Cognitive Approach to Construction Safety: Task Demand-Capability Model

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Abstract: In the evolution of safety research, the literature identifies three paradigms: normative, error-based, and cognitive engineering. Traditionally, strategies to improve construction safety have been based on the normative paradigm—compliance with prescribed safety rules. However, the normative approach ignores how the characteristics of the production system and team processes influence the work behaviors and the possibility of errors and accidents. These factors are the focus of the cognitive engineering perspective. This study develops a cognitive model of construction safety, which conceptualizes safety as an emergent property of the production system. The model proposes that during a task, the task demands and the applied capabilities determine the potential for errors and accidents. It also proposes that the production practices and the teamwork processes of the crew shape the work situations that the workers face—that is, the task demands and the applied capability. Empirical evidence from recent case studies is discussed. The cognitive perspective shifts the focus of accident prevention from conformance with rules to the issues of task demands and applied capabilities, and the factors affecting them—such as work design, workload, resource allocation, and team processes.

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Introduction

Over 70% of the aviation accidents are caused by failures in team coordination rather than deficiencies in technical proficiency. This was the conclusion of National Aeronautics and Space Administration (NASA) researchers who analyzed over 28,000 aviation accidents that took place between 1968 and 1976 (Cooper et al. 1980). Further simulator studies confirmed this finding. Even more intriguing was the finding that there were no differences between the severity of the errors made by effective and ineffective crews; rather, it was the ability of the effective crews to communicate that kept their errors from snowballing into undesirable outcomes. Based on these findings, NASA developed the crew resource management (CRM) training system to increase the ability of the crew to collectively identify threats and manage errors. The 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). The 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.

Compared to the high-risk systems (aviation, nuclear and chemical plants, etc.), 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 the work, even within the constraints set by regulations, project conditions, and available resources. For example, crews performing very similar work with the same methods and equipment may vary in crew size, composition (apprentices and journeymen), allocation of tasks, etc. As a result, the crew practices determine how the actual work is structured and coordinated (such as task allocation, sequencing, workload and pace, work coordination, collaborative behavior, etc.) and consequently shape the work situations that the workers face. Furthermore, the dynamic, unpredictable and often hostile construction tasks and environments, combined with high production pressures and workload create high likelihood of errors. On the other hand, the crew members' skills and teamwork practices affect the crew's ability to cope with the work situations. For these reasons, crew coordination and communication are essential for effective and safe performance of construction crews. Despite their importance, the current approach to construction safety ignores the role of production and teamwork practices on the likelihood of accident.

This paper formulates a model of construction safety based on the cognitive systems engineering (CSE) perspective. From this perspective, the work practices (the way the production process is organized and managed) and the team processes of the crew shape the work situations that the workers face, and determine the workers' ability to respond successfully to these situations. The model develops a new conceptualization of safety as an emergent property of the social and production system. This conceptualization is grounded on descriptive models of work behaviors, accident causation models from other sectors (high-risk systems, aviation, and traffic safety), and organizational theory. The model is supported with empirical evidence from recent case studies of construction operations.

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Safety Research Paradigms

Rasmussen (1997) identifies three paradigms in the evolution of accident research and occupational safety: (1) normative, prescriptive theories; (2) theories of error; and (3) cognitive science theories. The normative paradigm focuses on prescriptive theories concerning the way people ought to act. Efforts to prevent occupational accidents focus on the task design and the safe rules of conduct—they attempt to control behavior through normative instruction of the "one best way," selection and development of competent personnel, and motivation and punishment. Typical responses to errors and accidents are increased training and selection practices to eliminate "error-prone" individuals, and have the rest try harder through "zero defects" programs (Rasmussen 1997). The current safety practices in the construction sector are grounded on this paradigm.

The concept of human error emerged from studies of accidents. Error theories focus on models of work behavior in terms of deviations from the normative, "best way" of working—that is errors and biases. This paradigm guides efforts to control behavior by removing causes of errors. It includes studies of errors (Rigby 1970; Rasmussen et al. 1981), management errors, and resident pathogens (Reason 1990).

