Systems Model of Construction Accident Causation

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Abstract: The current approach to safety focuses on prescribing and enforcing "defenses;" that is, physical and procedural barriers that reduce the workers' exposure to hazards. Under this perspective, accidents occur because the prescribed defenses are violated due to lack of safety knowledge and/or commitment. This perspective has a limited view of accident causality, as it ignores the work system factors and their interactions that generate the hazardous situations and shape the work behaviors. Understanding and addressing these causal factors that lead to accidents is necessary to develop effective accident prevention strategies. This paper presents a new accident causation model of the factors affecting the likelihood of accidents during a construction activity. The model takes a systems view of accidents—it focuses on how the characteristics of the production system generate hazardous situations and shape the work behaviors, and analyzes the conditions that trigger the release of the hazards. The model is based on descriptive rather than prescriptive models of work behaviors—it takes into account the actual production behaviors, as opposed to the normative behaviors and procedures that workers "should" follow. The model identifies the critical role of task unpredictability in generating unexpected hazardous situations, and acknowledges the inevitability of exposures and errors. The model identifies the need for two accident prevention strategies: (1) reliable production planning to reduce task unpredictability, and (2) error management to increase the workers' ability to avoid, trap, and mitigate errors. The new causation model contributes to safety research by increasing understanding of the production system factors that affect the frequency of accident. The practical benefit of the model is that it provides practitioners with strategies to reduce the likelihood of accidents.

DOI: 10.1061/(ASCE)0733-9364(2005)131:7(816)

CE Database subject headings: Occupational safety; Construction site accidents; Accident prevention.

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Introduction

In recent years, construction accident rates have declined as a result of substantial effort by many parties. Increased pressures from OSHA and owners, and increased cost of accidents raised the contractors' awareness. In turn, contractors increased safety training and enforcement. These efforts have reduced the injury and illness rate from 12.2 in 1993 to 7.9 in 2001. However, the rate of fatalities has shown little improvement—since 1997, the number of fatalities per year is consistently over 1,100 (Bureau of Labor Statistics 2004).

The current approach to accident prevention is based on OSHA's violations approach and focuses on prescribing and enforcing "defenses;" that is, physical and procedural barriers that reduce the workers' exposure to hazards. The violations of the defenses are called "unsafe conditions" and "unsafe behaviors." This approach emphasizes (a) management commitment and policies to prevent unsafe conditions and (b) workers' training and motivation to prevent unsafe behaviors.

Safety programs, such as training, inspections, motivation, enforcement, penalties, etc., emphasize competency ("competent person" philosophy) and liability, and aim at increasing compliance with safety rules and increasing the cost of noncompliance. The violations approach has contributed to the reduction of accident rates, but it also has limitations, as high levels of compliance are costly and compliance does not ensure safety (Prichard 2002). The following are some limitations of the traditional approach.

(1) Reactive approach. The violations approach is reactive. It manages the hazards with defenses and relies on increased safety effort to reduce accidents. A proactive approach avoids hazards (e.g., by using a less hazardous method), reduces the safety risk of the production system and reduces accidents without increased safety effort.

(2) Conflict with production. The safety effort does not add value to production—it only replaces one type of unacceptable loss (human suffering and financial consequences) with a more acceptable cost. However, compliance requires significant safety effort and resources and in the short term, safety requirements are in conflict with production and cost goals. This often leads to noncompliance.

(3) Uncertainty limits the effectiveness of defenses. Compared to the well-structured, high-risk technical systems, such as nuclear and process plants, airplanes, etc., construction is a less structured and loosely coupled system (Rasmussen 1997). The ill-structured, dynamic nature of the construction process and the large number of poorly defined situational hazards limit the effectiveness of such defenses, as they create many circumstances in which the needed defenses are absent or existing defenses are bypassed. Furthermore, safety defenses cannot address all types

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Note. Discussion open until December 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on January 8, 2003; approved on September 2, 2004. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 131, No. 7, July 1, 2005. ©ASCE, ISSN 0733-9364/2005/7-816–825/$25.00.

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of hazards (e.g., ergonomic hazards), and in some cases cannot overcome the legacy of design and the need to work in dangerous circumstances (e.g., roofwork).

(4) Limited view of accident causality. The violations perspective attributes accidents to the managers' or workers' lack of safety knowledge and/or motivation. This approach perceives safety as a problem of "right versus wrong" (safe versus unsafe) choice, and ignores the fact that the dynamic nature of work does not involve conscious decision making or risk assessment. What seems to be a rational act under a particular work situation, may easily be judged as a unacceptable mistake on hindsight (Rasmussen 1990).

(5) Limited learning. The focus on violations limits the ability to learn from accidents. Accident investigation focuses on violations and liability and does not increase understanding of the accident phenomenon; rather, it perpetuates the current structure by assigning blame. An evaluation of 17 accident investigation methodologies used by public agencies found that OSHA's violations approach is among the lowest in its ability to identify root causes (Benner 1985).

Better models of accident causation are essential for developing effective accident prevention strategies. We argue that effective causation models need to take a systems view of safety and provide better understanding of how the characteristics of the production system generate hazardous situations and shape the work behaviors.

