A HUMAN ERROR PERSPECTIVE OF SAFETY PLANNING AND CONTROL

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ABSTRACT

This paper is concerned with the impact of a safety planning and control model (SPC) on human error. This model integrates safety into the production planning and control process and it adopts some safety management best practices reported in the literature. The analysis is based on data collected in four construction sites where the model was implemented.

The main conclusion of this investigation is that six elements of the model (safety planning, near miss reporting, training, percentage of safe work packages indicator, participatory cycle and planning and control diffusion) have a contribution in terms of making both the boundaries of safe work visible and respected. Safety planning also helps to make the production system error-tolerant to some extent. However, the analysis of causes of safety failures in the empirical studies pointed out a high incidence of violations of the boundaries (on average, 40% of the total safety failures), mostly by workers. Thus, the main drawback of the model regarding human error control is its modest contribution to ensure respect for the boundaries of safe work.

KEY WORDS

Safety, planning and control, human error, production management.

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INTRODUCTION

Several studies have proposed methods and practices to improve the poor safety record of the construction industry, beyond what can be achieved through the requirements established by regulations. A common approach has been to identify best practices that can lead to excellence in terms of safety (Hinze, 2002; Harper and Koehn, 1998; Jaselskis *et al.*; 1996).

However, Howell *et al.* (2002) alert to the fact that companies using best practice have achieved a plateau and that innovative approaches are necessary for further improving the safety performance of the construction industry. Moreover, the interactions between the so-called best practices as well as their underlying principles have not been sufficiently discussed in the literature. For instance, it remains unclear the types of root causes that can be tackled by each preventive method. In fact, it is even arguable whether the existing best practices are effective means to tackle some usual root causes such as those identified by Suraji and Duff (2001) – e.g. financial pressures and short program timescale.

Safety planning and control has been recognized as one of the critical measures required to achieve a zero accident target (Hinze, 2002; Liska *et al.*, 1993), and it has been the focus of several research studies (Hinze, 1998; Kartam, 1997). However, these studies have not fully considered safety planning and control as a broad managerial process, which should include the control function and not to be so focused on the production of safety plans. Considering this gap, the authors of this paper have proposed a Safety Planning and Control (SPC) model in a previous research project (Saurin *et al.*, 2004). This model adopts some best practices identified in previous studies (Hinze, 2002; Harper and Koehn, 1998; Jaselskis *et al.*, 1996), including pre-task safety planning, performance measurement, mechanisms for workers′ participation, and training.

In accordance with the recommendations of some authors (Hinze, 1998; Kartam, 1997), the SPC model integrates safety into the production planning and control process. From one hand, such integration is needed because typical production planning decisions - what will be done, when, how and by whom - are the basis to establish safety preventive measures. On the other hand, safety requirements must be taken into account in production planning. Otherwise, production plans may fail due to the lack of safety.

This paper is concerned with the impact of the model on human error, which is known as a major contributing factor in accident causation. Human error was chosen as a criterion for analyzing the model also because current best practices have been ineffective to reduce accidents that occur through workers putting themselves at risk (Howell *et al.*, 2002). Moreover, it is assumed that by understanding the limitations of the model regarding human error control, it will be possible to identify the preventive measures that are necessary to complement the proposed model.

BASIC CONCEPTS ON HUMAN ERROR

Human error is an inappropriate or undesirable human decision or behavior that reduces, or has the potential for reducing, effectiveness, safety or system performance (Sanders and McCormick, 1993). There have been several attempts to classify the types of errors that people make during task performance (Wickens *et al.*, 1998). An effective classification scheme can be of value in organizing data on human errors and for giving useful insights into the ways in which errors are caused and how they might be prevented (Sanders and McCormick, 1993).

In this study, the classification proposed by Lawton and Parker (1998) is adopted. Those authors group human errors in two basic types: (a) non-intentional errors: failures that are usually associated to cognitive factors, such as the limited human capacity for both information processing and short-term memory; (b) violations: deviations from the work method accepted as safe - in this case, the failure is originated in both psychological and social factors.

Several studies have found human error as a major contributing factor in accident causation, both in construction (Suraji and Duff, 2001) and in the manufacturing industry (DuPont, 2000; Lawton and Parker, 1998; Rasmussen *et al.*, 1994; Sanders and McCormick, 1993). However, the actual participation of human error as a causal factor has varied within a wide range, from 29,9% (Suraji and Duff, 2001) to 96% (DuPont, 2000). This variation might be explained by the subjectivity involved in determining root causes of accidents. In fact, since it is not possible to establish objective rules to terminate the search for causal explanations, the decision to stop and to accept an event as the root cause depends entirely on the discretion of the analyst (Rasmussen *et al.*, 1994).