The CSE is concerned with the analysis, design, and evaluation of complex sociotechnical systems, and aims at designing technological systems that are adapted to people (Vicente 1999, 2006). While ergonomics and human factors focus on the physical and psychological characteristics of individuals and their implications for task design, CSE is primarily concerned with how groups of individuals interact with the work system, as well as each other, in the organizational and production context. With regard to risk management, cognitive engineering is concerned with the characteristics of the work system (the features of the task, tools, and work context) that influence the decisions, behaviors, and the possibility of errors and failures (Rasmussen et al. 1994). The cognitive approach to safety attempts to prevent accidents by increasing the workers' ability to successfully adapt to the work environment, as well as making visible the constraints and work affordances of the workplace (Flach et al. 1998). Furthermore, from a cognitive perspective, an error is not simply a human failure but a symptom of a problem in the work system (Dekker 2006). Thus, to understand human error, we need to capture the systematic connections between human assessments and actions and features of people's tools, tasks, and operating environment.

In recent years, the term resilience engineering refers to the CSE applications on safety management (Hollnagel et al. 2006). The concept of resilience emphasizes the ability of a system to cope with disturbances, changes, and pressures. It is also concerned with the identification and monitoring of critical parameters to provide warnings that the system is approaching a safety limit. Most applications of CSE to safety management are related to high-risk operations in complex systems such as aviation, health care, nuclear, and chemical plants. In the area of construction safety, extensive research has been done based on the normative approach, but there is very little research based on errors or the cognitive perspective (with the exception of ergonomic studies). Saurin et al. (2007) examined site safety practices from a cognitive perspective, and the extent to which they contribute to workers' flexibility, learning, and awareness.

Current Strategies and Limitations

The current strategies for construction accident prevention are based on the normative paradigm—they focus on safety rules and means to control the behavior of individuals and organizations. This approach emphasizes management commitment and policies to prevent unsafe conditions, and workers' training and motivation to prevent unsafe behaviors. Safety programs—such as training, inspections, motivation, enforcement, etc., aim at increasing compliance with safety rules. Efforts toward safety culture and behavior-based safety also aim at increasing the workers' voluntary compliance with prescribed "safe behaviors." This approach has contributed to the reduction of accidents, but it also has significant theoretical and practical limitations.

While the normative approach aims at creating safe work behaviors, it ignores how the characteristics of the production system and team processes influence the work behaviors and affect the possibility of errors and accidents. First, it does not account for the production and economic pressures for efficiency, and the workers' natural tendency for least effort. Second, the normative approach does not account for the factors that shape the work situations such as, the production and teamwork practices of a crew. These factors generate the situations the workers face, and the crew's ability to cope with these situations.

Rasmussen et al. (1994) explains 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 toward 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 or costs; 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). A recent study of safety on international projects (Mahalingam and Levitt 2007) also illustrated that economic pressures were stronger determinants of work behavior than the safety regulations.

As a result of these pressures, efforts to improve safety through technical advancements (new methods and improved safety features) tend to be ineffective because the behavior "migrates" close to the new boundary of loss of control. Thus, human adaptation compensates for safety improvements. This phenomenon of "risk homeostasis" has been observed in transportation, navigation, and traffic research and explains why technological safety improvements have not generated the expected improvements in safety (Wilde 1985; Fuller 2005). Furthermore, in interdependent systems, the boundary of safe behavior for one actor depends on the possible violation of defenses by other actors (Rasmussen 1997). Thus, the stage for an accident may be prepared as a result of several actors' behaviors that erode the "error margin."

The conclusion from this discussion is that the current accident prevention strategies in construction, as well as our theoretical foundation are inadequate for the increasingly competitive and dynamic conditions of the workplace. With regard to safety, the challenge for researchers and practitioners is to develop work systems that are simultaneously highly productive and highly reliable and can function effectively in the dynamic, complex, and competitive conditions that infrastructure projects face. This re-

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quires a more fundamental understanding of the workplace elements and processes that generate accidents, and new approaches to accident prevention and work.

Background Review

This section reviews accident prevention research and developments from several sectors, and provides the theoretical grounding for the cognitive model of construction safety. The review highlights the following points. On one hand, research indicates that production practices and teamwork processes have strong effect on safety. However, the construction literature does not explain the mechanisms by which these factors affect safety. On the other hand, as discussed in the background review, the cognitive perspective emphasizes that work performance depends on the interaction between the workers (individuals or teams) and the characteristics of the work system. Based on the cognitive approach, the task-capability interface (TCI) model argues that traffic accidents result when task demands exceed capability (Fuller 2005).

This study integrates the above findings and develops a new model for construction safety. The model proposes that in construction, the production and teamwork practices of a crew shape the task demands and capabilities applied in a work situation, and consequently affect the safety performance. The section following the "Background Review" describes the model and provides empirical evidence to support these propositions.

