A COGNITIVE SYSTEMS ENGINEERING PERSPECTIVE OF CONSTRUCTION SAFETY

Tarcisio A. Saurin[1], Carlos T. Formoso[2], Fabricio B. Cambraia[3] and Gregory Howell[4]

ABSTRACT

In recent IGLC Conferences some papers have taken a cognitive systems engineering perspective of construction safety. The assumption underlying those papers has been that traditional safety management tools have failed to recognize that it is unavoidable to work close to edge where control is lost and that new mechanisms are necessary to increase the ability of workers to work safely under such circumstances. Based on data collected in five construction sites in which the authors have implemented a Safety Planning and Control model, this paper sets a preliminary discussion on the applicability of some cognitive systems engineering concepts to construction safety.

Due to the nature of the data available, the discussion is structured in four topics: identification of pressures and performance migrations towards unsafe zones of work; pre-task safety planning as a mechanism to develop judgment in workers; visibility of the boundaries of safe performance; incident analysis from the cognitive perspective. A set of opportunities for future research is outlined, such as the development of mechanisms to both identify and monitor pressures and the development of structured protocols to carry out investigations from a cognitive perspective.

KEY WORDS

Safety, Cognitive engineering, Human error, Boundaries.

INTRODUCTION

The quest for safety is never-ending, not only because of a growing need for the prevention of all remaining accidents, but also because of market demands, and the continuous individual search for new benefits that chronically exposes production systems to new risks (Polet et al. 2003).

As leading companies in construction safety have increased their performance and achieved a plateau (Howell et al., 2002), the remaining and most difficult to tackle accidents seemed to be mostly those in which human errors performed a major role. Although some safety management best practices have turned out their focus to workers´ behavior (e.g. observations of workers´ behavior) and participation (Hinze 2002), in general they do not properly take into account cognitive aspects of workers´ performance. Thus, errors and violations have been the hardest causal factors to deal with in the myriad of accident causation factors. It is worth emphasizing that in the new view of human error, it must be considered a symptom of trouble deeper inside a system, rather than a cause of accidents. In order to explain human failures one must find how people´s assessments and actions made sense at the time, given the circumstances that surrounded them (Dekker 2002).

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[1] Ph.D., Researcher at LOPP/UFRGS (Product and Process Optimization Laboratory, Federal University of Rio Grande do Sul). Praça Argentina nº 9, 2º andar. Porto Alegre, RS, Brasil. CEP 90040-020. Fax: 55-51-3316-4007. E-mail: tasaurin@terra.com.br

[2] Ph.D., Associate Professor at NORIE/UFRGS (Building Innovation Research Unit, Federal University of Rio Grande do Sul). Av. Osvaldo Aranha, 99, 3º andar. Porto Alegre, RS, Brasil. CEP 90040-020. Fax: 55-51-3316-4054. E-mail: formoso@vortex.ufrgs.br

[3] Ph.D. student at NORIE/UFRGS. Av. Osvaldo Aranha, 99, 3º andar. Porto Alegre, RS, Brasil. CEP 90040-020. E-mail: fabricio@ppgec.ufrgs.br

[4] Executive Director, Lean Construction Institute, PO Box 1003, Ketchum, ID 83340-1003, Phone +1 208/726-9989, FAX 707/238-1369, ghowell@leanconstruction.org

Underlying this new view is the assumption that the work system design is of primary importance to minimize possibility of errors. In fact, system design should recognize that human errors are inevitable (Rasmussen 1997). Even though performance incursions outside the safe field are limited by several means (e.g. hard-protections and regulations), once in service the socio-technical conditions of work create conditions for performance to migrate outside the expected safe field of use. Considering the impossibility of avoiding such migrations, it is advocated that potential migrations should be considered early in order to improve the robustness of safety analysis techniques (Polet et al. 2003).

