Safety as an Emergent Property: Investigation into the Work Practices of High-Reliability Framing Crews

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Abstract: With regards to safety, the challenge for researchers and practitioners is to develop work systems that can achieve at the same time high levels of productivity and safety. Towards this objective, this research investigates the work practices of high-reliability crews—that is, crews who perform high-risk work with exceptionally high productivity and safety. The objective of the research is to increase understanding of the work practices that reduce the likelihood of accidents while at the same time increase productivity. This paper presents the findings of an initial exploratory study that compares the work practices of two residential framing crews: one crew with consistently exceptional levels of safety and productivity, and one average-performing crew from the same company. The two crews did not show any difference in safety practices—both crews had high compliance with the company's safety requirements. However, the production practices of the high-reliability crew were shaped by a clear "guiding principle," which is a strong focus on avoiding errors and rework, and by specific strategies that support this principle. Such strategies include actions to prevent disruptions, controlling the production pressures, matching skills with task demands, and carefully preparing and coordinating the high demand tasks. These practices prevent production errors while also reducing the likelihood of accidents. The findings provide directions for further research.

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Introduction

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 behavior, 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 create a high likelihood of errors. Consequently, crew coordination and communication are essential for effective and safe performance of construction crews.

The National Occupational Research Agenda (NORA) for construction highlights the need to better understand in what way work organization factors affect health and safety outcomes. In addition to the long recognized job stress, the term work organization includes the scheduling of work (such as work-rest schedules, hours of work, and shift work), job design (such as complexity of tasks, skill and effort required, and degree of worker control), interpersonal aspects of work (such as relationships with supervisors and coworkers), career concerns (such as job security and growth opportunities), management style (such as participatory management practices and teamwork), and organizational characteristics (such as climate, culture, and communications).

Despite their importance, construction safety research has not investigated the effect of crew work practices on accident prevention. Traditionally, accident prevention has focused on hazards and safety programs, and not on production practices. The current approach to construction safety emphasizes means to control the behavior of individuals and organizations in order to increase compliance with safety rules. Thus, it neglects 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.

With regards to safety, the challenge for researchers and practitioners is to develop work practices and work teams that are at the same time highly productive and highly safe. With this goal in mind, this study investigates the work practices of "high-reliability" 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 who consistently achieve very high levels of both production and safety performance, higher than most other crews performing similar work.

This paper presents the findings of the initial exploratory field study. The goal was to investigate the work practices of a high-reliability crew, and better understand which work practices reduce the likelihood of accidents and support productivity, and

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how. This case study focused on residential framing crews. The researchers observed, analyzed, and compared the work practices of two residential framing crews from the same company: one crew with exceptionally high productivity and safety performance (high-reliability crew), and another crew with average levels of productivity and safety (average according to the company's performance).

The following sections review the background literature and discuss the research approach. The findings describe and compare the observed work practices of the two crews. The analysis discusses the importance of the crews' practices for their productivity and likelihood of accidents. The findings of this case study provide initial propositions towards developing new theory and knowledge on accident prevention.

Background Review

This section reviews findings in several sectors, such as organizational research, aviation safety, high-risk systems, and lean construction. The review identifies important constructs that establish the point of departure for the field studies.

Individual and Organizational Factors Affecting Safety

Construction safety research has emphasized individual and organizational factors. Individual factors focus on competency, attitudes, and behaviors. Competency emphasizes the knowledge of work hazards and safe practices, and is addressed through personnel training, retention, and selection. Workers' attitudes and behaviors are considered critical for safety, and efforts to reduce "at-risk" behaviors are directed towards training, motivation, enforcement, and behavior-based safety programs. On the other hand, ethnographic studies of construction safety (Gherardi and Nicolini 2002) argue that workers do not learn "safety"—they learn work practices that are socially constructed in a community of practice—thus, safety is an "emergent" competence that is realized in practice. Organizational factors associated with safety performance include top management's attitude towards safety (Levitt 1975), organizational culture (Molenaar et al. 2002), safety climate, and the owner's role in safety (Huang and Hinze 2006).

Research on HROs investigated the characteristics and operating principles of organizations that operate under extreme conditions and perform complex processes with a surprisingly low rate of serious incidents (Rochlin et al. 1987; Roberts 1993; Bigley and Roberts 2001). HROs use different organizational structures under different situations (centralized under normal conditions but decentralized under crisis), provide extensive training and job rotation, while at the same time they create a homogeneous set of assumptions and decision premises, which enable integration and coordination during crisis (Weick and Sutcliffe 2001).