Role of Production Factors in Construction Safety

Production Pressures

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. Hinze (1996) proposed the "distraction theory" of accidents, which describes how production tasks (among other distraction sources) can distract workers from the hazards. Mitropoulos et al. (2005) proposed that production system factors (task unpredictability, production pressures, efficient behaviors) affect the likelihood of errors and accidents during a construction operation.

Foreman's Practices

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.

Design, Methods, and Project Conditions

Construction researchers have also investigated the role of design in construction safety (Hinze and Wiegand 1992; Gambatese 2005) and the importance of work method (Everett 1999) and proposed technological interventions to improve the safety of specific construction operations (Bernold et al. 2001). These approaches focus on reducing the hazards, rather than increasing the safety effort. Suraji et al. (2001) argued that "distal factors" such as project conditions, design decisions, or management decisions can cause responses that create inappropriate conditions or actions that lead to accidents.

Lean Construction Practices

The Lean Construction Institute developed the Last Planner system of production control (Ballard and Howell 1998), which provides a set of principles for assignment planning. The Last Planner emphasizes the quality of work assignments as the primary means to reduce variability and increase process speed and productivity. The effect of the Last Planner on safety has been investigated by one study in Denmark (Thomassen et al. 2003). The study 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. However, the specific mechanisms that generate this outcome were not investigated.

Role of Teamwork in Safety

The importance of teamwork and social processes has been identified in industrial safety, aviation, organizational studies and to a lesser degree in construction safety.

Teamwork in Industrial Safety

When the work process involves several actors, the distribution of work and the coordination of the actors are critical for performance. Occupational safety research found that social support from supervisor and coworkers reduces injuries (Iverson and Erwin 1997). In a study of industrial accidents, 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 study of Wright (1986) on accidents in the oil industry reached a similar conclusion, while trying to understand why contract employees had a disproportionately high rate of accidents compared to regular employees. Wright discovered that production pressures and a focus on work speed encouraged the development of shortcuts, which eventually became accepted as normal operating conditions. For regular employees who were familiar with the plant conditions and processes, this did not present a problem. The shortcuts were much more hazardous for contract employees who were not part of the informal network of communications in the plant and were unaware of the potential risks associated with the shortcuts.

Crew Resource Management in Aviation

Research in commercial and military aviation found that team processes are critical for error prevention and accident avoidance. As a result, NASA developed the CRM training system to increase the ability of the crews to collectively identify threats and manage errors (Helmreich et al. 1999). The CRM considers critical the following team processes: crew briefings, contingency planning, workload management, cross-monitoring, communicating intentions, and assertiveness. The CRM has been implemented in sectors that require effective group interaction in complex environments such as hospital operating teams (Musson and Helmreich 2004), offshore oil platforms (Flin 1997), nuclear power operation centers and other sectors (Salas et al. 2001).

High-Reliability Organizations

High-reliability theory investigated the characteristics and operating principles of organizations such as aircraft carriers (Rochlin et al. 1998), and wildland firefighting crews (Bigley and Roberts 2001) who operate under extreme conditions, and perform complex processes with a surprising low rate of serious incidents. The high-reliability organizations (HROs) use different organizational

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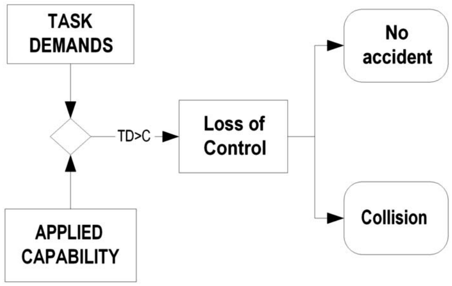

Fig. 1. Task-capability interface model [adapted by Fuller (2005)]

structures under different situations (centralized under normal conditions but decentralized under crisis), 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).

Teamwork 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. However, construction research did not investigate further these factors.

The above studies argue that production practices and social/teamwork factors affect safety. However, the literature does not explain the mechanisms by which these factors influence safety. The cognitive perspective provides a new understanding of the causes of accidents based on descriptive (rather than prescriptive) models of work behavior in terms of the behavior-shaping features of the work environment. Such models include Rasmussen's model of migration to accidents (Rasmussen 1997), the risk homeostasis theory (Wilde 1985; Taylor 1981), and the TCI model (Fuller 2005). The TCI model (described in the following section) provides a new conceptualization of accidents in traffic situations. In this study, the TCI model is used to explain the mechanism of accidents in construction settings and the mechanism by which production and teamwork factors affect the likelihood of accidents.