The ideas of Jeans Rasmussen (Rasmussen et al. 1994; Rasmussen 1997) have been advocated both in construction (Howell et al. 2002; Abdelhamid et al. 2003) as well as in other industries (Amalberti et al. 2003) as an effective basis for designing adaptive work systems that take into account the inevitable migrations of performance. Efforts to improve performance at the boundary to loss of control, in which work has already migrated to unsafe zones, can be based on different strategies (Rasmussen et al. 1994, p. 150):

a) Increase the sensitivity of actors for the boundary to loss-of-control by means of motivation and instruction campaigns that create a gradient close to the boundary compensating for the workload-cost gradient. This improvement, by its nature, will only be temporarily effective because its influence will tend to fade away. It only works as long as pressure that acts against the functional pressure of the work environment is maintained. Therefore, such a motivation based struggle for a good safety culture will never end;
b) Introduce indicators, and pre-warnings that indicate operation too close to the boundary to loss of control with the accompanying admonition to move back performance from this boundary; and
(c) Make the boundaries touchable and reversible. The trick in the design of reliable, adaptive systems can be to give the actors an opportunity to identify boundary characteristics and to learn coping strategies rather than constrain their behavior through a set of rules for safe conduct. To achieve this, it appears essential that the actors maintain contact with hazards in such a way that they will be familiar with the boundary to loss of control and will learn to recover.

Since the strategies stated above are quite abstract, it is likely that several known safety management techniques contribute to their implementation. In fact, it would be necessary to revisit the so-called best practices of safety management from this perspective, shedding light on their actual weaknesses and strengths. Therefore, rather than complying with Rasmussen´s strategies by chance, safety tools should systematically take his proposals into account. However, it is worth noting that such strategies were primarily devised to tackle organizational rather than individual accidents (Reason 1997) and that the extent to which they are applicable to construction is not yet fully known. Discussion on this matter has been mostly in theoretical terms (Howell et al. 2002; Abdelhamid et al. 2003; Saurin et al. 2004a), with little empirical basis.

Moreover, cognitive engineering concepts (e.g. levels of cognitive performance; error types) have not been focused in the context of construction safety research, perhaps because it has been assumed that construction work does not demand substantial information processing from workers. However, despite a Taylorist tradition of separation between planning and execution, loosely coupled work systems (Rasmussen et al. 2004) such as construction usually leave many degrees of freedom to workers, which means that they are frequently required to make important decisions in a dynamic work environment.

Thus, this paper aims to contribute to increase understanding on the applicability of cognitive systems engineering to safety management in construction, in line with research efforts currently in course in other domains, such as health care and aviation. The discussion is partly based on data collected in five construction sites in Brazil, in which the authors have implemented a Safety Planning and Control model (SPC model) developed in a previous study (Saurin et al. 2004b).

RESEARCH METHOD

The Safety Planning and Control (SPC) model was proposed by Saurin et al. (2004b), based on two action-research empirical studies carried out in a construction company from the South of Brazil. The model has also been implemented in three other projects of the same contractor. Table 1 presents a brief description of the five projects in which the model was implemented. Site D was deliberately chosen in order to test the model in a fairly different context.

The SPC model has four core elements: (a) integrated safety and production planning, which is divided into three hierarchical levels (long-term, medium-term and short-term); (b) safety control, which involves a set of pro-active and reactive performance indicators; (c) a hazard identification and control participatory cycle based on interviews with workers; (d) safety planning and

Table 1: Description of the projects in which the SPC model was implemented.

	Site A	Site B	Site C	Site D	Site E
Type of project	Refurbishment of a steel mill building	Construction of two labs in a petrochemical plant	Construction of an industrial building in a food manufacturer plant	Construction of a Hospital	Construction of pipe-rack foundations in an oil refinery
Average workforce	40 workers	90 workers	80 workers	300 workers	80 workers
% of the workforce subcontracted	40%	30%	25%	95%	25%
Were client demands strict regarding safety?	Yes	Yes	Yes	No	Yes
Period when the study was conducted	January 2001—July 2001	August 2001—November 2001	May 2003—October 2003	April 2003—October 2003	July 2004—October 2004

Notes:

- *In site D a joint venture was established between two contractors.*
- *Site A was the only one in which there was interference between the construction and industrial operations.*

control diffusion, which is achieved mostly through workers´ training and monthly evaluation meetings of safety performance. A detailed presentation of the SPC model can be found in Saurin et al. (2004b), while a discussion on its impact on human error control was carried out by Saurin et al. (2004a).