Several researchers have emphasized the importance of social relations and teamwork in accident prevention. In industrial 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. The Wright (1986) study of accidents in the oil industry reached a similar conclusion, while investigating why contract employees had a disproportionately high rate of accidents compared to regular employees. Aviation research found that a large portion of accidents were due to failures in teamwork, rather than lack of technical skills. Based on these findings, NASA developed the crew resource management (CRM) training system to increase the ability of the crews to collectively identify threats and manage errors. CRM emphasizes the key nontechnical skills and team processes that affect operational safety, such as crew planning and decision making, workload management, communication, and assertiveness (Helmreich et al. 1999). CRM has been implemented in several other sectors, such as emergency medical care, hospital operating teams, and nuclear power operation centers as a strategy for systematic error management.

In construction, Hinze and Gordon (1979) and Hinze (1981) reported that good working relationships with the foremen and other crew members were significantly related to reduced accidents. Other occupational research also found that social support from supervisor and coworkers reduces injuries (Iverson and Erwin 1997). However, construction researchers did not pursue this research path any further.

Production Factors Affecting Safety

Scharf et al. (2001) emphasized the importance of production complexity, uncertainty, and dynamism for safety, and proposed a typology of hazardous production environments based on the following characteristics of the work: controllability of the process and the hazards through engineering controls, predictability of the process and hazards, hidden/unexpected/obscure hazards, extent of restriction of equipment movement path, the degree of speed, force, and change in the hazards or the conditions, extent to which the hazard is required for the work to happen, multiple and interacting hazards, and the potential generation of hazards by humans.

Hinze and Parker (1978) found that job pressures and crew competition are related to more injuries, and suggested that job practices are more important than safety policies in preventing accidents. The Hinzes (1996) distraction theory held that production pressures can distract workers from hazards and increase the probability of accidents. Hinze (1978) reported that high levels of worker turnover increases construction accidents. Mohamed (2002) found that higher perceived work pressure is associated with a less positive safety climate. When pressures are either too low or too high, performance suffers. When production pressure is low, not much attention is devoted to task requirements, which may increase the likelihood of errors. A tight construction schedule is considered a serious factor that affects construction safety.

Rasmussen et al. (1994) explain how the workers' behaviors tend to migrate closer to the "boundary of loss of control" due to two primary pressures: the production pressures for increased efficiency, and the tendency for least effort, which is a response to increased workload. Safety programs attempt to counter the above pressures and prescribe "safe behaviors" away from the boundary. However, the pressures that push workers towards the boundary require that safety efforts are continuous. From a practical perspective, a key concern is that at the work level, there is a continuous tension between safety and production; in the short term, such conflicts are usually resolved in favor of production, because production efforts have relatively certain outcomes and receive rapid and rewarding feedback (Reason 1990).

Samelson (1977) and Levitt and Samelson (1987) found that successful foremen use the following labor management practices: conduct new workers' orientation, watch out for vulnerable crew members, analyze productivity problems with the crew, respond to good work, and create a calm and friendly job atmosphere. Lean production practices are increasingly accepted in the

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construction sector, as an opportunity to reduce waste and add value in infrastructure projects. The last planner system (LPS) of production control (Ballard and Howell 1998) emphasizes the quality of work assignments as the primary means to reduce variability and increase process speed and productivity. In Denmark, Thomassen et al. (2003) found that crews using LPS had 45% lower accident rate than crews in the same company performing similar work, who did not use the LPS. However, the mechanisms by which this improvement occurred have not been explained.

Points of Departure

The background literature identifies variables related to production and teamwork that may have significant influence on the likelihood of accidents and productivity.

Management of Uncertainty. Task uncertainty generates disruptions and "exceptions" (nonroutine situations). It may result in additional tasks (e.g., rework), higher task demands, and increased production pressures (rushing). Exceptions may also result in reallocation of resources and mismatch of capability and increased task demands (Mitropoulos et al. 2005). Planning reduces uncertainty, such as unexpected scope of task, missing or incorrect resources, or conditions different than expected.

Work Division. 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 Assignment. Determines the allocation of roles to the individual actors and consequently it determines the task demands the workers will face and the workload on the workers. The extent of specialization of the crew members determines the distribution of skills and roles in the crew.