Task-Capability Interface Model

With regard to traffic accidents, the TCI model (Fuller 2005) provides a new conceptualization of the process by which collisions occur and the determinants of such accidents. At the heart of the TCI model is the interface between (1) the demands of the task to achieve a safe outcome; and (2) the capability applied during the task. When the capability exceeds task demand, the driver has control of the situation. As Fig. 1 shows, when task demands exceed capability, the result is loss of control, which may result in a crash unless there is a compensatory action.

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 behavior (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 behavior 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.). To maintain control it is essential that the driver has effective feedback to correctly assess and anticipate the task demands. 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.

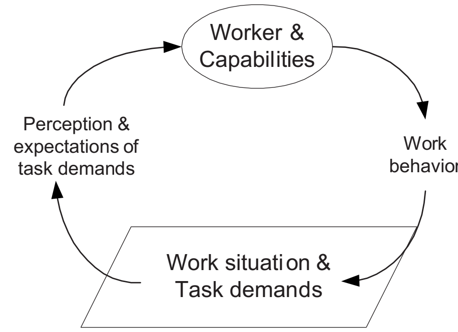

Fig. 2. Worker-task interaction

Cognitive Model of Construction Safety

Based on the background, this paper synthesizes a model of construction safety from the perspective of the cognitive engineering. The model develops three key propositions:

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

   The cognitive approach argues that the work behaviors are based on a perception of dynamic control and a balance between task difficulty and work behavior. Fig. 2 illustrates the dynamic interplay between the perceived/expected task demands (that is, the difficulty to achieve the desired outcome), which influence the work behavior (e.g., speed, shortcut), which in turn influences the work situation and task demands. Work behaviors are influenced by the workers' goals and other factors, such as production pressures, and tendency for least effort. During task interactions, the workers have multiple goals—to satisfy production goals, avoid injury, and reduce workload and effort. Correct assessment and anticipation of the work situation and task difficulty is essential, for a successful outcome.
2. *Construction 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 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. On the other hand, loss of control can also happen because of a sudden change in a task demand factor (e.g., a sudden wind). Loss of control does not necessarily result in injury—the consequences depend on the energy involved, the use of protective measures, and other situational factors.

   When task demand exceeds capability, the loss of control may result in other undesired outcomes, such as quality defects. Thus, a task can be successful in terms of safety, but unsuccessful in terms of quality—for example, a worker may use a skill saw safely, but may cut the component with less accuracy, or in the wrong dimension. The task demands with regard to safety are not necessarily the same as the task de-

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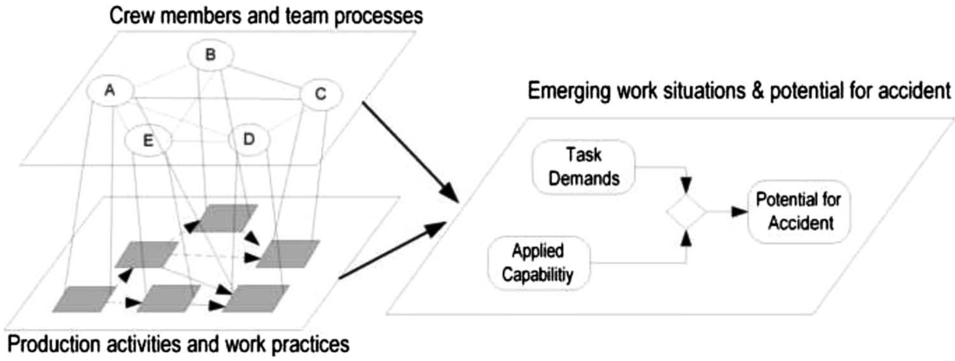

Fig. 3. Work practices and team processes affect task demands and applied capability

mands with regard to other performance dimensions. Because of the study's emphasis on safety, the model focuses on the outcomes in terms of safety and not in other performance dimensions. The factors affecting task demands and applied capabilities are discussed in more detail next.