In the current paper, some data collected in the five empirical studies were used to illustrate the applicability of cognitive engineering to construction safety. The existing data were considered to be useful to support a discussion on four topics: (a) pressures identification and performance migrations towards unsafe work in construction; (b) pre-task safety planning as a mechanism to develop judgment in workers; (c) visibility of boundaries of safe performance; (d) incident analysis from the cognitive perspective.

APPLICABILITY OF COGNITIVE ENGINEERING TO CONSTRUCTION SAFETY

PRESSURES AND MIGRATIONS

Since there are organizational and individual pressures that lead to migrations, it is necessary to have mechanisms to both identify and monitor the intensity of those pressures. Amalberti et al. (2004), based on the results of accident analysis in various fields (health care, aviation, rotary press, and chemical industry), found five recurrent root causes for the triggering conditions of migrations and related violations. All of them have parallels in construction, such as the search for external acknowledgment of an individual´s own expert status, and unachievable goals with safety constraints imposed on work, which make violations inevitable, no matter how well-intentioned the operators might be.

Generally speaking, all data resulting from the causal analysis of safety incidents are potential sources for the identification of pressures. However, a more pro-active and effective means for identifying pressures can be through surveying workers´ and managers´ perceptions on their work environment. It is important to get information from both workers and managers, since the pressures affecting each group are likely to be different, even though they all might ultimately result in lack of safety. For instance, in four out the five sites in which the authors implemented the SPC model, the owners (e.g. petrochemical industry and steel mill company) used to exert strong pressure on managers in terms of budget, schedule and adaptation to their bureaucratic structure. Regardless of this, those issues were not a concern to workers, who usually pointed out both human resource management and training issues as their main preoccupations—interviews with workers were conducted on a regular basis in the five sites studied.

Provided pressures are identified, workers and managers could make their monitoring through the fulfillment of questionnaires, preferably on a daily basis. The results of this monitoring could be posted in the site, keeping everybody aware of the extent to which migrations have happened. Also, acceptable levels for each pressure could be established, in which actions to recover performance to normal states (i.e. to recover the balance between production and prevention) would be triggered when the boundaries are crossed. Both a classification scheme of pressures and the delimitation of the types of pressures to be considered are basic issues to take into account when devising means to identify and monitor pressures. From one hand, some pressures seem to be more general (e.g. cost) while others might even be related to off-site factors (e.g. family problems). On the other hand, there are pressures that are dependent on the circumstances of either a specific work package or stage of construction (e.g. workload, interference with other gangs, inclement weather).

Depending on both the speed and intensity of migrations, emergency states could be identified. Although construction workers and managers are not trained to work under emergencies, in the sites that were investigated managers appeared to work often under emergency states, which could last days or weeks—in high-risk industries the emergency states usually have a more acute nature. Noticeably, these emergency states were more intense during the early stages of construction, because this period tended to require fast mobilization of resources (e.g. labor, material and equipment), familiarization with site constraints and adaptation to the owner management system.

Assuming that preparedness to deal with emergencies is really an issue for construction safety, it might be useful to adopt concepts from the emerging field of resilience engineering. According to Woods and Wreathall (2004) it is not enough systems to be reliable in order to keep the failure probability acceptably low; they must also be resilient and have the ability to recover from irregular variations, disruptions and a degradation of expected working conditions.

Also, it would be useful to investigate whether there is some association between the types of accidents (e.g. first aid, fatalities) and the nature of pressures and cognitive failures involved. Once patterns were identified, workers and managers could be made aware of this information in order to realize both how close they are to the boundary to loss of control and what is the expected loss if that boundary is crossed. For example, cumulative trauma disorders and overexertion injuries, which are as critical as traumatic type injuries, are likely to happen a long time after work at the unsafe zone has started. Those injuries might be associated to necessary violations, which are defined by Reason (1997) as violations in which non-compliance is seen as essential in order to get the job done. Necessary violations are commonly provoked by organizational failings with regard to the site, tools or equipment (Reason, 1997).