According to Rasmussen (1997), human errors cannot be eliminated, since human beings have an adaptive behavior. In dynamic work systems, such as construction sites, many degrees of freedom are left for adaptive modifications of procedures. Standardization and enforcement of work rules is generally limited due to financial and workload pressures. Therefore, people may be pushed to work in risky circumstances and they must be helped to develop and apply their judgment to avoid accidents (Rasmussen, 1997).

In this context, Rasmussen *et al.* (1994, p.148) proposes that the design of work systems minimizes human errors by focusing on the visibility of the boundaries around acceptable performance irrespective of the work procedures. Such boundaries must be defined in a way that they are respected or are made error-tolerant irrespective of the content of the current task (Rasmussen *et al.*, 1994, p. 148). Thus, three design mechanisms to reduce human errors might be identified: (a) to ensure visibility of boundaries to failures, (b) to ensure that those boundaries are respected, and (c) to make the production system error-tolerant. These mechanisms are consistent with the strategies to improve performance proposed by Rasmussen *et al.* (1994): increase the sensitivity of actors for the boundary to loss-of-control, introduce pre-warnings to indicate operations too close to the boundary to loss of control, and to make the boundaries touchable and reversible.

Based on the assumption that the approach of Rasmussen *et al.* (1994) to deal with human error constitutes a generic framework that is likely to encompass most safety management techniques, the three design mechanisms above mentioned were adopted as a reference to analyze the impact of the SPC model on human error control.

RESEARCH METHOD

The Safety Planning and Control (SPC) model was proposed by Saurin *et al.* (2004), based on two action-research empirical studies carried out in a construction company from the South of Brazil. Recently, the model has been implemented in two other projects of the same contractor. This company was chosen for two main reasons: it had a fairly well structured production planning and control system, and it was particularly interested in successfully implementing the SPC model. Figure 1 presents a brief description of the four projects in which the model was implemented. Site D was deliberately chosen in order to test the model in a fairly different context.

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

Notes: in Site D a joint venture was established between two main contractors. One of them was the same involved in sites A, B and C.

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

In the study of Saurin *et al.* (2004) two main criteria for evaluating the model were established: model effectiveness and ease of use. These criteria were broken up into sub-criteria (for instance, contribution to compliance with regulations and client requirements) and, for each of them, the main sources of evidence were identified in order to perform a comprehensive evaluation of the model. However, the contribution of the model to reduce human error was a criterion that has not yet been explored.

OVERVIEW OF THE SAFETY PLANNING AND CONTROL MODEL

Figure 2 presents an overview of the SPC model. Integrated safety and production planning and control take place in three hierarchical levels. Long-term planning is developed before starting construction, being updated and detailed at both medium-term and short-term levels. For each construction phase (e.g. bricklaying) a plan is produced using the Preliminary Hazard Analysis (PHA) technique.

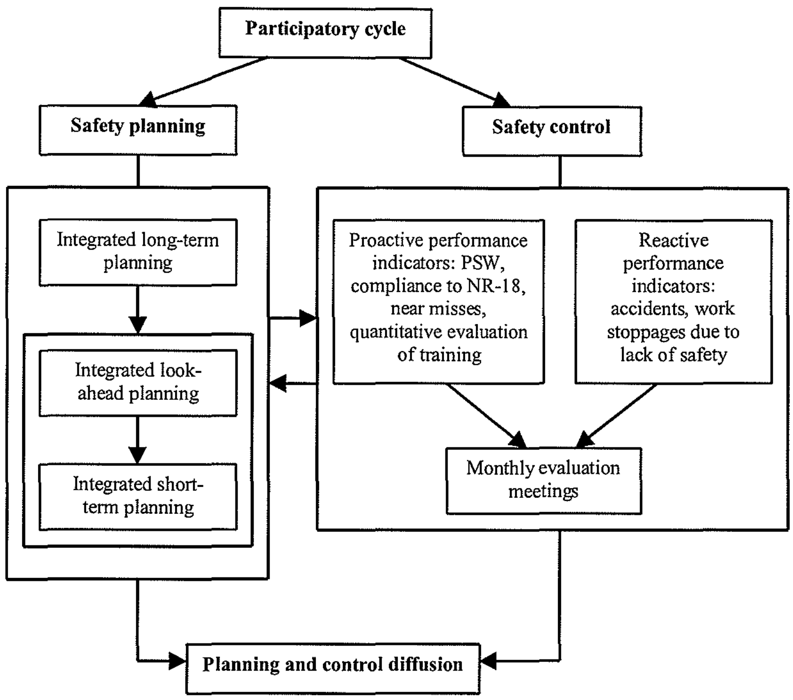

Figure 2: Overview of the SPC model.