This paper develops a new causation model of the factors and processes that generate construction accidents. The model presented here, has the following attributes:

- It focuses on the activity level, as opposed to event-based models that focus on the incident level. This model attempts to answer the question: "*What causal factors and processes influence the number of accidents during a construction operation?*" It is a conceptual model and at this stage it does not operationalize or quantify the variables.
- It takes a systems view of accidents—it is a causal modeling approach that moves away from looking at isolated events and looks at the production as a system made up of interacting variables (Sterman 2000). Thus, accidents are viewed as byproducts of the production system and the model focuses on the characteristics of the production system that generate the risks and shape the work behaviors.
- It is based on descriptive rather than prescriptive models of work behavior. That is, it takes into account the actual production behaviors, as opposed to the normative behaviors that workers "should" follow.

The model is based on previous research in accident causation, human error, and construction safety. The next section presents the background literature. We then present the model and discuss its implications. Based on the model, the paper proposes new directions for accident prevention.

Background Literature

Definitions

The National Safety Council (NSC) defines *safety* as "the control of recognized hazards to attain an acceptable level of risk." A *hazard* is defined as "an unsafe condition or activity that, if left uncontrolled, can contribute to an accident." *Risk* is a term applied to the individual or combined assessments of "probability of loss" and "potential amount of loss." NSC defines *accident* as "an occurrence in a sequence of events that produces unintended injury, death, or property damage. Accident refers to the event, not the result of the event."

Accident Causation Models

Accident causation models attempt to understand the factors and processes involved in accidents in order to develop strategies for accident prevention. The different models are based on different perception of the accident process. Some of the most influential accident causation models and methodologies are: (1) the **Single Event** concept; (2) the **Determinant Variable** concept; (3) the **Domino Theory** (Heinrich 1936); (4) the **Fault Tree** analytical methodology; (5) the **Energy-Barriers-Targets** model, which views the accident process as an unwanted release of energy due to inadequate physical or procedural barriers; (6) the **Management Oversight and Risk Tree**, which focuses on "what" barriers failed and "why" they failed—that is, what management elements permitted the barrier failure (DOE 1992); (7) Petersen's **Multiple Causation** model (1971); and (8) Reason's (1990) '**Swiss Cheese**' model of human error, and the "resident pathogens" or "latent failures."

Construction Safety Literature

Construction researchers have proposed several accident causation models and root causes. McClay's (1989) "universal framework" identified three key elements of accidents: hazards, human actions, and functional limitations. Hinze's distraction theory (1996) argued that production pressures can distract workers from the hazards and increase the probability of accidents. Abdelhamid and Everett (2000) identified management deficiencies, training, and workers' attitude as the three general root causes. The "constraints-response" model (Suraji et al. 2001) argues that project conditions or management decisions (distal factors) can cause responses that create inappropriate conditions or actions (proximal factors) that lead to accidents.

Organizational factors associated with safety performance include top management's attitude toward safety (Levitt 1975), organizational culture (Molenaar et al. 2002), safety climate (Mohamed 2002), superintendent practices (Levitt and Samelson 1987; Hinze and Gordon 1979), and turnover (Hinze 1978). Hinze and Parker (1978) found that job pressures and crew competition are related to more injuries. Hinze (1981) found that good working relationships improve safety.

In terms of safety practices, Jaselskis et al. (1996) identified the frequency of formal safety meetings with project supervisors, and safety budget as factors related to lower incident rates. The Construction Industry Institute identified five best practices (Liska et al. 1993): preproject and pretask planning for safety, safety orientation and training, safety incentives (the effect of this has been debated), alcohol and substance abuse programs, and incident investigations. Toole (2002) identified eight root causes of accidents: lack of proper training, safety equipment not provided, deficient enforcement of safety, unsafe equipment, method, or condition, poor safety attitude, and isolated deviation from prescribed behavior.

Few researchers have emphasized the role of design in construction safety (Hinze and Wiegand 1992; Gambatese 2000) and the importance of task characteristics and work method (Everett 1999) and proposed technological interventions to improve the

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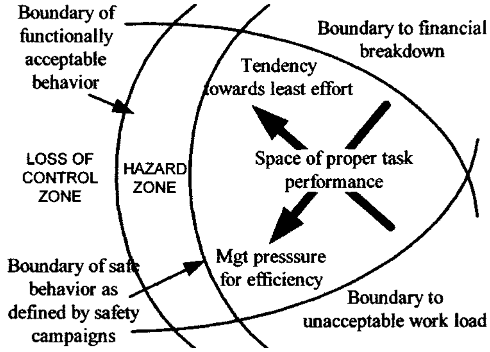

Fig. 1. Rasumussen's work behavior model (adapted from Rasmussen et al. 1994)

safety of specific construction operations (Bernhold et al. 2001). These approaches focus on reducing the safety risks, rather than increasing the safety effort.

The construction safety literature has paid little attention to worker errors and effective ways to manage errors in the workplace.

Human Error

Human error is a central element in accidents and has been researched extensively by researchers of high-risk systems. Rigby (1970) defines an error as a set of human actions that exceeds some level of acceptability. Traditionally, the standard of judgment is the normative (prescribed) behavior. From this perspective, human error is a deviation from a normative procedure. Reason (1990) classified unsafe acts in three types of errors, and two types of violations.