DEVELOPING JUDGMENT IN WORKERS

Even though system design might reduce human errors and mitigate their effects, safety ultimately depends on workers´ abilities both to detect the boundaries of safe work and recover control. Due to this fact, it is essential to adopt preventive measures directly focused on workers´ learning so that they are able both to identify signs of lack of safety in their work environment and know how to apply the proper rules. Moreover, in construction most problems may be easily solved by analysis and the application of rule-based solutions. There are few occasions in which extensive knowledge-based processing is likely to be required (Reason, 1997).

In line with these ideas, in one out of the five sites studied, the research team has tested an approach to actively involve workers in pre-task safety planning, in which the time horizon was the duration of the next work package. According to Hinze (2002) pre-task safety planning is one of the most effective techniques to achieve a zero accident target. This job enrichment was expected to have several beneficial effects: increasing motivation, since workers would have an opportunity to make a broader use of their cognitive skills; allowing managers to check whether workers were really paying attention on major hazards in their environment; sharing responsibilities on safety among managers and workers; increase workers´ knowledge of good safety rules, as a result of critically analyzing their safety plans effectiveness by the end of the work packages. This last benefit is particularly important, since as far as possible work at the knowledge-based level of performance (i.e. novel situations in which people have to improvise a suitable course of action) should be avoided. At this level, the odds of coming up with the right answers fall dramatically (Reason, 1997).

In the pilot study, a team of four workers who performed activities at confined spaces was involved in pre-task safety planning. Similarly to the situation of the vast majority of construction workforce in Brazil, the team members had attended no more than the primary school. The proposed methodology for carrying out safety planning started with a visual inspection of the area where the work package was to be undertaken. The major constraints in terms of access, team interferences and the need for safeguards were overviewed. Next, the leader of the team, who was assigned by the co-workers rather than management, gathered the group together and discussed the pre-task safety planning. This involved checking whether the personal protective equipment was available, defining a task sequence, identifying hazards and their respective control measures. Eventually, a self-assessment of the plans effectiveness was undertaken, after the work package was finished. Both incidents and suggestions for improvement were to be documented in the planning form.

The team involved in the pilot study carried out pre-task safety planning during eleven working days. They undertook the same tasks—in different site locations—along this period. The planning meetings took ten minutes, on average, and each team member coordinated the planning meeting at least once, based on decisions by the group.

The workers involved in this experiment reported in the planning forms nine different hazards and control measures, one accident (first-aid case), three near misses and three execution failures, in which production rather than safety was their main concern. It is worth emphasizing that site managers had not realized most of the incidents reported, including the first-aid case.

Regardless of this, several shortcomings were detected in the pilot study: (a) the pre-task planning was not carried out every day; (b) sometimes workers filled out the forms incorrectly; (c) production managers and foremen did not fully support the experiment—they were supposed to check the content of the plans on a regular basis, but this did not happen; (d) the detailed preliminary hazard analysis of the task, which was supposed to be the basis for the team to carry out the pre-task safety planning was poorly written by management and so it was of little help; (e) more hazards could have been identified. Concerning hazard identification, the most frequent type of hazard identified by workers was interference from other crews. Also, the large number of hazards related to interferences illustrates the fact that physical boundaries in construction are quite dynamic, demanding careful monitoring from workers. This supports the idea that the crews must have the opportunity of discussing their work instead of simply relying on the planning of others. In this respect, it can be said that accidents have a clearly social dimension—it means that they might be reduced if people talked to each other about the boundaries while they are in action.

Overall, one of the main contributions of the pilot study was that it pointed out the feasibility of developing safety planning and control skills at front-line workers. In fact, the production manager did not believe that workers would be able to plan and assess their own tasks by themselves. Indeed, although the relatively low level of formal education may be considered as a drawback, it was not impeditive for conducting the experiment at all. Moreover, it should be recognized that, despite of being a minority, some workers in the construction site had attended at least eight years of school.