3. *The work practices and team processes of a construction work crew shape the work situations (the task demands and applied capability) and consequently the likelihood of accidents.*

   Fig. 3 illustrates that the work practices and team processes determine the task demands of the work situations, as well as the applied capability. At the crew level, the figure illustrates the crew members and their interactions. At the production level, the figure illustrates the network of tasks. The lines connecting the crew members with the tasks indicate the task assignments. The team practices and the work processes affect the task demands and applied capabilities, and consequently the potential for accidents. The mechanisms by which the work and team practices affect task demands and capabilities are discussed below.

Task Demand and Applied Capability

Task demand indicates the "objective difficulty" of the task. It is the capability needed to successfully complete the production task and successfully control or avoid the hazards. Task demands include both physical (ergonomic) and cognitive demands (e.g., attention required to perform the task and monitor the threats outside the task). The greater the task demands, the greater is the likelihood of error and loss of control of the process.

The task demands increase with the number of elements to be controlled (task complexity) and the difficulty to control these elements. Scharf et al. (2001) 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.

As shown in Fig. 4, the model proposes that the factors affecting task demands are grouped into three categories: (1) task factors; (2) environmental factors; and (3) work behaviors. For example, the task demands for a crane operation depend on task characteristics (type of load, distance and angle, blind lift), environmental factors (soil stability, wind, visibility, proximity with power lines), and work behaviors (such as speed or other tasks that the operator may perform). These factors determine the task difficulty and the likelihood of errors and accidents.

The factors listed below are based on safety and ergonomics literature, and on empirical understanding of factors that increase the difficulty of a construction task. This is not intended to be a complete list and different factors are relevant to different construction tasks.

Task factors affecting the physical and cognitive demands for the successful completion of the task include the following:

- Task complexity, uncertainty, unpredictability (Scharf et al. 2001).
- Tools and equipment characteristics and the difficulty involved in their use (Saurin and Guimaraes 2008).
- Material handling requirements and conditions (Van der Molen et al. 2004).

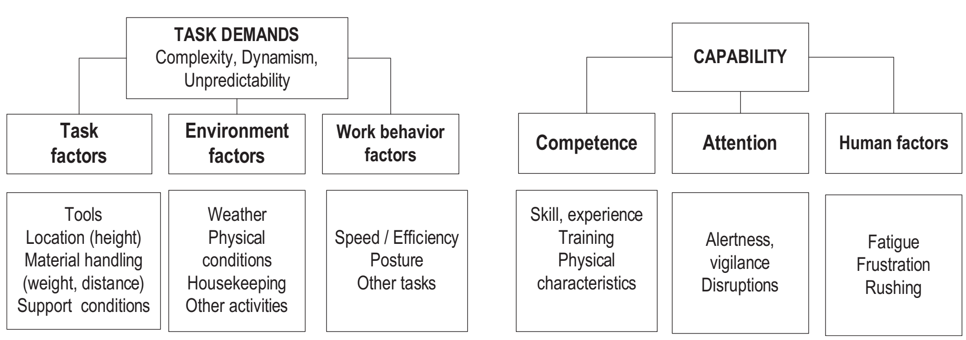

Fig. 4. Variables of task demands and applied capability

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- Support conditions (ladder, scaffold, beam) may affect the difficulty of performing the task productively (on time) and safely (e.g, maintain balance) (Hsiao and Simeonov 2001).
- Coordination requirements.
- Accuracy requirements/tolerance for error.

The construction method used has strong effect on task demands. Design attributes also affect task demands not only because they influence what material and tasks are required, but they may also affect the accuracy and coordination requirements. For example, "bull nose" trusses require more careful coordination during truss erection to avoid pulling the truss (and the coworker) off the beam while positioning it. Safety measures can reduce the task demands—for example, the installation of perimeter cable for fall protection reduces the task difficulty, as the tasks requires less attention with regards to the location.

Environmental factors refer to the conditions of the work area. The same task under different conditions may involve different degree of difficulty. Such conditions include

- Weather conditions (wind, rain, visibility, temperature) affect task difficulty.
- Proximity to hazards outside the activity (trenches, moving equipment of other activities, power lines, etc.) creates additional requirements for attention.
- Housekeeping conditions affect task demands, as poor conditions increase the difficulty of the task and the potential for errors and accidents.

The uncertainty, variability and unpredictability of the conditions may result in work situations with unexpectedly high task demands (Scharf et al. 2001). For example, if a worker is carrying a piece of plywood on a roof, a sudden wind can increase the task demands beyond the worker's ability to control the task.