Errors. Slips and lapses are "skill-based" errors and occur with little or no conscious thought. A slip is an unintended error in the execution of an otherwise correct plan. Mistakes (or decision errors) involve the correct execution of a wrong plan. In other words, mistakes are intentional behaviors that involve incorrect choice of action (inappropriate for the situation). Perceptual errors are actions that result from misinterpretation of the actual situation.

Violations. Routine violations are habitual departures from the rules and often tolerated by supervision. This may involve behaviors that are established practice as opposed to the specified practice, such as driving 5–10 mph faster than the speed limit. *Exceptional violations* are neither typical of the individual nor condoned by management.

Rasmussen's Descriptive Model of Work Behavior

Descriptive models of work behavior attempt to understand accidents without reference to normative concepts of errors or violations. An important descriptive model is the one proposed by Rasmussen et al. (1994). According to Rasmussen, workers operate within a work system shaped by objectives and constraints (economic, functional, safety related, etc.). A worker searches freely within those boundaries guided by criteria such as workload, cost effectiveness, risk of failure, joy of exploration, etc. Figure 1 illustrates how the work behaviors tend to migrate closer to the boundary of functionally acceptable performance (limit 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. Managers supply the "cost gradient" and the worker searches and finds a "least effort gradient." The result is a "*systematic migration toward the boundary of acceptable performance, and when crossing an irreversible boundary, work will no longer be successful due to a 'human error'*" (Rasmussen et al. 1994, p. 149). A breakdown in work performance indicates an operation too close to its capability limits and/or the limits of the ability to recover control.

Safety programs attempt to counter the pressures outlined in the Rasmussen model and prescribe "safe behaviors" away from the boundary. However, the pressures that push workers toward the boundary require that safety efforts are continuous. Furthermore, efforts to improve system safety lead to human adaptation that compensates for safety improvements. Thus, the work behavior is likely to be maintained close to the boundary of loss of control. To address these problems, Rasmussen proposes that accident prevention efforts should focus on development of error-tolerant work systems that make the boundary of loss of control visible and reversible.

Based on Rasmussen's framework, Howell et al. (2003) identify three zones of operation: (a) the "safe zone," where the workers' behaviors are within the boundary defined by safety rules (b) the "hazard zone" (or "near the edge"), and (c) the "loss of control" zone.

Accident Causation Model

Model Overview

Figure 2 presents the accident causation model, which builds on the Rasmussen model and previous construction accident causation models. This conceptual framework identifies the variables that influence the likelihood of accidents during a construction activity. The arrows indicate cause-effect relationships. The signs indicate the direction of the relationship between the factors; a positive sign indicates that when the causal factor X changes, the effect Y changes in the same direction (X increase→Y increase or X decrease→Y decrease). A negative sign indicates that the effect changes in the opposite direction (X increase→Y decrease, X decrease→Y increase).

The characteristics of the activity and work context, and the task unpredictability shape the work situations within which the workers operate, and create hazardous situations. Different activities involve different hazardous situations, depending on the material, tools, location, etc. Furthermore, the same activity performed under different method or context (physical conditions and surrounding activities) involves different hazards. Task unpredictability leads to unplanned tasks and unexpected situations that also create hazardous situations. Safety efforts to control conditions reduce the hazardous situations.

Workers' behaviors determine both the production outcome, as well as the exposure to hazards. Production pressures and workload and the tendency for competent action drive workers to adopt more efficient work behaviors (such as working faster, taking shortcuts, or working without the required safety procedures), which increase production, but also increase exposure to hazards. The shaded section where the "hazardous work situations" and "work behaviors" overlap indicates work behaviors in the hazard zone that expose workers to hazards. Safety efforts to control workers' behaviors reduce exposures to hazards.

Exposures to hazards create the potential for incidents, but do not necessarily lead to incidents. For an incident to occur, the

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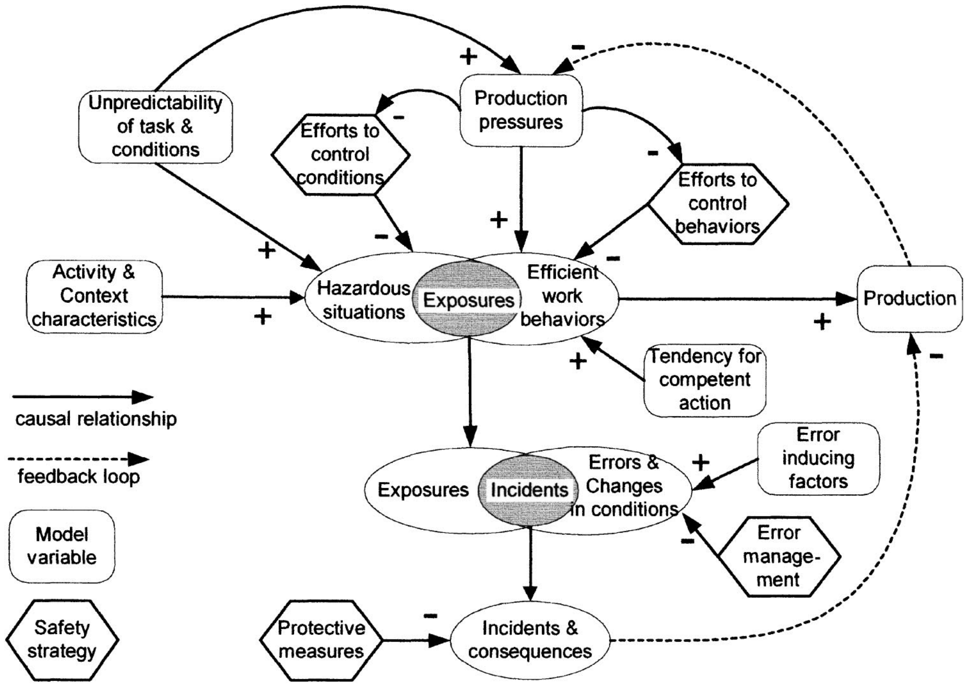