MAKING THE BOUNDARIES VISIBLE

Concerning the visibility of boundaries, it is important to note that Rasmussen et al. (1994) establish two major boundaries of failure: (a) the boundary of safe behavior as defined by safety campaigns, which when crossed leads workers from the safe zone to the hazard zone of work and; (b) the boundary of functionally acceptable behavior, beyond which the control of productive processes is lost, work is unsuccessful or accidents happen. The space between those boundaries might be considered as a margin of error, which should be included in the system design to allow recovery to a safe work zone.

In practice, the boundaries exist by means of barriers in the work system. According to Hollnagel (1999), such barriers might be of four types: (a) material or physical barriers, which physically prevent an action or limit the negative consequences of an event; (b) functional barriers which logically or temporally link actions and events; (c) symbolic barriers—they require interpretation; (d) immaterial barriers which are not physically present in the work situation.

The implementation of the barriers does not necessarily imply that they are visible to whom they are supposed to be. This failure might be caused by several reasons, such as: (a) the barrier was not properly implemented, so workers do not recognize it as a barrier; the perceptions of the boundaries might be variable among individuals; (b) workers were not informed on both the existence and role of the barriers; and (c) barriers are so ingrained in the work system that they become invisible.

Even though some barriers might remain invisible, they should become visible when they are either crossed or closely approached. In this respect, safety management could be made more effective by incorporating some lean production ideas. In particular, safety can be improved by applying the tacit rule of the Toyota Production System (TPS) which states that all work shall be highly specified as to content, sequence, timing and outcome (Spear and Bowen, 1999). Although writing out safety procedures is a fairly common approach in construction, the mechanisms to detect deviations in real time are poorly developed. By contrast, in the TPS process transparency allows prompt identification of deviations from standards. In line with the fact that migrations are unavoidable—either safety or production migrations—the TPS is not so concerned with avoiding deviations as it is with their identification. Similarly, the existence of buffer stocks could be considered as another recognition of the TPS on the nature of migrations. The more unreliable the manufacturing system (i.e. the more prone to migrate to poor performance) the greater the buffer stocks needed. Since some degree of unreliability will always exist, some buffer stock will always be necessary. The size of those buffers is established considering a margin of error, similarly to what is made in the design of safe systems. However, while the TPS proposes continuous decrease of buffer stocks, good safety design should increase the error margin, making it as large and as visible as possible.

Transparency for safety purposes, such as in the case of production control, must be implemented through simple mechanisms. For instance, in one of the sites in which the authors implemented the SPC model, physical barriers were designed at the end of a ramp to establish a boundary of acceptable behavior (Figure 1). There was no error margin in this example—i.e. if the worker stepped beyond the marks, the ramp would turn around. Of course, additional preventive measures could have made the work safer, such as both coloring different areas of the ramp and to anchor the ramp in the ground. If it had been colored, an error margin could have been easily defined, since there could be a green area on the ramp (safe zone), a yellow area (hazard zone) and a red area (lost of control zone), in which stepping would be strictly prohibited. Both safe and hazard zones could be enlarged once the ramp was anchored.

Besides process transparency, visibility of boundaries could also be implemented based on the TPS principle of autonomation. It means that machines are designed to stop working automatically either when a defective piece is produced or when the desired output is achieved. Autonomation was also extended to people in the TPS, since workers were given autonomy to stop the whole assembly line when they find out a problem that they cannot manage by themselves. As an extension of this principle to construction safety, workers should be given autonomy not to work whenever they feel in danger. However, disciplinary measures should be adopted when someone consistently refuses to work in areas understood by managers, most workers, regulations and safety plans as normally safe.