Work behaviors also affect task demands. Safe behaviors (that is, compliance with safety rules) may reduce task demands or mitigate the negative consequences when control is lost. Efficient work behaviors (i.e., speed, shortcuts) increase productivity by reducing the time to perform the task, by omitting tasks, or by overlapping tasks, but may increase task demand. For example, a team of two workers may decide to perform independently tasks that they are supposed to perform together to save time, thus increasing the task demand on each one of them. As discussed earlier, workload and production pressures are very important factors influencing work behavior and consequently task demands.

Applied Capability

The applied capability determines the ability to cope with the task demands, and depends on (1) the overall competency of the actor(s), which is developed though technical and safety training, and experience with similar situations. It also includes the actors' skill and physical condition (strength, reaction time, etc.). (2) Human factors that reduce competency. A study of injuries and fatalities in the railroad sector identified four states of mind as key factors related to accidents: rushing, fatigue, frustration, and complacency (Threlfall 2000). (3) The level of activation and attention given to the task and the hazards. Attention is a limited resource—multiple task demands (due to task complexity) reduce the attention to any single demand, and distractions can divert the attention from the task or the hazards. Hinze's distraction theory (Hinze 1996) described how the attention to the production task can act as a distraction from the hazards.

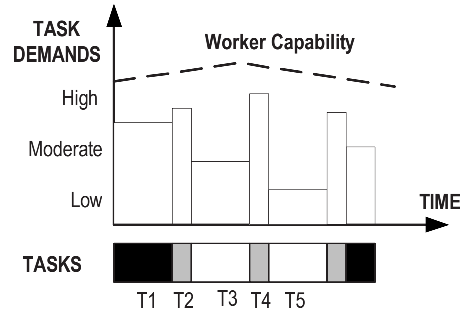

Fig. 5. Work situations described by the tasks, task demands, and capabilities

Work Situations and Potential for Accident

Work situations can be understood in terms of task demands and capabilities, which together determine the potential for accidents. Fig. 5 illustrates how the tasks, task demands, and capabilities change over time. The tasks (T1, T2, etc.) are shown along the time axis *x*, while the level of task demands is illustrated along the *y*-axis. The applied capability is illustrated as a line that may change over time—e.g., can be reduced due to fatigue or increase due to repetition and learning.

Successful performance requires that the applied capabilities exceed the task demands. Loss of control results when task demands exceed applied capabilities—this may be caused by a sudden/unexpected increase in task demands (such as a sudden wind, a component breaking), or a task demand not identified (such as stepping on an unsupported component), or a drop in capability (e.g., a slip or mistake due problems with attention, fatigue, etc.). As discussed earlier, correct assessment and anticipation of the work situation and task demands is essential.

Depending on the factors that generate the task demands, different responses are appropriate. For example, for highly dynamic conditions, the ability to cope can increase by having other people contribute to assessment of what is going on. For complex tasks with higher uncertainty, resources with greater experience are required, who can better anticipate and respond to the task demands. Task demands due to high workload can be managed by having other people to off-load tasks.

Work Practices and Team Processes

The background review identified several production and teamwork practices that affect safety. The model proposes that production and teamwork practices affect safety by affecting task demands and applied capabilities. This section discusses in more detail how the production practices and team processes influence the task demands and applied capabilities and presents empirical evidence to illustrate the effect of these factors. Several of the factors discussed below are those identified in the background review, but other factors that can affect the task demands or the applied capabilities are also proposed. The empirical evidence is based on recent field studies: an investigation of the work practices of high performance residential framing crews (Mitropoulos and Cupido 2007) and case studies of concrete paving and concrete wall formwork operations (Namboodiri 2007).

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Work Practices

Work Division and Task Assignment

As discussed earlier, the distribution of work strongly affects the "boundary" of the safe operation (Rasmussen 1997). The work division determines the individual tasks and consequently affects the task demands and 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.

The structure, sequence, and overlapping of the work affects the task demands. In the concrete paving operation, the coupling of the tasks affected the task demands—when specific tasks were decoupled, sometimes they were performed concurrently (the concrete truck was backing up while the worker was performing another task), which increased the task demands for the worker.

The task assignments to crew members determine the resources and capabilities assigned to the tasks. The study of residential framing found that a common strategy used by foremen is to match the workers' abilities with the task demands. The foremen have a clear understanding of the high-demand high-risk tasks and try to assign the most experienced workers to the most difficult tasks. This indicates that task specialization may reduce the likelihood of accidents, but this point requires further investigation.