Fig. 2. Accident causation model

hazard must be released. Human errors and changes in conditions create a "mismatch" between conditions and actions and trigger the release of hazards. Not all errors release hazards—many errors are inconsequential, while other errors are "trapped" and control is recovered before the hazard is released. The shaded section where "Exposures" and "Errors & Changes in conditions" overlap, indicates the errors under condition of exposure that release hazards and generate incidents. The likelihood of errors depends on the task, the environment, and the workers' capacity factors. Depending on the consequences, an incident may be a "near miss," an injury accident, or a fatality.

The causation model in Fig. 2 depicts the key factors and processes that lead to accidents. Several other relationships and feedback loops exist, which are discussed briefly as they are not as critical for understanding the accident process.

Hazardous Work Situations

In this paper, hazardous situations are defined as "situations with the potential to cause injury, unless the worker can detect and avoid the hazard, without exposing themselves to a greater hazard." This definition acknowledges the subjective and situational nature of many hazards. In other words, what is a threat for one person may not be for another, depending on the ability to detect and avoid the hazard. Furthermore, what is a hazard in one situation may not be in another. The hazardous situations definition is consistent with NSC's definition, because the ability to detect and avoid a hazard reduces its potential to contribute to an accident.

As shown in Fig. 2, the nature and number of hazardous work situations during an activity depend on the following factors: (1) characteristics of the activity and context, (2) safety efforts to control conditions, and (3) task unpredictability. A discussion of these factors follows.

Activity and Context Characteristics

Different activities involve different hazards. Surveying in an empty site involves few hazards, while steel erection includes many more. Furthermore, the same activity involves different hazardous situations if performed with a different method or under different conditions. There are three main sources of hazards: (a) the work technology, (b) the physical conditions, and (c) the surrounding activities.

(a) Work technology. The work technology includes the objects and actions necessary to perform the task, such as the tools and equipment (scaffolds, power tools, cranes, heavy equipment), the material (e.g., heavy or sharp objects, chemicals, electricity), the physical tasks required (material handling), and the byproducts of the production task (scrap metal, etc.). The same activity may be performed with different tools and equipment (ladders, scaffolds, or mechanical lifts), or at different locations (on the ground or at elevation) and involve different hazards.

(b) Physical conditions. The physical environment of the activity (such as high elevations, floor openings, trenches, confined space, overhead power lines, and housekeeping conditions) creates another set of hazards. Environmental conditions (such as cold, heat, illumination, vibrations, noise, vapors, etc.) may create additional sources of hazards.

(c) Surrounding activities. Surrounding activities also generate "threats," such as falling objects, heavy equipment traffic, debris, etc. The project schedule (sequence and timing of activities) affects the work context. For example, out-of-sequence work may increase the difficulty and the hazards of the activity.

The number and nature of hazardous work situations changes during the course of an activity. Some hazard sources exist before the activity starts, while other hazards develop during the activity (e.g., a trench is excavated), tools and equipment wear out, conditions change, and surrounding activities start and end.

Task Unpredictability

Task unpredictability means that the work cannot be completed as planned—the scope of the task may be different than anticipated, the actual conditions are different than expected, or resources may be missing (information, tool, material, etc.). Workers' errors also

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increase task unpredictability as errors by one crew may create unpredictable conditions for a following crew. Task unpredictability increases both the likelihood of hazardous situations, and the production pressures and workload.

Unpredictability Generates Hazardous Situations. First, the resources, equipment, manpower, or safety measures required may not be available for the unexpected tasks or conditions, e.g., the crew planned for a 6 ft. ladder, but some locations require an 8 ft. ladder. Even if a crew performs safety pretask planning, the plan will be inadequate if the task is unpredictable. Second, unpredictable tasks and conditions require increased effort, more movement of workers and equipment, increased material handling, increased need to improvise, more out-of-sequence tasks, and involve much chaos and confusion.

Unpredictability Increases Workload and Production Pressures. This generates interruptions and "urgent/last minute" problems that have to be resolved promptly, otherwise production can be significantly disrupted. This creates temporary "peaks" of production pressure and sudden changes to production pace, even if the overall activity is not under particular schedule pressure. Furthermore, resolving the interruptions takes time and reduces the time available for the planned task.

