# SAFETY AS AN EMERGENT PROPERTY OF THE PRODUCTION SYSTEM: HOW LEAN PRACTICES REDUCE THE LIKELIHOOD OF ACCIDENTS

**Panagiotis Mitropoulos[1], Gerardo Cupido[2] and Manoj Namboodiri[3]**


## ABSTRACT

The current approach to accident prevention does not account for the effect of work practices on the likelihood of accidents. This paper addresses the question "How do the production practices, and particularly lean practices, affect the likelihood of accidents in construction operations?" First we propose that the production system affects the likelihood of accidents in two ways: (1) by generating (or preventing) situations with increased task demands (increased potential of accident), and (2) by affecting the workers' ability to cope with these situations (capabilities) and avoid errors. Then, we review the production system factors (technical and social) that influence the likelihood of accidents. The effect of production practices was examined through an exploratory field study of framing operations. The case study compared the production practices of a High Performance crew (in terms of productivity and safety) with the practices of an average performance crew. The evidence indicates that a focus on reducing uncertainty, errors and rework (practices consistent with lean production practices) and matching skills to task demands increased productivity while reducing the likelihood of accidents.



## KEYWORDS

Safety management, Accident prevention, Production management


## INTRODUCTION

Compared to the high risk sectors (such as nuclear and chemical plants, aviation, etc.) construction involves more frequent but smaller scale accidents, with many and diverse hazard sources. Construction work involves a large number of work processes that need to adapt to the project-specific requirements and context. In contrast to the well-defined procedures of the high-risk systems, the loosely-defined construction work processes allow the work crews many degrees of freedom in how they organize and coordinate the work. As a result, construction crew practices determine largely how the actual work is structured and coordinated (such as task allocation, sequencing, workload and pace, work coordination, collaborative behaviour, etc.) and consequently they shape the evolving work situations that the workers face. Furthermore, the dynamic, unpredictable and often hostile construction tasks and environments, combined with high production pressures


[1] Assistant Professor, Del E. Webb School of Construction, Arizona State University, Tempe AZ, 85287-0204. Email: takism@asu.edu.

2 Previously graduate assistant, Del E. Webb School of Construction, Arizona State University, Tempe AZ, 85287-0204. Email: gcupido@periniwest.com

[3] Graduate assistant, Del E. Webb School of Construction, Arizona State University, Tempe AZ, 85287-0204. Email: manoj.namboodiri@asu.edu.

and workload create high likelihood of errors. For these reasons, crew coordination and communication are essential for effective and safe performance of construction crews.

Despite their importance, construction safety research has not investigated the effect of crew work practices on accident prevention. Current best practices in construction safety emphasize training and compliance to prevent unsafe conditions and behaviours, and neglect the potentially large effect of work design and team coordination. As a result, our current understanding of how the work practices and the team processes generate the potential for accidents and affect the crews' ability to avoid errors and accidents is very limited.

This paper discusses how the production practices affect the likelihood of accidents. The paper first proposes the Task demand-Capability Interface (TCI) model as an appropriate model for construction accident causation. The TCI model provides a framework for relating the effect of work practices and team processes on the likelihood of accidents. Then, the paper discusses how the production practices affect the task demand and capability during the operations. Finally, the paper presents empirical evidence; it examines the differences in the production practices used by two residential framing crews: one crew with high productivity and safety performance and another crew with average productivity and safety performance.

## SAFETY RESEARCH PARADIGMS

Rasmussen (1997) identifies three paradigms in the evolution of research on accidents and occupational safety. The first paradigm focuses on normative, prescriptive theories concerning the way people ought to act. Efforts to prevent occupational accidents focus on task design and safe rules of conduct—they attempt to control behaviour through normative instruction of the 'one best way,' selection and development of 'competent' personnel, and motivation and punishment. The current safety practices in the construction sector are grounded on this safety paradigm.