Cooperation and Coordination. When task execution depends on the cooperation of several actors, the performance of the individuals and the reliability of the system are strongly influenced by the patterns of cooperation (Rasmussen et al. 1994). The division of work determines the allocation of roles and the content of the communications required for coordination. On the other hand, the social role configuration chosen by (or imposed on) the team influences the communication and social interaction within the team.

Production Pressures. Workload and production pressures affect work behaviors and performance. Effective management of the production pressures is essential for safety. In the literature, the relationship between pressures (stress) and performance is indicated with an inverted "U." When the pressures are low or high, the performance is low.

Performance Control. Refers to the strategies used to control for product defects and the process errors. High-reliability crews (HRCs) are expected to have more effective strategies to prevent defects or detect them early.

These variables provide a point of departure and a set of focus areas for the investigation of the practices of high-reliability crews.

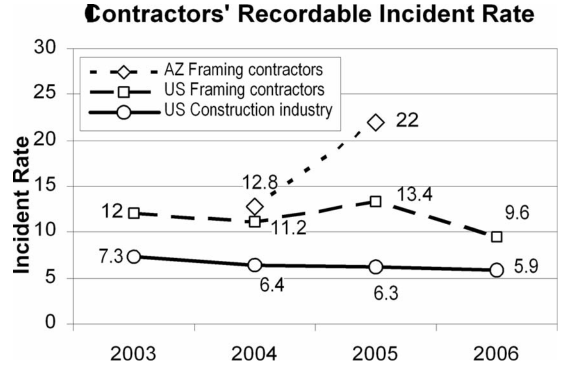

Fig. 1. Framing contractors' incident rates

Research Approach

The research objective is to identify the work practices of HRCs and better understand how they plan, organize, and control the work, what problems they face, and what strategies they use to deal with those situations. The research approach involves in-depth field studies of high-reliability crews in action, and comparison with the work practices of average-performing crews. The first step of the research was to identify and gain access to high-reliability crews.

Selection of Trade, Company, and Crews

This initial exploratory study focused on residential framing crews for two main reasons: first, framing contractors consistently have the highest rate of nonfatal injuries in the construction industry. Fig. 1 shows the incident rates for the US industry overall, the framing contractors (NAICS code 23813), and framing contractors in Arizona. Between 2004 and 2005 in Arizona, the employment in framing contractors increased by 34% while the injuries increased by 120%. The BLS data do not provide incident rates for framing contractors for 2006. The second reason for selecting residential framing operations was that the crews work together over time, and their operations are repetitive and typically independent of other trades, which makes them easier to study.

To identify high-reliability crews, the researchers contacted large framing contractors in Arizona. The company that participated is one of the largest framing contractors in the state and with operations in several other states. The contractor has over 1 million labor hours every year and employees between 70–90 framing crews (excluding the personnel at the fabrication yard).

The selection of the crews for the study was based on their productivity performance and frequency of incidents. To evaluate the productivity performance, the researchers used the foremen's production score that the company calculates on a monthly basis. Every month, the company scores the foremen's performance on production, quality, and safety. These scores are the basis for foreman bonuses. In terms of productivity, the company scores the foremen based on the budgeted versus actual cost of each house. Quality and safety scores are based on field audits and compliance with the company's safety and quality standards. The company's evaluation of the safety score does not consider the number or the severity of accidents that a foreman's crew has. Safety incidents are tracked separately.

For the purpose of this study, the crews' safety performance was evaluated based on the number of incidents a crew had over

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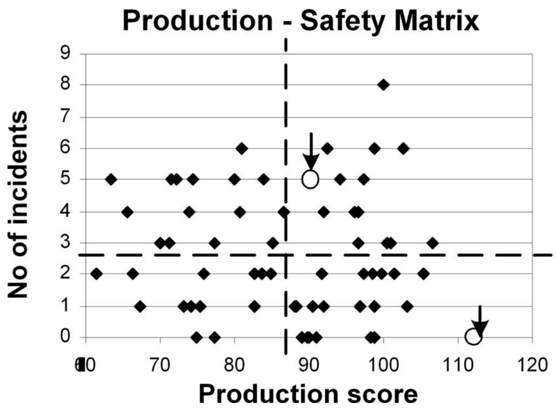

Fig. 2. Matrix indicating foremen's production and safety performance

a 2-year period, as well as the severity of the incidents (as indicated by the workers' compensation costs). The company maintains detailed records and investigates any incident that involves workers' compensation costs. The incident records indicate the foreman of the injured person. The matrix in Fig. 2 shows the production score and the incidents for each foreman over a 2-year period, excluding foremen who were in the position less than 1 year.