INCIDENT ANALYSIS FROM THE COGNITIVE PERSPECTIVE

In all five sites investigated, the lack of safeguards (physical barriers) implementation or maintenance was a category of failure hard to deal with. This is in line with Hollnagel (1999), for whom regular and effective maintenance is the main weakness of physical barriers. Three examples of this type of failure are given: (a) lack of implementation of walkways over the iron bars for floors—besides its safety role (e.g. avoiding trips), this measure was also necessary for quality purposes, since the walkways avoided damaging of bars; (b) lack of isolation of hazardous areas, such as places below scaffolds and above excavations; (c) lack of lamps and fire extinguishers in the formwork shop. Written procedures (Preliminary Hazard Analysis—PHA) established the need for the safety measures listed above (walkways, isolation and lamps and extinguishers). While managers (production manager, safety specialist and foreman) were aware of these measures by being involved in the PHA development process, workers´ were trained based on those procedures. Moreover, such basic safety measures were somehow repetitive, since they were necessary for activities that usually take place at all construction sites of this contractor. Therefore, both managers and many workers were supposed to be familiar with those safeguards—their implementation was typically a rule-based decision. In spite of this, the safeguards were either often not installed or, when implemented, they were not properly maintained—i.e. if either an area isolation or lamp was damaged, there was no immediate repair. Some

Figure 1: Example of visual device to define the boundary of acceptable behavior.

reasons are presented below as potential contributing factors for the violations described:

a) the responsibilities for implementing and maintaining the safeguards were not clearly defined;
b) perhaps both workers and managers considered that those safeguards were not really essential for working at an acceptable safety level. This perception was probably reinforced by the fact that, even though the violations were commonplace, no serious accident had been caused by the lack of those safeguards. This situation illustrates that the longer the work in the hazard zone, the harder is the task to recognize this as risky and to return to the safe zone;
c) workers perceived production demands as priorities, in detriment of installing and maintaining safeguards, which are non-adding value activities. Similarly, the safety specialist overlooked the lack of those safeguards either because he was more concerned with riskier construction areas or because he was involved with bureaucratic work at his office; and
d) workers had no autonomy to refuse to work under unsafe conditions.

Some accidents detected in the sites studied illustrated the importance of both anticipating how barriers may fail and the consequences of not identifying all barriers that were necessary. Three events are briefly described below:

Accident 1: a concrete vibrator machine fell down from a tower scaffold—there were only material damages. Even though the vibrator was tied to the scaffold metallic frame, the rope was too close to the vibrator´s engine. Thus, as a result of heat release from the engine, the rope broke and the vibrator fell down. The investigation of this accident pointed out that a steel cable should have been used rather than a rope. This accident points out to the need of including failure modes analysis in safety planning, which was not adopted in the Preliminary Hazard Analysis technique that was used. While no easily identifiable migration of behavior has occurred in this accident, a migration of machinery (vibrator) performance has taken place. That is an important insight, since it calls attention to the fact that not only human behavior migrates, but rather this might also happen to the other non-human actors in the site (machines, tools, safeguards, procedures). In such situations, the search for both performance and individual advantages are no longer the immediate drivers for migration, since these non-human actors do not make decisions either consciously or unconsciously. Of course, at some point in the chain of events, it is likely that a poor human decision has performed a role to trigger the migration of the non-human actors. However, such poor decision might be simply a non-intentional error that was not caused by any kind of individual or performance pressure.

In the example given above, the immediate cause of the migration was the degradation of properties of the physical barrier (the rope)—a root cause was a failure mode not identified by safety planning. Anyway, workers did not realize that the migration was in course. As a failure of the investigation carried out in this accident, it was not considered the speed of the migration—i.e. was it either an abrupt collapse of the rope or did the degradation take place slowly, with visible signs that were ignored by everybody? Indeed, workers should be capable to detect the earliest signs of deterioration of barriers and have a stock of rule-based decisions on how to act under such circumstances.

Figure 2: The pulley of a crane involved in accident 2.

Accident 2: a worker's finger was caught in the pulley of a crane (Figure 2). In order to stop the recipient of concrete, the worker put his hand on the pulley, which was the only mobile part of the device—fortunately the worker managed to take his hand out of the pulley before being seriously injured and just some first aid was necessary. The accident investigation pointed out some important root causes: (a) the worker was subcontracted and it was his first day on this site; (b) a safeguard could have been installed in order to make it impossible for someone's finger to reach the mobile parts. While no barrier was in place in this accident, a performance pressure that caused migration was identified, since in order to comply with the schedule, site management considered careful training of new workers as unnecessary. By contrast, it seemed that there was no search for individual advantage of the worker involved in this accident—the decision to grab in the pulley looked more as a slip than like a decision driven by the desire to take the path of least effort.