The second paradigm focuses on descriptive models of work behaviour in terms of deviations from the normative, 'best way' of working—that is errors and biases. This paradigm guides efforts to control behaviour by removing causes of errors. It includes studies of errors (Rigby 1970, Rasmussen et al.1981), management errors and resident pathogens (Reason 1990). The third paradigm takes a cognitive approach to safety and develops descriptive models of work behaviour in terms of the behaviour-shaping features of the work environment. Such models include the risk homeostasis theory (Wilde 1976, 1985), Rasmussen's (1997) model of migration to accidents and the Task-Capability Interface Model (Fuller 2000, 2005). The cognitive approach to safety aims at making visible the constraints and work affordances of the workplace (Flach et al. 1998).

### THE TASK DEMAND-CAPABILITY INTERFACE MODEL

Rasmussen's model of 'migration to accidents' (1997) described how the pressures for efficiency, and the tendency for least effort (which is a response to increased workload), cause the work behaviours to systematically migrate closer to the boundary of functionally acceptable performance (limit of loss of control). Efforts to improve system safety with technical means lead to human adaptation that compensates for safety improvements. As a result, the work behaviour is likely to be maintained close to the boundary of loss of control (risk homeostasis).

In traffic research, the risk homeostasis theory (Wilde 1976, Taylor 1981) proposed that drivers adapt their behaviour to maintain an 'acceptable level of risk.' Later researchers proposed that driver behaviour is controlled by the maintenance of 'safety margins,' such as time to lane-crossing and time-to-collision. More recent studies found that drivers adjust their behaviour (e.g., by changing their speed) based not on the perceived 'risk of crash,' but on the *perceived task difficulty*. The Task-Capability Interface (TCI) model (Fuller 2005) provides a new conceptualization of the driving task and the process by which collisions occur. As shown in Figure 1, at the heart of the TCI model is the interface between (a) the demands of the driving task to achieve a safe outcome and (b) the capability applied during the task. When the Capability exceeds Task Demand, the driver has control of the situation. If Task Demands exceed Capability, the result is loss of control, which may (or may not) result in a crash; e.g., if there is a compensatory action by others.

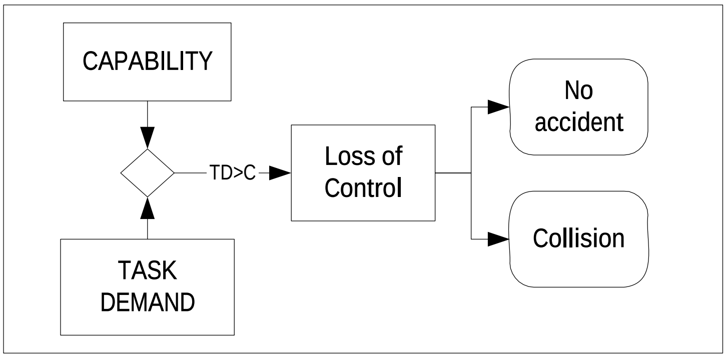


Figure 1. The TCI model

**Task Demands** are determined by factors related to the vehicle, the road, the traffic conditions, the speed, and other tasks that the driver may perform (talking on a cell phone). The driver's speed has a central role in safety and is affected by the driver's goals (such as minimizing time to arrival), and motives inherent in the behaviour of human beings when in movement, such as maintaining speed and conservation of effort. The **Capability applied during the task** depends on the driver's competency (training and experience), the level of activation, and human factors (fatigue, etc.). Task Demand and Capability are not independent—changes in the perceived task demand, change the driver's level of activation and consequently the Capability. The level of Task Difficulty and Capability changes over time, as both the driving conditions (road, environment, traffic, speed) and the capability-related factors (fatigue, level of activation) change. Thus, to maintain control, it is essential that the driver has effective feedback to correctly assess (and anticipate) the task demands.

## THE TCI MODEL FOR CONSTRUCTION ACCIDENTS

The background provides the following principles for conceptualizing the construction accident phenomenon.

**1. A construction task is conceptualized as a dynamic interaction between the worker and the elements of the task and the environment (the tools, materials, physical environment and other workers).**

During task interactions, the worker has a dual goal—to satisfy production goals and avoid injury.