At the medium-term planning level, a look-ahead plan is weekly produced. One of its main roles is constraint analysis, i.e. identifying and removing constraints (e.g. space) that might prevent work packages from being undertaken within the established schedule (Ballard, 2000). Safety constraints were systematically included in the look-ahead constraint analysis. Similarly to what happens at the medium-term planning level, safety measures are also discussed in short-term planning meetings. Then, a final review of both work methods and constraints is made and work packages are assigned to production crews.

In the SPC model, safety control involves a set of proactive and reactive metrics that provide feedback to safety planning. The results should be discussed in a monthly meeting involving representatives of the top management, production managers and safety specialists. However, emphasis is given to proactive measures, such as the PSW indicator (Percentage of Safe Work Packages), which is the main metric used to evaluate safety effectiveness.

PSW indicates the percentage of work packages that are safely carried out. A work package is considered to be safe when (a) no failure in the conception of safety plans has been detected; (b) there has been no failure in their implementation; and (c) no accidents or near misses have been observed. The PSW assessment consists of checking the written safety plans against the actual work being performed – risks that are retained by the contractor are not taken into account in this assessment. The formulae for calculating PSW is presented below:

$$\text{PSW} = \frac{\sum \text{number of work packages safely carried out}}{\;} \qquad (4.1)$$

$\sum$ total number of work packages

Figure 3 schematically presents the form used for data collection in the empirical studies. Similarly to the Last Planner System, an analysis of the causes of safety planning failures must be conducted. If possible, data must be collected on a daily rather than on a weekly basis, because some safety problems can be only identified through careful and frequent observations of site activities. The observer must walk around the construction site and identify where each work package is being carried out, and watch how each activity is being performed, checking whether the safety measures listed in the respective PHA are being implemented.

Site: Steel mill	**Observer**: Diego		**Date:** 10/05/01		
Observation period: 10h to 12h			**SAFE?**		
Gang	**WORK PACKAGES**	**PHA n°**	**Yes**	**No**	**Problem**
SH	Change roof from column 5 to 7	PHA 5		X	B. harn. badly tied
	Activities not clearly associated to work packages				
BSF	Common circulation areas	PHA 8	X		

Figure 3: Example of the data collection form used for monitoring PSW.

Workers' opinions are taken into account through a hazard identification and control participatory cycle, that is divided into four stages: (a) interviews with small groups of workers, in which they are asked to point out problems concerning their work environment; (b) development of an action plan to respond to workers' complaints; (c) a feedback meeting, in which managers and workers discuss the action plan; (d) a new round of interviews, in which new demands are pointed out and an evaluation of workers' degree of satisfaction is performed after the improvements have taken place.

Safety planning diffusion is achieved mostly by training workers based on safety plans before they start carrying out their tasks. In addition to the monthly evaluation meetings, safety performance measures are also disseminated in weekly planning meetings. Moreover, this information is posted on bulletin boards all over the site.

HUMAN ERROR'S PERSPECTIVE

MAIN TYPES OF HUMAN ERRORS DETECTED IN THE EMPIRICAL STUDIES

Table 1 presents the distribution of causes of safety failures in the construction sites, based on the data collected for both near misses and the PSW indicator. It is worth noting that some of the violations presented in Table 1 (notes) are immediate causes (for instance, lack of PPE use) rather than root causes. In fact, this happened because sometimes there was no information available to identify clearly the underlying cause of the violations. Moreover, as it usually occurs in the search for causal explanations (Rasmussen *et al.*, 1994) there is some degree of subjectivity in the failure analysis conducted in this study. Because of this drawback, some of the failures that were classified as violations can actually have been either non-intentional errors or planning and control failures. For instance, a worker could have operated a machine imprudently because he/she had not fully understood the procedures taught in the training sessions rather than because he consciously made the decision of not following the safe method. Even though this is a source of unreliability in the data collected, it must be emphasized that a cause was classified as a violation as the last alternative – i.e. all apparent possibilities that the failures had been generated by non-intentional errors and planning and control failures were considered before. Also, the causes of failures were assigned by a consensus between a member of the research team and the safety specialist. Based on the feedback given to workers during PSW collection (see next item), the failure analysis also took workers′ perceptions into account. This happened to some extent since it was impractical to discuss with workers the underlying reasons of safety failures for all work packages observed.

Table 1: Causes of safety failures in the empirical studies.