Production Pressures and Workload Management

Production pressures and workload have been found to affect safety (Hinze and Parker 1978). Workload and production pressures affect work behaviors. In the literature, the relationship between pressures (stress) and performance is indicated with an inverted "U"—when the pressures are very low or very high, errors increase and performance is low. Production pressures can increase task demands in several ways: they may increase efficient behaviors, may result in changes in work division (such as increasing task overlap), or they may reduce the time allocated to support tasks (such as, housekeeping and maintenance of safety barriers). Production pressures can also reduce the applied capability as they may reduce the resources allocated to tasks (i.e., workers may try to work on tasks alone), may reduce coordination, and may increase rushing and fatigue.

In the concrete paving operation, the supervisor assigned very few tasks to the two workers working in front of the paver, to avoid having their attention distracted. The organized preparation of the operation (material layout) also contributed in minimizing the time spent to secondary tasks during the operation. During the operation, the supervisor was also watching out for changes in the situation, and was assisting when workload was increasing for the workers. His assistance provided some extra capacity that was used when the workload for the workers was high.

Production Planning

Thomassen et. al (2003) emphasized the effect of production planning on safety. Planning reduces task uncertainty and errors. Task uncertainty and unpredictability generates disruptions and "exceptions" (nonroutine situations). Such exceptions include unexpected task requirements, unexpected conditions, missing or incorrect resources, etc. Exceptions may result in additional tasks (e.g., provide the appropriate tools), higher task demands (e.g., perform the task with the tools available, which may not be the most appropriate), and may increase production pressures, rushing, and frustration. For example, during a concrete wall formwork operation, the crane operator was absent 1 day and the crew transported some of the smaller forms manually. Disruptions may also result in reallocation of resources and mismatch of capability and task demands.

Errors during task execution are another element of uncertainty. During a recent study of residential framing, it was observed that errors committed during truss erection (incorrectly installed trusses), not only resulted in rework, but the rework had higher risks and task demands than the regular truss installation, as it involved more movement and changing positions of the workers on the trusses, in a process that is relatively unusual. Furthermore, the least experienced of the three framers on the trusses ended up at the most demanding position—at the top of the trusses.

Planning reduces uncertainty and disruptions as it improves the anticipation of task demands, and identifies the required resources. Better planning and preparation of the work can also prevent errors (although not all errors can be avoided by better planning). A framing foreman reviewed the plans to identify framing details that his crew was not familiar with. Because there areas have higher probability for errors and rework, the foreman worked on these areas himself (as the most experienced carpenter in the crew), or he directly supervised that work.

Monitoring System Status and Performance Migrations

In resilience engineering a key concern is the identification and the monitoring of key parameters that indicate if the system is approaching a safety limit (Hollnagel et al. 2006). In construction, we can identify several dynamic degradation processes ("drifts") that over time, systematically increase the task demands and reduce capabilities, bringing work closer to the safety limit.

- Physical barriers gradually degrade, especially in the dynamic construction environment. The lack of regular and effective maintenance is the main weakness of physical barriers (Hollnagel 2004).
- Housekeeping conditions deteriorate as a by-product of the work and increase task demands. Regular and consistent effort is needed to maintain good housekeeping conditions.
- Actions by other actors may change the safety limit (system status). For example, a crew, in an effort to achieve its own production goals, may create hazardous conditions that "normally" would not affect others (e.g., leave unsupported components on a roof area where no work is supposed to happen for a while). If however, another crew starts working in that area, it would be at high risk, especially if they expected all the components to be supported.
- Increasing production pressures motivate behaviors closer to the boundary.
- Attention systematically 'drifts' from identified hazards to production. As a safety expert expressed it "*it is never the first bucket that touches the power line*."
- Fatigue increases and reduces applied capabilities.

Systematic monitoring of both the system status and the performance and capabilities is required to avoid accidents due to such processes.

Team Processes

The background review identified the importance of teamwork. Teamwork behaviors affect the likelihood of accidents in three ways: they can reduce the task demands, they can increase the resources allocated to a task, and they can increase the worker's

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awareness of task demands. Specific behaviors that have been identified in the literature as important are the following:

- **Team planning and briefings** establish a shared mental model and increase understanding of each other's work and needs.
- **Collaborative behaviors**—offering and accepting help increases the resources allocated to a task and reduces workload. Warnings and instructions increase awareness of task factors and conditions.
- **Cross monitoring** and cross checking for actions critical to safety and productivity reduces errors. For highly dynamic conditions, the ability to cope can increase by having other people contribute to the assessment of what is going on. Cross monitoring can also detect reduction in capabilities.
- **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.