**2. Accidents are a result of loss of control when Task Demands exceed Capabilities. Consequently, the likelihood of accidents during a construction operation depends on the Task-Capability Interface (TCI).**

This conceptualization is a significant departure from normative models. From this perspective, an 'error' is defined not as a deviation from a prescribed procedure, but as a failure of the applied capability to match the demands of the task. With regards to safety, we are concerned with those task interactions where loss of control is likely to result in injury. Task Demands and Capabilities change during an operation as workers perform different tasks, task conditions change, and the workers' capabilities change (due to fatigue, disruptions, etc.).

**3. The Work Practices and Team Processes of a work crew 'shape' the quantity and quality of Task Interactions (Task Demands-Capabilities) and consequently the likelihood of accidents.**

Figure 2 illustrates that work practices and team processes affect the likelihood of accidents by affecting: (a) the number of Tasks Interactions with high demands; (b) the match between Task Demands and Capabilities, and (c) the worker's ability to recognize the task demands.

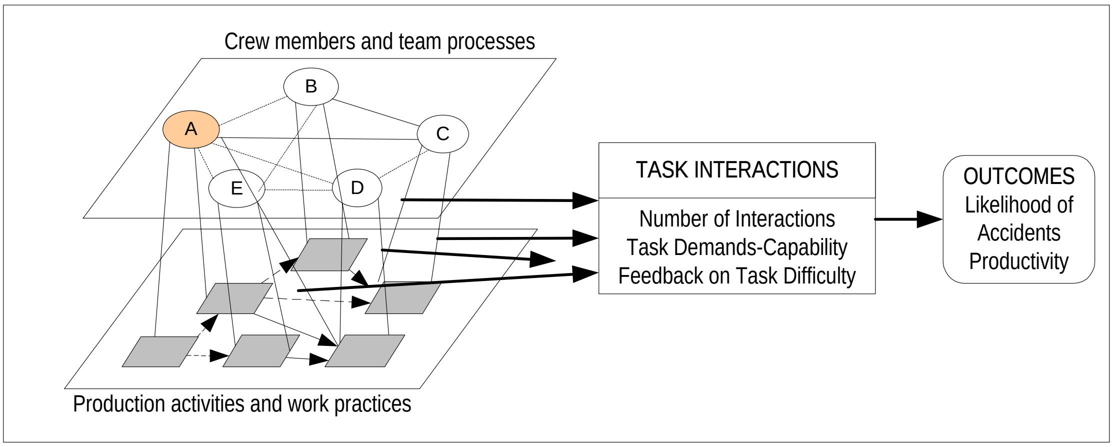


Figure 2. Influence of work practices and team processes on task interactions.

**PRODUCTION PRACTICES AFFECTING LIKELIHOOD OF ACCIDENTS**

A review of the background identified the following production and team processes that influence both productivity and the likelihood of accidents.

**Task uncertainty.** Task uncertainty generates disruptions and 'exceptions' (non routine situations). It may result in additional tasks (e.g., rework), higher task demands and increased production pressures (rushing). Exceptions may result in reallocation of resources and mismatch of capability and task demands. Planning reduces uncertainty, such as unexpected scope of task, missing or incorrect resources, or conditions different than expected. Scharf et al (2001) highlighted the importance of task predictability, complexity and dynamism in the likelihood of accidents. Thomassen (2003) found that crews using Last Planner had about 45% lower accident rate than crews in the same company performing similar work, who did not use the Last Planner system.

**Work decomposition.** The division of work determines the individual tasks, the task demands and the capabilities needed. It also determines the dependence between tasks. The dependence and coupling of the tasks affects the productivity of the operation. (Howell et al. 1993). The distribution of interdependent tasks to different actors creates the need for coordination. The coordination processes determine how well the crew performs dependent tasks.

**Task assignments** to crew members determine how the capabilities of the workers are matched with the task demands. As a result, it determines workload and task demands the workers will face.