The average productivity score was 86 and the average number of injuries per crew was 2.9—this, however, is an approximate indicator as the crews have different amount of labor hours. Ideally, the goal was to use the incident rate (based on the crew's labor hours), but information regarding the total labor hours of each crew was not available. However, with the exception of very few crews, most crews had six to seven members, and their labor hours were very similar—as a result, the comparison was considered acceptable.

The incident rate for the 2-year period was 27.2 (that is, 27.2 incidents per 200,000 labor hours) and the average workers' compensation cost per crew for the 2-year period was $17,390. The arrows in Fig. 2 point to the two crews selected for observation and comparison. Crew A (the high-reliability crew) had the highest production score (110/100) and zero incidents. With regards to the comparison crew, the goal was to select a crew with performance around the average and avoid the very problematic performers. Other criteria for selection included the crew location (so we could make frequent observations of the operations), and the foreman's willingness to participate in the study. Crew B (the "average" crew) had productivity score 90 (slightly above the average), and five incidents over the 2-year period. The workers' comp costs for Crew B was $19,727 (just above the average). According to the safety director and superintendents, the two crews perform very similar work in terms of the size, complexity, and schedule of the houses. Both crews perform some "panelized construction" (preassembled walls). Furthermore, the two crews did not have any significant differences in size or overtime work.

With regards to the company's safety score, both crews consistently have high scores (Crew A 98/100, and Crew B 99/100). With regards to the score on quality, Crew A scored 98, and Crew B 88.

Data Collection

Data collection involved interviews of field personnel and observations of the crews over a period of time. Foreman interviews focused on the following issues: crew characteristics (composition, turnover, relationships, etc.), planning and organization (how do the foreman and crews plan and organize the work), foreman's key concerns and strategies to address them. Field observations focused on the actual organization and execution of the work. The researchers observed each crew on different projects, and during all the major framing operations: (1) framing walls; (2) erecting trusses; (3) framing the roof trusses (installing fascia, bracing, and blocking); and (4) installing roof plywood.

The points of departure focused the field observations on the following issues: work methods, work division to crew members, unexpected events and problems, production pressures and work pace, coordination, errors, etc. The researchers were also sensitive to other potentially important factors. The following sections describe the findings from the interviews and the observations, and discuss the practices that support the crew's productivity and safety.

Findings

Organizational Context

The foremen have complete control over how they organize the work, the number of people on their crew, and they make the hiring and firing decisions. The project superintendents decide on which project and houses the crews will work. The foremen have no choice on the type of construction they work on (panelized walls or traditional framing).

The company provides the power tools and any equipment required (e.g., forklift) and the carpenters and laborers bring their own handtools. However, within each crew, each foreman establishes the specific "rules" regarding the use of tools, for example, who is allowed to use power tools, and for what operations.

Crew Description

With regards to the size, the two crews were the same. Both foremen are "working foremen"—they perform work and they are not just supervising. The **high-reliability crew** (Crew A) consisted of the foreman and six members: the leadman (who is the foreman's brother and has been working with him for 7 years), three crew members who have been with the foreman for two years (one is his brother-in-law), and two relatively new members who have been with the crew for 9 months). The foreman has 7 years of experience in framing, has been with the company for 6 years, and has been a foreman for 2 years. According to the foreman, the crew members and the foreman have very good relationships and often socialize after work.

The **average crew** (Crew B) also consisted of the foreman and six members. The foreman has 4 years of experience in framing, has been with the company for 2-1/2 years, and has been a foreman for 1-1/2 years. Three members have been with him for 1-1/2 years—one of them is his brother-in-law. These three members are considered the "core" crew members. Two other crew members who had been with the crew for 6 months were absent without notice the day of our first visit to 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. According to the foreman, he was going to lay them off because of repetitive absenteeism. The newest member had been with the crew for 3 weeks, but the foreman considered him a good carpenter and wanted to keep him with the crew. The

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foreman stated that he had very good relationships with the crew members—he was referring to the three "core" crew members.

Both foreman hire one or two extra temporary laborers for larger houses or projects. Both crews were primarily Hispanic.

High-Reliability Crew

Safety Measures

The foreman and his crew have consistently high a safety score, which indicates compliance with the company's safety requirements. The foremen are evaluated against 10 key points that include personal protective equipment (PPE), use of ladders, slide guards, safety poster, wall erection procedure, truss erection, leading edge protection, housekeeping, use of power tools, and sawhorses/plywood stands.

