. For instance, Mondays and Thursdays were the busiest days for the deck crew; during these days they had full access to crane, while the other crews had limited access. The limited access to the crane forced the crews to find ways to make the best use of the crane's time, and minimize their lifts. This required extensive preparation and detailed planning for the lifts, to make sure that they have everything they need. During the early stages of construction, other resources also turned out to be critical. Some simple materials like 2×4 and straps to bundle materials for lift were shared by all crews and sometimes they were taking each other's material, which created some delays.

SAFETY HAZARDS AND PRACTICES

The project had in place a strong safety program, with extensive safety planning, training, and inspections. Every morning, the supervisor would discuss the safety hazards of workers' immediate tasks. His general strategy was to repeat the safety requirements until they become "second nature" for the workers. The three most important safety concerns for the concrete crews were: falls, crane operations and heat sickness /dehydration. To prevent falls, the contra tor enforced a 100% tie off policy. To prevent dehydration (1) the contractors provided extra water, (2) rotated workers to task in the sun, and (3) he taught the symptoms of dehydration to his crew and asked them to monitor each other's wellness. Furthermore, the work schedule only required half the crew on Wednesdays. This provided some additional rest to those who performed the hardest tasks on Mondays and Thursdays.

PERFORMANCE OUTCOME

The concrete crew successfully finished the project on schedule with no recordable injuries. With regards to work quality, the crew had few mistakes including: (1) on the fourth floor, the concrete deck was not level, and had about 1.5 inch "hump" at the mid-point of the slab. This issue created extra work for the vertical crew as they had to adjust their wall formworks to accommodate the levelness problem. (2) Both concrete deck and vertical work crews missed one embed, however the structural engineer found a solution that did not require adding the missing embeds.

SUMMARY AND DISCUSSION

The production practices that contributed to successful performance under high production pressures, addressed the tasks, the work process and the resources. **At the task level**, the main strategies involved (1) reducing task complexity and task difficulty, (2) matching high demands with high capability. Such actions at the task level not only reduce the task duration and errors/rework, but reduce task variability and contribute to more reliable work flow. **At the work process level** two important strategies are identified: (1) increase reliability of the work flow, and (2) provide resources to manage the variability and performance problems. **At the resource level**, he exploited the resource bottleneck (crane) and provided additional resources where possible.

REDUCE TASK COMPLEXITY AND TASK DIFFICULTY

At the task level, there was a systematic effort to reduce the task complexity and task difficulty. (1) Use Z metal. This method required fewer steps, less measuring and cutting, and less likelihood of mistakes. (2) Design the table layout to reduce the difficulty of flying them. (3) Decouple and error-proof tasks, so they can be performed ahead of time, and have less likelihood of errors during installation, such as the pre-marking of the table legs. (4) Use rubber mallets to reduce the effect of hammering on the workers.

MATCH HIGH TASK DEMANDS WITH HIGH CAPABILITY

The selection of experienced crew members, who understood the work process, required less supervision and could plan ahead of their task, was very important, as this operation was in "performance mode, not learning mode." Furthermore, the assignment of the more skilled crew members to the tasks with the higher accuracy requirements reduced the likelihood of errors and rework in critical areas where mistakes would be very detrimental to performance

ESTABLISH RELIABLE WORK FLOW

Because of the schedule the operations were very tightly dependent—any significant disturbance in one operation would affect the entire work flow. Hence, the primary concern was to reliably meet the timetable, not to maximize productivity. The strategies to accomplish reliable work flow included: (1) standardizing the work process; (2) dividing the work to specialized crews (deck and walls); (3) providing adequate manpower; (4) emphasis on preventing absenteeism; (5) work rotation; (6) multiple checks to prevent rework; and (7) a clear policy for handling performance variability and problems. If a crew member had a problem or difficulty, the other crew members should not stop their work to help them. The deck foreman was responsible to handle the problem and re-assign workers as needed. The foreman knew the status of all tasks and he could assign resources so that other tasks would not be delayed.

EXPLOIT BOTTLENECK RESOURCES

Another factor essential for work flow reliability was the effective management of resource constraints. This was achieved with two strategies: (1) Provide additional resources where possible, as in the case of 2×4s and straps for crane lifts. (2) In the case of the crane, where a second crane could not be provided, the resource constraint was exploited by minimizing the number of lifts. This in turn, required detailed planning and preparation of the lifts.

CONCLUSION

This case study analyzed the work practices of a high-reliability field supervisor in concrete construction. The findings indicate that the supervisor's emphasis was on performance reliability and on avoiding variability, rather than on maximizing productivity. The production strategies he used to manage the tasks, the work process and the resources taken together created high quality of work assignments, a highly reliable workflow with low variability and very few errors and rework.

As discussed earlier, the Last Planner System (LPS) emphasizes reliability of workflow in order to reduce waste and increase speed. In the LPS system, the main means for achieving reliability is securing the directives and resources needed for the work assignments. In this case, securing the resources was a major concern for the supervisor. This was reflected in his selection of experienced crew members, the emphasis on preventing absenteeism, the management of bottleneck resources (crane, etc.) and the availability of slack resources.

In addition to managing the resources for reliable performance, this case illustrates that the design of the work activities was a major consideration in achieving reliable and fast work flow. First, reducing the task demands and particularly task complexity reduces the resources required, as well as the likelihood and consequences of errors. For example, using Z metal instead of 2×4 and plywood required much less measurement, cutting, nailing and inspecting. This required the task duration, resources required, time pressure and possibility of mistakes. Second, reducing the coupling of the tasks reduces the resource requirements during installation—for example, pre-marking (and pre-inspecting) the legs of the tables reduced the tasks and resources needed during table installation. It also reduces the time pressure on the installation activity. Thus, preparing as many tasks as possible ahead of time, and organizing the material to reduce searching, reduces the number of tasks during installation, and consequently reduces potential mistakes and production pressures.

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