**Production pressures.** Workload and production pressures affect work behaviours and performance. Rasmussen (1997) identified production pressures and the tendency to minimize workload as important factors that bring workers near the edge. Production pressures may result for many different reasons (aggressive goals, manpower variability, schedule and quality problems, etc.

**Performance control** refers to the strategies for preventing process errors and product defects. Mitropoulos et al. (2005) proposed that violations are necessary but not sufficient conditions for an accident, and that accidents require that an errors or a change in the state of the system result in loss of control. Saurin et al (2006) emphasized the importance of error proofing and other strategies to deal with variability.

### TEAM PROCESSES AFFECTING LIKELIHOOD OF ACCIDENTS

Research in occupational safety and accidents has acknowledged the importance of social relationships and team coordination on safety. Dwyer and Raftery (1991) found that accidents are produced by the social relations at work, and argued against the more traditional perspective that accidents are mainly produced by unsafe acts and conditions. Wright's (1986) study of accidents in the oil industry reached a similar conclusion. The aviation sector developed the Crew Resource Management (CRM) training system to increase the ability of the crews to collectively identify threats and manage errors (Helmreich et al. 1999). CRM emphasizes non-technical skills and team processes. High Reliability theory investigated the characteristics and operating principles of organizations such as nuclear power plans, aircraft carriers (Rochlin et. al 1987) and wildland firefighting crews who operate under extreme conditions, and perform complex processes with a surprising low rate of serious incidents. Teamwork behaviours that influence the Task Demands and Capabilities include the following:

**Team planning and briefings** establish a shared mental model and increase understanding of the state of the system, as well as each other's work and needs.

**Collaborative behaviours**. Offering and accepting help reduces workload and task demands. Warnings and instructions increase awareness of task factors and conditions.

**Cross monitoring** and cross checking for actions critical to safety and productivity reduces errors. It also detects reduced capabilities (such as fatigue, etc.).

**Assertiveness** enables team members to point out threats to production and safety and prevent or correct errors.

**Communicating intentions** helps avoid mistakes if the intended action by one actor is not supported by the knowledge of another.

**Management of new employees** appears to be an important factor as new employees have a disproportionate number of accidents.

The next section presents empirical evidence regarding the effect of production practices on the likelihood of accidents.

## EMPIRICAL CASE STUDY

To investigate how the production practices affect the likelihood of accidents, we conducted an exploratory field study where we compared the production practices of two residential framing crews—one high-performance crew (with consistently high level of productivity and safety) and a crew with average productivity and safety performance.

The goal was to identify the practices of the HP crew that contribute to increased productivity and reduced likelihood of accidents. Using the TCI model as a point of departure, we expected that the work practices of the HP crew would result in (1) fewer situations of high task demands, and (2) better match of the task and capability. Finally, we compared the practices of the successful crew to the lean production principles.

The study was conducted with the participation of a large residential framing company. At the time of the study the participating company had 88 framing crews. The company assisted in the selection of the crews and provided access to the jobsite and the crews. The company consistently tracks the following items for each foreman: (1) productivity factor (based on estimated over actual labour hours), (2) safety compliance, (3) quality compliance, and (4) accidents. The foremen's bonuses are based on the monthly score on the first three indicators. Accidents are tracked but are not part of the bonus system.

The 2 crews studied work under the same company "rules" (e.g. workers pay, safety requirements) and degree of autonomy (freedom of crew size, hiring, firing, organizing the work, etc.). The crews were selected based on their productivity and safety performance. The high performance (HP) crew had the highest productivity score among all crews in 2004 and 2005 (110/100). This crew also had zero recordable accidents in 2004 and 2005 (which also continued through 2006). The average crew had productivity score 90/100 slightly higher than the average 86/100, and had 5 recordable accidents in 2004 and 2005. Both crews had very high scores on safety compliance—above 95 / 100.