According to the foreman, the crew does not take any special safety precautions during work performed on the ground, as the crew is "experienced carpenters and they know how to take care of themselves." Erecting trusses and working at the edge of the roof are the tasks he considers most hazardous. During truss erection "there is major coordination by all the crew members."

Foreman Focus

In Crew A, the primary concern of the foreman was to prevent errors and rework—"every time you have to go back to fix something, or when you have to bring down a wall because is was not framed correctly, that increases your duration by almost three times." He does not like to work in a hurry and he wants to be sure that the crew does not have any rework. His work philosophy is "go a little slower to avoid mistakes." This emphasis on avoiding mistakes and rework drives several elements of his work practices:

- Identification of framing areas that may be difficult or complex for his crew, and working on these himself;
- Thorough checking of the material packages ordered and the material delivered;
- The pace of work to avoid errors; and
- Personal attention to specific operations, especially lifting up walls, and setting trusses. Before lifting the walls in place, he makes sure that the walls are framed correctly. During truss erection, the foreman is personally releasing the trusses in the right order. These are operations where errors are more costly to correct.

Work Planning and Organization

When the foreman first reviews the plans in preparation for the next house, he pays particular attention to the following issues. First, the foreman is looking for framing details or options that his crew is not familiar with. If there are any difficult or complex areas, he discusses them with the crew and explains how they will frame it. He also directs the crew to wait for him before they start working on those areas, to prevent errors.

Second, he checks that the lumber package is complete and that no components are missing. He checks all material packages including hardware package and trusses. Once, he did not realize that one of the trusses was missing when the package was delivered, and he had to stop setting up the trusses until that truss was delivered. For the house he was framing at the time of the interview, the main beam for the garage opening was not delivered, but he found the error and ordered it so that it did not affect the schedule.

Third, the foreman orders the crane for truss erection at least 1 day in advance. During planning, the foreman estimates the time it will take them to bring up the walls and be ready for trusses. Typically, he orders the crane 2–3 h after his expected completion time, to allow some room in case things do not go as planned. He does not want the presence of the crane or the crane operator to put pressure on his crew and make them rush. Almost always he is ready as estimated, and calls for the crane to come earlier.

During the operation, the foreman typically assigns two crew members on each of the three sides of the house (right, left, and back, leaving the front side for the end) and they build from the outside walls to the inside of the house. The foreman pays personal attention to specific operations—building complex assemblies, lifting up walls, setting trusses, and working at the edge of the roof. In one of the field observations, the foreman was framing a complex assembly with the help of a less experienced crew member, while at the same time training the apprentice.

These are operations where errors are more costly for productivity or safety. Before they lift walls in place, both the foreman and the lead man check the walls to identify potential errors and avoid extensive rework later.

According to the foreman, during truss erection "there is major coordination by all the crew members" and each crew member knows his role. The lead man is in charge of the highest risk points for this activity—he is the one on the top of the trusses installing the temporary bracing, or performing any difficult connections between trusses. The foreman releases the trusses, and one framer is on each side of the roof. One or two other crew members nail blocks at the bottom of the trusses, after the trusses are temporarily supported.

The foreman allows only specific individuals to perform the high-risk tasks. If the lead man is present, he is the one who will be at the top of the trusses during truss erection, and will install the first row of plywood (another high-risk activity). If the lead man was to be absent, the next more experienced person would perform this task. In the rare occasion that they are both absent, the crew will not perform these activities. According to the foreman, this only happened twice in the last year. Another safety-related rule that the foreman uses is that he does not allow inexperienced workers to use power tools.

During the work, the foreman checks that the crew is working at a comfortable pace and not rushed. According to the foreman, a behavior that he does not tolerate from his crew members is talking to the point that becomes a distraction from their task. To prevent distractions and errors, the foreman may also turn the music off, as the company's safety director also confirmed.

Field Observations: Truss Erection

The researchers observed Crew A performing several tasks: framing walls (twice), truss erection of two roofs (one small and simple, the other larger and more complex), installing fascia, and installing plywood on the roof. Truss erection was observed twice, as it is considered a high-risk activity. In both cases, the work was well organized and coordinated:

- The day before truss erection, the foreman called to confirm the arrival of the crane.
- The trusses were laid out neatly. The foreman had reorganized the trusses in the order that they had to be erected—when they

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are delivered the trusses are packaged by size, not necessarily erection order.