The increased production pressures may lead the workers (or supervisors) to do the work in any way they can ("make do") without the appropriate safety measures or resources. For example, lack of adequate manpower may lead a worker to individually perform tasks that normally require two people (e.g., move heavy material, enter confined space, etc.). Or, if a ladder is not tall enough for all the work locations, the worker may step on the last two steps, rather than look for an appropriate ladder.

Much of the complexity and dynamism of the work in construction is caused by a failure to reliably plan and coordinate the work activities.

Safety Effort to Control Conditions

Safety measures to control conditions are barriers that confine the hazard sources, and prevent exposure to the hazards, such as perimeter cable, support of deep trenches, and closing-off the area under steel erection. OSHA regulations define what conditions are hazardous and what safety barriers are needed. Safety efforts to control conditions include training and inspections to identify hazardous conditions, and the time and resources needed to provide and maintain the safety measures. Economic pressures and time or personnel shortage may prevent management from providing and maintaining the required safety measures. Management commitment and policies that support safety increase the likelihood that the safety resources and effort will be committed.

Efficient Work Behaviors

Efficient work behaviors increase production, but in the presence of hazards such behaviors also bring the workers in the hazard zone (expose workers to the hazards), which in turn increases the likelihood of incidents that may disrupt production and counter any prior gains. Thus, under hazardous conditions, less efficient work behavior is required to prevent exposure.

Efficient work behavior is shaped by: (1) production pressures and workload, which increase efficient behavior, (2) the tendency for competent action, which increases efficient behaviors, and (3) safety efforts to control behaviors, which reduce efficient behaviors and consequently exposures.

Production Pressures and Workload

Rasmussen's framework illustrates that production pressures and efforts to reduce workload may lead workers to avoid safety measures, or not follow the safety rules if they slow down production. Similarly, cost pressures may prevent management from providing the required safety measures or appropriate tools and equipment.

Tendency for Competent Action

The tendency for efficient, competent action is another behavior-shaping factor, which pushes workers close to the boundary of loss of control, even in the absence of high production pressures. Workers take shortcuts or exert excessive effort to reduce the time to perform a task. These behaviors are typically considered "risk-taking." However, from the perspective of the worker, it is competent action—experienced professionals develop shortcuts and tricks of the trade as efficient ways to perform the work. Such behaviors often are established trade practices that may violate prescribed procedures—they are "routine violations" typically tolerated by supervisors. Such behaviors protect and enhance the workers' feeling of competency. They are very efficient under normal conditions, but under special circumstances they may lead to accidents.

Safety Effort to Control Behaviors

When hazards cannot be contained with physical barriers, safety procedures are prescribed to prevent exposure to the hazards (lockout-tag out, or testing the air in confined spaces). "Unsafe behaviors" are those acts that violate prescribed procedure. Safety programs and campaigns attempt to increase compliance with safety rules, and maintain work behaviors in the "safe zone" away from the boundary.

The prevailing view is that unsafe behaviors are caused by lack of knowledge of the hazards (competent person philosophy) or poor safety attitude. As a result, management actions to reduce unsafe behaviors focus on training and motivating workers to comply with the safety rules. Such practices include training in safety rules and procedures, incentives and motivational campaigns (such as safety culture and value-based safety), enforcement and punishments, and behavior-based safety.

The main limitation of these practices is that they do not address the systemic forces that push workers near the edge. First, the dynamic nature of work does not involve conscious decision making or risk assessment; workers immersed in the dynamic flow of work do not make decisions based on careful situation analysis but on know-how, heuristics, and a perception of dynamic control, and they cannot follow prescriptive procedures prepared by outside experts (Rasmussen 1997). Second, short-term conflicts between safety and production are usually resolved in favor of production, as efforts for production have relatively certain outcomes and receive rapid and rewarding feedback (Reason 1990). Finally, because the workers' behaviors migrate toward the boundary, safety needs to maintain continuous counter pressures. Last, but not least, in an unstructured, complex and dynamic environment like a construction jobsite, there are many hazardous situations not covered by work rules.

Production

Efficient work behaviors increase production. Increased production reduces production pressures, which in turn reduce efficient

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work behaviors. Production is also affected by accidents—when the number and severity of incidents increase, production is reduced.

Exposure to Hazards

Exposure to hazards exists when the work behavior brings the worker in the "hazard zone" and near the boundary of loss of control, where events can take place faster than the worker can detect and avoid the danger. Exposure are the result of: (a) efficient behavior that leads to routine violations, (b) exceptional violations, (c) proper actions that are near the limits of the worker's ability (such as physical effort and ergonomic exposures), or (d) unrecognized hazards: if a hazard is not identified, a normal work behavior may expose a worker to the hazard without the worker's knowledge.

Examples of exposures are working in a deep trench without sloping or trench protection, working near an unprotected opening at high elevation without fall protection, working with defective tools and equipment (knowingly or unknowingly), performing electrical work without lockout-tag out, working in an area with heavy equipment traffic, operating equipment close to power lines, working under another crew, handling heavy material, etc.

Exposure to hazards creates the potential for accident, but does not automatically lead to accident: a worker near an unprotected edge will not necessarily fall. In other words, "unsafe" conditions and actions are not sufficient to cause an accident. For an accident to occur, the hazard must be released. Errors and changes in conditions trigger the release of the hazard: in both cases there is a "mismatch" between the situation and the action.