Data collection involved foreman interviews, field observations and videotaping of the work. The interviews focused on the following issues: crew characteristics (composition, turnover, relationships, etc.), planning and organization (how does the foreman and crews plan and organize the work), and foreman's key concerns and strategies for managing the work. Field observations focused on the actual organization and execution of the work. We observed each crew on different projects, and during all the major framing operations—framing walls, erecting and framing roof trusses, installing fascia, and installing roof plywood. However, the videotaping was "spotty" and did not allow detailed analysis of the entire tasks.

### CREW DESCRIPTION

Both crews consisted of the foreman and six members: the leadman (the most experienced crew member after the foreman), three carpenters and two labourers. Both crews were Hispanic. The crew members have good relationships and often socialize after work. Both foremen are 'working foremen'—they are not just supervising. The company sets the budget and schedule goals. The foremen decide the size of the crew, they hire and fire crew members, and they plan and organize the work.

**High Performance Crew**: The foreman has seven years of experience in framing, has been with the company for six years, and has been a foreman for two years. The leadman is the foreman's brother and has been working with him for 7 years. Three carpenters have been with the foreman for 2 years (one is his brother in law), and two relatively new members have been with the crew for 9 months.

**Average crew**: The foreman has 4 years of experience in framing, has been with the company for 2-½ years, and has been a foreman for 1-½ years. Three members have been with him for 1-½ years—one of them is his brother-in-law. One new member has been with the crew for 3 weeks. Two other crewmembers had been with the crew for six months but were absent without notice the first time we met the crew. Their absence created a cleanup problem at the site, as the rest of the crew was in a hurry to finish the two story house that was slightly behind schedule. The foremen he was going to fire them because of repetitive absenteeism.

## FIELD OBSERVATIONS: HIGH PERFORMANCE CREW

In the HP crew, the primary concern of the foreman was to prevent errors and rework. This focus on avoiding mistakes and rework drove several of the crew's work practices.

### Work Planning and Organization

- The foreman checks thoroughly if the lumber order is complete (including hardware and trusses). For the house he was framing at the time of the study, the main beam for the garage was missing and he was able to order it before they started framing.
- The foreman reviews the plans to identify framing details that his crew is not familiar with. If there are any difficult or complex areas, he discusses them with the crew and he supervises these areas himself, to prevent errors.
- The foreman orders the crane (for truss erection) ahead of time. He estimates when he will be ready for trusses and orders the crane 2-3 hours after his expected completion time as he does not want the presence of the crane to rush his crew.
- The foreman assigns two crew members on each of the 3 sides of the house (leaving the front side last) and they build from the outside walls to the inside of the house.
- He makes sure that the crew is working at a comfortable pace and not rushed. The foreman also stated that a behaviour that he does not tolerate from his crew members is talking to the point that becomes a distraction from their task.
- Both the foreman and the leadman check the walls before they lift them in place to identify potential errors and avoid extensive rework.
- The foreman pays personal attention to specific operations—building complex assemblies, lifting up walls, and setting trusses. These are operations where errors are more costly for productivity or safety.
- According to the foreman, the crew does not take any special safety precautions during work performed on the ground. Lifting walls, erecting trusses and working at the edge of the roof are the tasks he considers most hazardous.
- The crew has a well defined hierarchy of skills and task assignment. Only the most skilled crew members (foreman and leadman) perform the high-risk tasks such as

erecting trusses and installing the first row of roof plywood. If the leadman was to be absent, the next more experienced person would perform this task.

### Truss Erection

Because truss erection is one of the high-risk tasks, we observed the HP crew erecting trusses on two houses. In both cases, the work was well organized and coordinated:

- The previous day, the foreman called to confirm the arrival of the crane.
- The material was laid out neatly. The foreman himself was releasing the trusses and checking that the correct truss was erected. No errors were observed.
- The crew was set in place waiting for the trusses, very much like a team waiting for the kick-off. The leadman was at the high point, and the next two most experienced workers on the wall plates. The pace was stable and at no point the crew was rushed.
- The crane erected two trusses at a time (typical). At some point the foreman hooked 3 trusses but the leadman (at the top) asked for only 2 trusses at-a-time.