Teamwork behaviors may also include actions that do not require interaction of coworkers, but affect others indirectly. For example, a framing foreman indicated that an important teamwork behavior is "a worker cleaning up after himself," which creates good housekeeping conditions for others. Teamwork and production practices influence each other—for example, the way the work is divided into tasks and distributed to the crew, determines the task interdependencies between the crew members, which in turn may lead to the development of specific coordination and teamwork practices.

To identify which practices and behaviors affect the likelihood of accidents and to what extent, further research and validation is needed, as empirical studies and evidence from construction are very limited.

Model Discussion and Implications

The model presented in this paper takes a cognitive perspective of construction safety and proposes an explanation of why and how production practices and teamwork processes affect the likelihood of accidents. The propositions of the model are based on previous literature and supported with empirical evidence from recent case studies. Validation will be performed primarily through comparative analysis of the teamwork processes and production processes of construction crews who perform similar work, but with different levels of productivity and safety.

The model contributes to research by providing a new way to conceptualize construction safety as an outcome of the work situations, which are expressed in terms of the task demands and applied capabilities. The model provides a new explanation of the underlying mechanism by which the production and teamwork practices shape the work situations and the potential for errors and accidents. The proposed conceptualization emphasizes the design and organization of the work (which determine the task difficulty and demands) and the teamwork processes. With regard to accident analysis, the model suggests that rather than focusing on compliance, accident analysis should focus on the task demands and how they were generated (including the work design as well as the work behaviors), the capabilities applied, and the difficulty of the worker(s) to perceive and anticipate the actual task demands.

With regards to practice, the model has implications for accident prevention strategies, as it shifts the focus from compliance with safe behaviors and conditions to control of task demands and capabilities. The model recognizes the role of safe behaviors and "safe conditions" as factors that reduce the task demands or increase the applied capability. However, it argues that there are no inherently "safe/unsafe" conditions or behaviors, only conditions with higher or lower task demands, and that the outcome depends heavily on the capability applied.

The model emphasizes the role of teamwork and production processes as part of the safety strategies. While the model requires further validation in the construction setting, several of the concepts have been validated in other sectors. As discussed in the background review, the importance of teamwork has been well established and supported in industrial safety and aviation, and team training is already been implemented in health care, power plants, and other high-risk operations that require coordinated action. The construction industry can also implement and benefit from such knowledge, without waiting for validation of all the elements of the proposed model. Reducing physical task demands to prevent ergonomic injuries has been the focus of ergonomics. Although new methods are needed to account for all task demands and hazards, construction practitioners can use existing ergonomic methods to reduce task demands and risk of injuries (NIOSH 2007). Thus, the model has implications for the role of the safety professionals—it implies that safety professionals need to focus more on analyzing, evaluating and designing the production process, and developing the teamwork abilities of the crew.

Finally, the model integrates the study of safety and productivity, as it provides a new basis for understanding and analyzing the relationship between productivity and safety. Reducing the task demands and increasing the crews' ability to cope with such demands, could improve safety while at the same time improve productivity. Similar examples can be found in ergonomics where interventions often result in improvements in both safety and productivity (NIOSH 2007). Thus, an important research question is "what are the production practices and teamwork processes that reduce the likelihood of accidents while at the same time improve productivity." This is an important area of future research. The proposed model directs safety research toward the following topics:

- **Task demands and errors.** This research direction will increase understanding of the important features of the work system that increase the likelihood of errors and accidents. The long-term goal is to develop a systematic approach to analyze, design, and error proof the production task to reduce the task demands and the likelihood for errors.
- **Production practices.** To develop highly productive and safe production systems it is critical to understand how the production practices affect the likelihood of accidents. This research direction will focus on understanding how the production variables and practices influence the task demands, the capability applied, and the likelihood of accidents.
- **Teamwork practices**. The development of CRM underscores that effective team processes can increase the crews' ability to cope with task demands, to detect threats, and to avoid or recover from errors. Such a team-based approach to error management can provide an important strategy in construction that complements current practices. This research direction will identify the teamwork behaviors that reduce the likelihood of accidents, and will investigate the deeper determinants of effective teamwork (such as shared mental models, capabilities, etc.).

Together, these research directions will contribute to the development of work systems that are at the same time highly productive and safe.

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