Errors and Changes in Conditions

Unlike violations, errors are unintended actions that fail to achieve their intended outcome. As discussed in the literature review, human error involves slips (unintentional loss of control), mistakes (selection of incorrect course of action) and perceptual errors. Huang and Hinze (2003) found that misjudgment of hazardous situation was a significant factor in over 30% of fall accidents.

Not all errors release hazards. An error will have no safety consequences if there is no exposure to a hazard; e.g., errors made in flight simulators are inconsequential. However, if a worker is in the hazard zone, an error may push him over the boundary of loss of control, and release the hazard. If the worker detects the error soon enough to "trap" the error and recover control, then the error will not release the hazard.

Hazards are also released by changes in the state of the system, such as mechanical failures, loss of soil stability, etc. If the worker can react fast enough and adjust the behavior to one appropriate for the new conditions, then the accident can be avoided. If the change in the conditions is too sudden for the worker to recover control, it results in an accident. Error management and situation awareness increase the ability to correct errors, detect changes, and prevent or avoid the release of hazards.

Error Inducing Factors

The likelihood of errors depends on the task demands (complexity, dynamism, pressures), the environment, and the workers' capacity. According to Rasmussen et al. (1981), causes of human "malfunction" include external events (such as distractions, component failures, or the physical environment), excessive task demands (due to task characteristics and situation), performance shaping factors (such as work load, skills, and stress factors), reduced capacity (due to fatigue, etc.), or intrinsic human variability.

Table 1. Hazard Scenarios on Construction Operations

Hazard	Exposure to hazard	Incident
Unprotected edge (physical condition)	Worker near unprotected edge	Worker slips and falls
Saw with dull blade (undermaintained tool)	Worker using saw with dull blade	Saw jams and kicks back
Material handling (activity element)	Worker lifts material	A muscle exceeds functional limit
Surrounding activities	Worker in same area w/excavator	Excavator turns and hits worker
Surrounding activities	Working under another crew	Object falls and hits worker
Unsecured power source (physical condition)	Working without lockout-tag out	Another worker turns on the power

Natural drive toward economy of cognitive effects may lead to wrong assessment of situations and task demands, and wrong rules to be applied (Reason 1990). Many perceptual errors are the result of "cognitive confusion;" that is, the selection of a motor program to execute a previously learned task while not considering the new conditions of the environment the task is performed in or the new dimensions or design of the tools or equipment being used.

Error Management

Error management is a set of strategies that enable the workers detect and correct errors before onset of consequences. Error management strategies for individuals and team have been developed in other sectors (primarily in military and commercial aviation) and have focused primarily on improving situation awareness (Endsley 1988), and developing effective team processes to increase a team's collective situation awareness and decision-making (Helmreich et al. 1999).

In construction, the primary error-management strategy is the use of warnings, such as signs, spotters, backup alarms, etc., which alert workers when approaching a hazard. The effectiveness of such warning measures is limited. Blackmon and Gramopadhye (1995) found that the effectiveness of backup alarms is low because of the general noise level of the jobsite, the operators' reliance on the alarms, and reduced attention.

Incidents and Consequences

An incident is the undesired event that results from the release of the hazard. A hazard may be released by the same worker who is exposed to the hazard (e.g., a worker loses control of the equipment), or by another worker (e.g., another worker drops an object). Table 1 lists examples of typical exposure to hazard scenarios found on construction sites, and possible subsequent scenarios of the release of hazards.

Depending on the consequences, an incident can be a near miss, an injury, or a fatality accident. If the worker can react fast enough to avoid the hazard or interrupt the flow of events, then the incident is a near miss. The ability to react depends on the speed of the hazard release: when the loss of control is very sudden, there is no time to react. Worker's experience and situational awareness is critical in anticipating hazard release and taking appropriate action.

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Protective measures are "the last line of defense" and can mitigate the consequences of an incident. Personal protective equipment increases the error tolerance of the system (e.g., fall protection equipment reduces the consequences of falls). The magnitude of injury also depends on situational factors that may aggravate or mitigate the injury (including the individual's tolerance, and luck).

Taxonomy of Incidents

The model identifies three different types of accidents, based on the source of exposure and the action that releases the hazard. This taxonomy is based on etiology of accidents, and differs from OSHA's classifications.

(a) *Loss of control.* The first type involves situations where the person who is exposed to the hazard is also the one who releases the hazard. For example, a worker near an unprotected opening may slip or not see the opening and fall. Or a crane is working near a power line and comes in contact with the line. In these cases, the release of the hazard is due to loss of control, or perceptual failure to detect the boundary (the edge of the slab, the distance from the power line).

(b) *Coordination.* In the second type of incidents, the person who releases the hazard is different than the one who is exposed to the hazard. For example, a worker is working near heavy equipment, and the equipment operator turns and unintentionally strikes him. Or a worker is under another crew, and the worker above drops an object. What makes such accidents difficult to prevent is that they happen under normal work behaviors. Although the actions of both workers may be independently "safe," they fail to adjust their behavior in the new conditions created by the presence of the other worker. Safety rules try to separate the crews and determine rules of "priority" and responsibility, but the dynamic conditions on the jobsite create many such situations.