- The foreman himself was selecting the trusses to be erected and checked that the correct truss was erected. No errors were observed.
- Crew A had a clearly defined hierarchy of skills and task assignment. The lead man was at the high point, and the next two most experienced framers on the wall plates.
- The crane erected two trusses at a time (typical). At some point, the foreman (on the ground) hooked three trusses but the lead man asked for only two trusses at a time.
- The crew was set in place waiting for the trusses, very much like a team waiting for the kick off, and the pace was stable and at no point was the crew rushed. The foreman did not release the trusses until the crew was ready to receive them.

Crew B: Average-Performing Crew

Safety Measures

The foreman has been consistently receiving very high scores on safety, which indicates strong compliance with the company's safety requirements. However, his crew had a total of five incidents in the previous 2 years. In terms of workers' compensation costs, four of the incidents were less than $500 each and one saw cut incident cost over $18,000. The foreman believes safety is a combination of being very careful, but also being lucky (or not too lucky in his case).

Foreman Focus

The foreman identified safety, productivity, and quality as important factors that the company emphasizes. His primary focus was finishing on time and complying with the safety requirements. With regards to quality, he believed that he could improve, and could reduce the amount of his rework. The foreman attributes his productivity primarily to the repetitiveness of the framing design and the experience of the carpenters (the three core members of the crew).

Work Planning and Organization

When he is planning for the next house, first, he considers the days he has to finish the house on schedule and under budget. According to the foreman, "it doesn't take him too much time to plan and prepare for each project. When he is told the type of house he needs to frame next, he looks at the plans and then he pretty much knows what he has to do."

He assigns three workers on each side of the house and they go from the outside walls to the inside. After they finish the exterior and some interior walls, they set the trusses. As described in the following section in more detail, Crew B organizes truss erection the same way as Crew A, but with some differences on the allocation of the roles.

After the trusses are erected, the crew works on finishing the roof. They then finish any remaining interior framing. The foreman inspects the house and checks for punchlist items that need to be fixed. These details are usually fixed by one of the laborers "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 Crew A. Similarly to Crew A, the high-risk tasks are assigned to the more experienced workers. However, the field observations indicated some problems during truss erection.

According to the foreman, he invests a lot of time training his laborers to do the work correctly, but he often has complaints from new workers. The one thing he does not tolerate is "*when workers don't pay attention and perform poorly*."

Field Observations: Truss Erection

The researchers observed Crew B during wall framing, two truss erection operations, and roof sheeting. Compared to Crew A, Crew B had a somewhat different allocation of roles.

- Unlike the HR crew, the foreman was overseeing the operation and the leadman was releasing the trusses. On the roof, an experienced worker was on the ridge, and one other worker on each side. The worker on the left side of the roof was the newest member of the crew.
- The crane lifted two trusses at a time—same as Crew A.
- The crew used a 2-ft brace to connect the top of the trusses during erection (the HR crew used a 4-ft brace)
- During truss erection on the first house, the crew was not well prepared for the operation. Two of the framers were working on a roof detail, when the first truss assembly was lifted. The crew members started taking their positions after the assembly was in the air; one member rushed back and forth walking on the plate.
- In addition, there was a problem with erecting a larger assembly—because of the position of the crane and the assembly the crane could not swing in place, as the path was blocked by the adjacent house. The crew had to pull the assembly hard to clear the adjacent house.
- During truss erection on the second house, the leadman made two mistakes: in one case he released 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 one and a half hour of rework, as several trusses had to be taken down and reinstalled. Another result of the changes and the movement on the trusses, was that the newest crew member ended up at the higher risk position (on the top).

Fig. 3 illustrates the duration and task demand of truss erection with and without rework. Task demand indicates the level of difficulty in terms of safety risk. The normal truss erection task is considered high demand task (level 3). Truss removal is considered a very high demand task (level 4) because it involves taking apart components (thus, reducing the stability of the trusses), it involves more movement of the workers on the trusses, and it is a more infrequent task. The assessment of task demand is subjective—it is a qualitative indicator of the safety risk of the task.

As shown in Fig. 3, the result of the errors were that the crew spent an additional 1.5 h on rework (removing and reinstalling some trusses), which affected productivity, and exposed the three workers to a very high-risk task. It was also observed that the rework resulted in a redistribution of the roles—after the changes in positions, a less experienced worker ended up at the higher risk position, which further increases the likelihood of errors and accidents. Despite the additional time, the workers did not appear to be rushed.