## FIELD OBSERVATIONS: AVERAGE CREW

The main concerns for the foreman of the average-performing crew are to finish on schedule and to comply with the safety requirements. The foreman believed that the crew could improve the quality and reduce rework. He attributed his productivity primarily to the repetitiveness of the framing design and the experience of the carpenters in the crew.

### Work Planning and Organization

- According to the foreman, it does not take him too much time to plan and prepare for each house—he looks at the plans and pretty much knows what he has to do.
- He assigns three workers on two side of the house and they go from the outside walls to the inside. Then, they set the trusses. Then he walks around the house to check for the details that need to be fixed. These details are usually fixed by one of the labours.
- Each person has specific tasks, especially when it comes to finishing the house, one crew member takes care of the inside, the other takes care of the outside and the other is in charge of finishing the roof. The activities he considers high risk are setting up trusses and working on heights—same as the foreman in the HP crew. These tasks are assigned to the more experienced crew members. However, the field observations indicated some problems during truss erection, which we discuss below.
- The one thing he does not tolerate is "when workers don't pay attention and perform poorly." He invests a lot of time training his labourers to do the work correctly, but he often has complaints from new workers. He believes safety is a combination of being very careful, but also being lucky (or not too lucky in his case).

### Truss Erection

We observed the average crew erecting roof trusses on two houses. The organization of the average crew was somewhat different than the HP crew.

- On the roof, an experienced worker was on the ridge, and one worker on each side. This is similar to the HP crew. One difference was that the foremen was overseeing the operation and the leadman was releasing the trusses. Another was that one worker on the wall was a new member of the crew.

- The crew erected 2 trusses at a time (typical). Used different brace from the HP crew.
- In the first roof, the leadman made two mistakes: in one case he sent the wrong truss, and in another, the truss was installed with the wrong orientation. The errors were discovered after several other trusses were installed. The result was about 1.5 additional hours of rework, as several trusses had to be taken down and reinstalled. Another result of the rework was that the newest crew member ended up at the higher risk position (on the ridge).
- The second time we observed the average crew, the crew was not well prepared to start the operation. Two of the framers were working on a roof detail, when the first truss assembly was lifted. The crew started taking their positions after the assembly was in the air, and one member rushed back and forth on the wall plate.
- In addition, there was a problem with the lifting of the larger assembly—because of the position of the crane and the size of the assembly, the assembly could not swing in place, as the path was blocked by the adjacent house. Several crew members had to pull the assembly hard to clear the adjacent house.

The errors and rework increased in the duration of the activity from 2 to about 3.5 hours. Furthermore, they created an increased task demand for the crew. Table 1 presents a comparison of the task demands and exposures to task hazards for the truss erection activity with and without the rework.

Table 1. Task demands and exposures for truss erection with and without rework.

| Task | Task demand | Task duration (hrs) | Workers | Total exposure (task demand x duration) |
|---|---|---|---|---|
| **Set trusses (no rework)** | 2.5 | 2 | 3 | 15 |
| **Truss removal** | 3.5 | 1.0 | 3 | 10.5 |
| **Re-install trusses** | 2.5 | 0.5 | 3 | 3.75 |
| **Set trusses with rework** | | | | 30.75 |

Task demand: 1=Low, 2=Moderate, 3=High, 4=Very high

The assessment of task demand is subjective. The normal truss erection task was considered a moderate-high demand task. The crew spent an additional 1.5 hour on rework (removing and re-installing some trusses). Truss removal is considered a high-very high demand task because it is less familiar, and may increase the production pressures. As observed in the field, the rework resulted in a redistribution of tasks and a less experienced worker ended up at the higher risk position. Thus, the likelihood of errors increased. On the other hand, the demands can be reduced if the workers work slower and pay more attention to the task.

It should be mentioned however, that in the absence of rework, the crew would work on another activity which would involve some task demands and likelihood of accidents. However, the effect of rework can be significant (1) if the rework is on high demand tasks, (2) if rework further increases the high task demands (such as unfamiliar tasks and rushing), or (3) leads to task-skill mismatch, and therefore higher likelihood of errors.