Accident 3: a worker who was carrying a plank tripped on a small pile of planks that was left on the ground by himself a few minutes before. The pathway to the place where the planks were unloaded was narrow and the ground was uneven. Even though a safer pathway was available, it was not adopted because it was longer. According to the workers, they were told by the foreman to choose the shorter but less safe access. Thus, both foreman and workers were driven by performance and individual advantages in this accident. On the one hand, the foreman ordered workers to choose the shorter path to increase productivity (performance advantage). On the other hand, workers made the decision of storing planks poorly on the ground. Since the planks were manually transported and they were fairly heavy, workers did not properly pile them up on the ground, in order to reduce workload (individual advantage). In this accident there was a set of hazards (e.g. narrow and uneven access, manual handling of heavy materials, productivity pressures) that were fully ignored by safety planning. In fact, management assumed wrongly that workers would know how to deal with the hazards.

CONCLUSIONS

Regarding pressures, the data available pointed out that while managers were more concerned about budget, schedule and adaptation to the owner's bureaucratic structure, workers had as primary concerns human resource management and training issues. This might imply that the migration mechanisms towards unsafe work take fairly different pathways either workers or managers are focused. Of course, migration of workers´ behavior is likely to be often triggered by poor decision-making of managers (i.e. migration of management performance). Also, pressures seemed to be stronger and more hazardous in the early stages of construction, when both workers and managers had not yet adapted to their managerial and physical work environment. It is worth noting that pressures in this paper were considered in a broad context, including both on-site (e.g. interference with other gangs) and off-site factors (e.g. social condition of workers). However, additional research is necessary to develop well-defined classification schemes of pressures as well as mechanisms to monitor their intensity on a near real-time basis. This could help site personnel to realize how close its performance is to the boundary of loss of control.

Pre-task safety planning, a well-known and effective safety management technique, was analyzed in terms of the job enrichment it provides. Regardless of site managers´ disbelief that poorly educated workers would be able to carry out formal planning, a pilot study undertaken with a crew reinforced the appropriateness of this approach. Besides having an opportunity to make a broader use of their cognitive skills, formalize and document their knowledge, the crew of the pilot study pointed out hazards and incidents that otherwise would have remained undetected by management. In spite of this, systematic research is necessary to assess the extent to which pre-task planning is feasible to be implemented (e.g. in many sites crews do not remain together more than a shift or two) as well as to extend the idea of pre-planning beyond safety and include productivity, quality and environmental issues. Also, both requirements and effects of increasing degrees of autonomy to crews should be studied.

Ensuring visibility of boundaries is mentioned in the cognitive engineering literature as a key principle to avoid accidents. Based on lean production principles, some strategies to increase visibility were suggested: (a) boundaries should be so unambiguous as possible so that the influence of different risk perceptions of workers is minimized (e.g. a safeguard should be well maintained so it actually looks like a safeguard); (b) visual management should be adopted to a large extent to make promptly visible when boundaries are either crossed or closely approached—as for production, fail-safe devices either with a shutdown or alarm function should be carefully embedded into the design of operations; (c) workers should be given autonomy not to work whenever they feel in danger. In fact, it must be noticed that the key issue when discussing visibility is to alert the workers about the hazards. Therefore, human speaking is in the spectrum of the measures that are useful for ensuring visibility. Thus, both the discussion of work methods and safety while in action are effective strategies to make the boundaries visible.

Eventually, three accidents were analyzed from the cognitive perspective. The underlying causes of both violations and non-intentional errors involved in those accidents were discussed, as an attempt to identify both the pressures and the migratory steps followed by the actors involved in the accidents. Similar analysis of a broader set of accidents (and near misses) could lead to improved understanding on the cognitive mechanisms involved in construction accidents, encompassing issues such as the types of barriers that were crossed, the types of errors involved in the accidents, whether there was an error margin, the speed of the migration and, the actors involved in each migratory step. The development of structured protocols to carry out investigations from this viewpoint is another opportunity for future research.

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