(c) *Unrecognized hazard.* Another type of accidents involves situations where the worker is exposed to a "hidden" hazard. The hidden hazard can be a component near its functional limit (such as an unsecured deck) and a normal behavior (such as walking on the deck) may release the hazard. The hidden hazard may have been created by an error of a previous crew. The issue of how to address unrecognized hazards is a particularly difficult one since many things are not recognized as hazards until after they manifest themselves (Prichard 2002). Ergonomic hazards may be also included in this category, as the workers cannot recognize if they are approaching the limit of physical tolerance (the limit of how much weight the worker can safely lift, the time before the onset of cumulative trauma disorders such as tendonitis, etc.).

Other Causal Relationships

Several other relationships and feedback loops exist, which are not depicted in Fig. 2, such as (a) safety incidents increase safety efforts, as management typically responds to incidents with increased efforts to control conditions and behaviors; and (b) safety incidents reduce efficient behaviors, at least in the short term, as workers behave more carefully after an accident. The paper focused on the causal factors and relationships necessary to understand the main forces at work. A model that considers the likelihood of accidents over time should take the additional relationships into account.

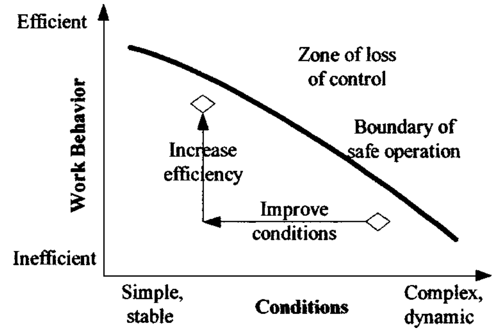

Fig. 3. Work conditions, work behavior, and safe operation

Model Discussion and Implications

The next section discusses some of the issues raised by the model. It provides some supporting evidence, but mostly it raises questions, proposes hypotheses, and identifies directions for future work.

Importance of Task Unpredictability

The model argues that the unpredictability of the task and the environment leads to increased accidents because it increases the number of hazardous situations, the production pressures, and the likelihood of errors. As a result, "*unlikely events are likely to happen, because there are so many unlikely events that could happen*" (Per Bak 1996).

The effect of task unpredictability on accidents requires further investigation. However, there is some initial evidence that it may be significant. A recent study (Thomassen et al. 2003) found that projects that used the Last Planner System® (LPS) for production control (Ballard and Howell 1998) had an incident rate of 7.85 (12 incidents in 305,604 labor-hours), while the incident rate on projects that did not use LPS was 14.13 (41 incidents in 580,371 labor-hours). Both groups of projects were performed by the same contractor, were of similar nature, and used same safety practices. These initial findings suggest that effective production planning can have significant effect on safety, possibly because it reduces the task unpredictability.

Task Unpredictability, Work Behaviors, and Safety

The model highlights the conflict between safety measures and the pressures for efficient behavior. Current safety measures constraint productive behaviors with a set of rules to keep workers away from the hazard zone. Instead of asking how can we keep workers from acting in more efficient ways, we should be asking: "***How can we make it safe for workers to work more efficiently?***"

Figure 3 proposes a relationship between task conditions, work behaviors, and accidents. The curve indicates the limit of loss of control. The figure illustrates that when task conditions become more complex and unpredictable, the efficiency of the work behavior must be reduced to avoid an accident.

In a simple example, the safe speed on a road (for a specific driver and vehicle) depends on the condition of the road, the visibility, the traffic load, etc. To safely increase the speed, we need to create conditions that reduce the likelihood of loss of control. This may include increasing visibility around curves, widening the road, reducing the potholes and obstacles, etc. It is

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important to stabilize the work conditions and prevent sudden deterioration when workers are at a point of high efficiency.

Error Management

As discussed earlier, production pressures, tendency for least effort and task unpredictability often result in the workers operating in the hazard zone. In addition, human error cannot be eliminated, especially in complex and dynamic work situations. Because of the inevitability of exposures and errors, effective error management is necessary in order to increase the workers' ability to cope with hazardous situations.

Error management provides a set of error countermeasures with three lines of defense: (1) error avoidance, (2) error trapping (to prevent errors from propagating), and (3) error mitigation to reduce the consequences of those errors that are not trapped.

Error management strategies have been developed first in military and commercial aviation and have focused primarily on increasing situation awareness, and establishing effective team processes to increase a team's collective situation awareness and decision-making.

Situation Awareness

In aviation, problems with situation awareness have been identified as the leading causal factor in accidents associated with human error. Situation Awareness (SA) is the *perception* of the elements in the current environment within a volume of time and space, the *comprehension* of their meaning (the "forces at work"), and the *projection* of their status in the near future (Endsley 1988). SA is affected by individual factors (capabilities, experience, fatigue/stress, set expectations, and "press-on-regardless" mentality), task factors (task overload and underload, objectives), and environmental factors (complexity, interruptions, and degraded operating conditions).