Summarizing the truss erection observations, the HP crew was better in planning and coordinating the work (material layout, clear start of operations, no out-of position workers), there were no errors, the pace was uninterrupted, and no-one appeared to be rushing. In contrast, the average performing crew appeared less prepared, made more errors, and had some more points of difficulty.

## DISCUSSION

Overall, we identified several differences in the production practices of the two crews. The following practices appear to contribute to the higher productivity and safety of the HP crew. These practices are very similar to lean production practices, as they increase predictability and reduce errors, and consequently reduce waste.

- **Focus on avoiding errors and rework.** The focus of the HP crew foreman on avoiding rework appears to be a key factor increasing productivity while at the same reducing the risk of accidents. This focus led to extensive planning and careful control of tasks with high-demands and high-consequences (for productivity or safety). It resulted in exposing the crew to fewer risks during truss erection compared to the average crew, where the errors observed exposed the crew to a higher hazard task for a longer period of time. This focus is similar to the focus of waste elimination in lean production. Avoiding errors and rework is also a primary concern of lean production systems.
- **Extensive planning** resulted in better preparation of the work, availability of material needed, and personal supervision by the foreman of the more difficult tasks (complex framing areas, wall lifting and truss setting). It reduced interruptions and prevented errors. This preplanning is very similar to the development of sound activities in the Last Planner.
- **Matching skills with task assignments**. Both foremen assigned the most experienced crewmembers to the most demanding tasks. The HP crew appeared to apply this principle more consistently and to a greater extent, as indicated by the personal supervision by the foreman of selected important tasks (complex framing areas, wall lifting and truss setting) and the fact that only the leadman was allowed to perform the most hazardous tasks. This is particularly important for accident avoidance, as the leadman had a lower likelihood of error.
- **Preventing rushing and distractions.** Another strategy that the HP foreman used to prevent errors was to control the production pressures on the crew, and prevent rushing. This was reflected in the ordering of the crane, as well as the pace and coordination of truss erection. Lastly, the foreman's 'rule' of no talking to the point of distraction, contributes to fewer distractions and errors. The foreman set the production goals in a way that increased the reliability of his planning—ensuring that there was enough time for the crew to complete the task and reduced the likelihood of errors. In a similar way, an important consideration in the Last planner is matching the manpower to the task—this results in higher reliability that the work will be completed as planned.
- **Crew members stability and reliability**. Both crews had a core group of stable and reliable carpenters who have been working together for long time. The HP crew had lower turnover (the newest crew members were with the crew for 9 months)and absenteeism, which reduces variability in manpower and makes production more

predictable. The reliability and stability of the crew increases the reliability of the production, and reduces the likelihood of errors.

## CONCLUSIONS

In summary, the work practices of the HP crew were consistent with lean production principles as they emphasized preventing interruptions, errors and rework (waste). From the perspective of the TCI model, the production practices of the HP crew 'managed' the task demands (as prevention of errors and rework prevented increased task demands and exposures). They also emphasized the matching of the capabilities with task demands.

The higher experience of the HP crew is another possible reason for their increased performance. However, the case illustrated that there were identifiable differences in the production strategies of the two foremen and crews, not only the experience. In both crews, the production practices were driven by the foreman—this is typical of the framing crews in this company, because of the degree of autonomy the foremen have (freedom of crew size, hiring, firing, organizing the work, etc.). In this situation, the role of the foreman in identifying or developing effective production practices is essential.

This case was an exploratory study in the effect of the production practices on the safety performance. The focus on residential framing crews has advantages (identifiable crew, easy to observe the work, highly repetitive operations,) but has also limitations (e.g., crews independent from other crews, low complexity of operations). Finally, the study did not examine systematically the teamwork practices of the crews. However we observed cooperative behaviours (such as warnings during truss erection) in both crews. In the case of the average crew, we observed more instances where workers were working alone in an area compared to the HP crew.

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