Table 1 calculates the safety risk of the operation with and

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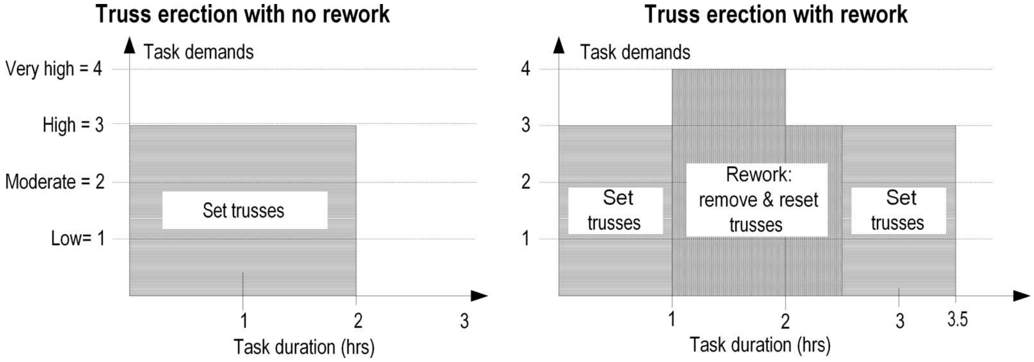

Fig. 3. Task duration and task demands for truss erection with and without rework

without rework. The safety risk is calculated by multiplying the task demand × duration × workers. The safety risk without rework is 18, and with rework is 34.5. The metric provides a qualitative indicator of the increase of the likelihood of accidents. It should be noted, however, that in the absence of rework, the crew would work on another activity, which would involve some level of task demands and likelihood of accidents. However, the case of truss erection indicates that the effect of rework can be significant: (1) if the rework is on high demand tasks; (2) if the rework further increases the task demands (due to unfamiliar tasks, greater exposure, rushing, etc.); or (3) leads to task-skill mismatch, and, therefore, higher likelihood of errors.

In summary, Crew A was better in planning, preparing, and coordinating the truss erection operation (material layout, clear start of operations, no out-of-position workers, no rushing to take position). The result was fewer errors, a stable and uninterrupted pace where no one appeared to be rushing. In contrast, Crew B appeared less prepared, made more errors, and had some more points of difficulty.

Discussion of Findings

The main finding from this exploratory study is that the production practices of the high-reliability crew show a clear "guiding principle," as well as specific strategies that support this principle. The "guiding principle" in this case is the focus of the foreman on *avoiding errors and rework*. This focus drives the crew's production practices and strategies summarized below. This focus on error prevention appears to be a key factor for increasing productivity while at the same time reducing the risk of accidents:

- **Thorough material checking** of both the material ordered and the material received reduces disruptions and delays during the activities. This finding is consistent with Thomassen et al. (2003) report that the last planner (which involves much more detailed planning) reduced the incident rate. This practice is more important when the material management system is less effective—in other words, if material ordering and delivery involved no mistakes or omissions, the foreman's check would not make a difference.
- **Identification of risk areas**. Through a thorough review of the plans, the foreman develops a clear understanding of the potential areas of production risks—these are the more complex framing areas that the crew is not very familiar with. These risk points are managed directly by the foreman, and also become opportunities for training.
- **Prevent errors in high-risk tasks**. The careful planning, preparation, coordination, and control of the high-risk tasks is a key for the safety of these activities. As illustrated by the rework of Crew B, preventing errors in high-risk tasks improves productivity and reduces the likelihood of accidents.
- **Matching skills with task demands**. Assign more experienced crew members to more demanding tasks is a practice that both foremen follow. Crew A 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, the fact that only the lead man was allowed to perform the most hazardous tasks, and that the inexperienced crew members are not allowed to use power tools.
- **Reducing production pressures**. A critical element of foreman A's ability to prevent errors is how he controls the pace and prevents excessive production pressures and rushing. The foreman sets the production goals and orders the crane in a way that ensures that there was enough time for the crew to complete the task without rushing. This is the opposite strategy than many foremen who use the following crew to put pressure on the previous trade. This finding is consistent with previous research findings regarding the importance of job pressures (Hinze and Parker 1978).
- **Monitoring attention to prevent distractions**. The foreman's "rule" of no talking to the point of distraction, is a strategy to manage the crew's attention and keep them focused on the task. It contributes to fewer distractions and errors. The foreman's actions to mitigate production pressures and reduce other distractions are consistent with the propositions of the distraction theory (Hinze 1996).
- **Crew stability and reliability**. Another factor that appears to facilitate these practices in Crew A is the low levels of turnover and absenteeism. Crew A was more reliable and stable than Crew B. This may be important for two reasons: first, for coordination during high-risk tasks. Second, it reduces variations in the crew's capacity both in the day-to-day basis (low