Team Processes (Crew Resource Management)

Crew Resource Management (CRM) was first developed in aviation to reduce accidents due to "pilot error." CRM is an active process by crewmembers to identify significant threats to an operation, communicate them to the pilot and carry out a plan to avoid or mitigate each threat (Helmreich et al. 1999). In recent years, CRM has been adopted by other high-risk operations where effective work performance requires coordinated action, such as hospital operating teams, oil platforms, and power plant control centers.

Based on analysis of over 28,000 aviation accidents, NASA discovered that over 70% of the accidents were due to failures in team communication and coordination rather than deficiencies in technical proficiency. Further simulator studies confirmed that crew performance was more closely associated with the quality of crew communication than with the technical proficiency of individual pilots. No differences were found 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 Cockpit Resource Management system (later called Crew Resource Management) to improve the crews' situational awareness and decision making.

CRM emphasizes the key nontechnical skills and team processes that affect operational safety. CRM training addresses *situation awareness*, *contingency planning* to identify ahead of time the proper response to abnormal situations, assign responsibilities for handling problems, and predetermine crew roles for high-workload phases of flight, *stress management*, and *crew communication* such as cross checking and communicating intentions before the execution of actions, so that another crew member can identify an inappropriate intention or action and correct it before the error happens, soliciting input from all crew members, and *assertiveness* in alerting team members and supervisor of identified threats and errors.

Other Error Management Strategies

Error proofing involves design of tools and equipment in a way that they can detect an abnormal condition and shut down or independently act to prevent failure (such as stability control systems in cars). Rasmussen (1997) proposed that an alternative strategy to safety rules is to increase the visibility of the boundary. The concept of boundary however is not well defined and it may include a physical boundary (the edge of the slab), point of loss of control (the crane's point of loss of stability), or a functional limit (the load a muscle can take).

Directions for Accident Prevention

The model identifies several potential interventions that can influence the safety outcome of a construction operation. For a given activity, the hazards can be reduced by changing the construction method, the work sequence or the physical environment. Of course, the activities required depend on design choices (e.g., cast in place concrete versus steel structure). However, given a construction method, the model identifies two important directions for accident prevention: (1) reduce task unpredictability, and (2) increase error management capability. These strategies do not replace the safety defenses and technical training but complement them.

Reduce Task Unpredictability

Reducing unpredictability will reduce unexpected tasks and hazardous situations, interruptions and 'short-term' production pressures, and will reduce the likelihood of errors. The current approach does not deal with the fact that workers face many unpredictable situations. Safety pretask planning addresses the predictable hazards involved in an activity. However, in an unpredictable task or environment, there will be situations and hazards that safety pretask planning will not address. When task unpredictability is reduced, the task can be executed as planned, the hazards will be predictable, and the defenses can be set.

This strategy shifts safety's focus from controlling the actions of management and workers (follow the rules) to stabilizing the work conditions.

Unpredictability can be reduced if the production planning system produces high quality work assignments. Ballard and Howell (1998) identify five requirements for high quality work assignments: (a) *definition* (work assignment is specific enough so that the right material can be provided, work can be coordinated with other trades, and at the end of the week it can be determined if the assignment was completed), (b) *soundness* (all design information, material, prerequisite work, work area and other resources needed to complete the assignment are available), (c) *sequence* (work is released in the correct sequence), (d) *size* (the assignments are sized to the productive capability of the crew), and (e) *learning* (assignments not completed are tracked and the reasons identified).

Only assignments that meet the quality criteria should be in-

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cluded in the weekly work plans. In addition, the work process and conditions must be controlled to support efficient behaviors (clear access, layout, location and sequence of subtasks). Finally, during the task, the crew needs to periodically re-evaluate the task and conditions to prevent degradation.

Increase Error Management Capability

Construction has not developed systematic ways to train individual and teams in error management. The most developed component is training in hazard identification which is essential, but not sufficient. The skills related to situation awareness and team processes are developed incidentally through experience. The need for awareness and effective team processes (within a crew and between different crews) becomes more important on activities and projects with high uncertainty and complexity, compressed schedules, and limited work areas.

CRM's main difference from existing safety practices is that it focuses on critical nontechnical aspects of the workers' interaction that enable the crew to successfully recognize, cope with, and recover from hazardous situations and errors.

A simple version of CRM adapted for construction has been proposed by Mitropoulos et al. (2003). In this approach management requires crewmembers to speak up when they identify conditions that exceed their "comfort zone" in terms of ability to perform the work effectively and safely. Members can raise concerns about the work method, the conditions in the work area, the sequence of the work, the lack of safety measures and equipment, lack of appropriate equipment for the task, etc. To support such an approach, management must take a non punitive policy toward errors, and must create a team environment that supports and develops workers' assertiveness.

Conclusions

The accident causation model presented in this paper investigated the production factors that generate hazardous situations and push the workers into the hazard zone. It also examined the limitations of current safety strategies in counteracting the problems generated by the production factors. The paper argued that exposures and errors are inevitable and proposed two alternative strategies; reducing task unpredictability and improving error management capabilities. A limitation of the model is that it may have not considered other important factors and causal relationships that contribute to accidents. The model should be considered as propositions for testing. Future research should focus on better understanding the effect of task unpredictability, and on developing error management strategies.

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