Table 1. Safety Risk Calculation for Truss Erection with and without Rework

Task	Task demand	Task duration	Number of workers	Safety risk
(1) Set trusses (no rework)	3	2.0	3	18.0
(2) Truss removal	4	1.0	3	12.0
(3) Reinstall trusses	3	0.5	3	4.5
(4) Set trusses with rework (4)=(1)+(2)+(3)				34.5

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absenteeism) and in the long term (low turnover). This way, the foreman can estimate the duration more reliably and knows the capabilities of the crews, and the strengths and weaknesses of the crew members. This observation is consistent with the Hinze (1978) findings that high levels of worker turnover increase construction accidents. The case provides new insights into how the crew stability and reliability can influence workload and production pressures, and possibly reduce errors.

While several of the findings support previous research, this case study makes some new contributions: (1) the findings provide additional insights into how these factors (social relations, planning, control of pressures, turnover) affect the actual performance by influencing the likelihood of errors; (2) while the literature identifies many and diverse factors affecting safety, this study suggests that there is a significant common thread between these factors, which is the prevention of errors. In this crew, all these elements were parts of a greater set of tactics that all together converge to prevent errors; and (3) furthermore, it should be noted that the foreman did not emphasize a culture of safety but a culture of quality—not only in terms of the quality of the final product, but as the prevention of errors during the process. Such an emphasis on error prevention appears to prevent both errors that result in product defects and rework, as well as errors that result in injuries.

Finally, the case also raises questions regarding the role of *crew experience*. As indicated earlier, Crew A has greater length of employment with the company and greater overall experience. It is possible that experience may have resulted in the development of the more effective work practices in Crew A. While this is an interesting issue, the primary research question in this study is what are the successful production practices, independent of how these practices came about? This is an interesting direction of future studies—to address how crews learn from experience and what they learn (as they do not necessarily learn the right lesson), and why some crews may learn better than others.

Conclusions

The study attempts to explain the macrolevel performance of HRCs (the consistently high productivity and safety) by analyzing and understanding the microlevel behaviors (practices and strategies) at the work level from a limited number of situations.

The study identified and analyzed a high-reliability crew in residential framing, and compared it with an average-performing crew. The interviews and observations found that the HRC had a strong and clear "guiding principle" and a set of strategies that focused on preventing errors and rework. The findings indicate that the strategies used to prevent production errors also appear to reduce the likelihood of accidents. The study found evidence that preventing disruptions, controlling the production pressures, and matching skills with task demands are important considerations for both productivity and safety. Future studies will use the above observations as propositions for further investigation and validation.

As an exploratory study, this case has several limitations. First, is the identified crew a high-reliability crew? The researchers have continued monitoring the performance of the crew. As of mid-2008, the foreman continued to have zero accidents and the highest production score. Second, the limited observations do not imply that the two crews always follow the same practices or have similar outcomes—for example, we cannot generalize that Crew B has the same frequency of errors. However, the in-depth analysis of a few operations provided evidence regarding the effect of errors on both productivity and safety risk. The fact that framing crews are independent of other trades is another limitation of the study, as their practices may be successful for the particular task characteristics, and different practices may be needed in tasks that are strongly affected by other trades. This will be investigated in the future by studying different trades. Finally, the study did not focus on how the crew practices were developed, although this is an important question for future research.

With regards to the contributions to practice, the study indicates that a crew's productivity and safety performance can be improved by following closer the practices of the high performance crew. When a more complete and validated set of practices has been identified, that set of successful practices can be used as criteria for evaluating the foreman's performance and focusing the improvement efforts at the individual or company level.

For example, a company may focus on improving the material management system, so that errors and omissions are not left to the foremen to discover. Or companies can focus on increasing the foremen's competence in planning to identify risk areas, by providing planning support for foremen. Finally, improvement efforts should focus on the foreman's and crew's ability to understand and address the sources of in-process errors, so they can prevent them in subsequent projects. Although some factors may not be under the control of the foreman (e.g., turnover) following closer the successful strategies is expected to improve the performance of the average crews.

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