	Site A	Site B	Site C	Site D
Planning and control failures	51,6 %	51,4 %	66,7%	35,4%
Non-intentional errors (workers)	0,0 %	0,0 %	2,2%	0,0%
Non-intentional errors (managers)	2,2%	1,7%	5,9%	1,3%
Violations (workers)	16,5%	27,8%	12,6%	54,7%
Violations (managers)	9,9%	19,1%	12,6%	8,6%
Client interference	19,8 %	0,0%	0,0%	0,0%
Total	100%	100%	100%	100%

Notes:
<u>Planning and control</u>: training was not provided, interference among crews, risks and preventive measures badly specified, failures in methods planning, risk not identified, failures in safeguards planning;
<u>Non-intentional errors (workers)</u>: poor communication among crew members;
<u>Non-intentional errors (managers)</u>: ineffective training;
<u>Violations (workers)</u>: imprudent operation of equipment, lack of PPE use and, other unsafe acts;
<u>Violations (managers)</u>: lack of safeguards implementation or maintenance.

Improper planning and control decisions were regarded as a distinct category of causes, in order to emphasize the failures in the planning and control process itself. However, these failures ultimately might be considered as a form of non-intentional errors in which managers are the key players.

As shown in Table 1, planning and control failures were major causal factors for safety failures in the four sites (on average, 51,3% of the total safety failures). These figures are consistent with those found by Suraji *et al.* (2001), who concluded that planning and control failures related both to safety and production itself were major contributing factors to accidents in construction sites in the UK. Due to its major role as causal factors, and also because they are easier to be controlled by site management compared to behavioral failures, it seems reasonable to emphasize the reduction of planning and control failures in the early stages of safety management improvement initiatives.

Four out of the six human error categories identified can be primarily classified as violations (imprudent operation of equipment, lack of PPE use, lack of safeguards installation or maintenance and other unsafe acts), while the remaining two are typically non-intentional errors (ineffective training and poor communication between crew members). Violations accounted for the vast majority of human errors (92% in site A, 96% in site B, 76% in site C and 98% in site D). The most frequent types of violations in each study were the lack of safeguards installation or maintenance (35% of total human error failures in study A and 38% in study C) and the lack of PPE use (43% of total human error failures in study B and 55% in study D). Despite of the previously mentioned sources of unreliability in the failure analysis, the lower incidence of non-intentional errors can be expected due to the fact that construction work is usually more physically demanding rather than mentally demanding. However, both workers′ and managers′ physical and mental workload was not assessed in the sites studied.

It should be noticed that workers were not the key players in two categories of failures. The lack of safeguards implementation or maintenance was mostly caused by the site management – that includes production managers, foremen and safety specialists. These were not effective in making sure that safeguards were properly installed and maintained, following what had been agreed in planning meetings. The main causes of that violation were time pressures and unclear assignment of responsibilities for safeguards installation and maintenance. Ineffective training was a non-intentional error whose root cause is the lack of a well-structured training program at corporate level.

The percentage of human errors made by workers in relation to the total of safety failures was fairly similar in sites A (16,5%), B (27,8%) and C (14,8%), and higher in site D (54,7%). To some extent, the lower percentages in sites A, B and C might be explained both by the stricter safety rules imposed by the client in those sites and by the fact that a smaller percentage of the workforce was subcontracted – less than 40%. By contrast, in the hospital building project (site D) there was virtually no demand from the client regarding safety performance and the vast majority of the workforce was subcontracted – more than 95%. The site observations indicated that most subcontractors working in that site had poor safety culture[1], and that the main contractors were ineffective in terms of enforcing a subcontractor safety management program. In fact, the contractor has not yet realized that it can have a greater influence on its subcontractors′ safety, by playing a role similar to that performed by its industrial clients.

The above data should be regarded as an important form of feedback for the improvement of preventive methods. Improvement initiatives should start by identifying the behavior shaping mechanisms that lead to violations (for instance, propensity to take risks, poor understanding of the accident causation mechanisms, individual differences in risk perception, complacency towards hazards due to poor safety culture) before choosing any specific best practice.

Contribution of the SPC Model for the Reduction of Human Errors

In this item, the SPC model is analyzed from the perspective of the design mechanisms to reduce human error previously discussed in this paper, based on the proposals of Rasmussen *et al.* (1994). Concerning the visibility of boundaries, it is important to note that Rasmussen

[1] [Safety culture is a subfacet of organizational culture, which affects workers′ attitudes and behaviour in relation to an organization′ on-going safety performance (Mohamed, 2003)].

et al. (1994) establish two major boundaries to failures: (a) the boundary of safe behavior as defined by safety campaigns, which when crossed leads workers from the safe zone to the hazardous work zone and; (b) the boundary of functionally acceptable behavior, beyond which the control of production processes is lost, work is unsuccessful or accidents happen. It is not an intrinsic property of the SPC model to make visible any of those boundaries. Rather, this is mostly in the scope of the operations design. When a hazardous zone is designed beyond the safe zone (this is always desirable because it allows recovery of control) there is room to make both boundaries visible. By contrast, when there is no recovery zone, the only boundary that might be made visible is the boundary of functionally acceptable behavior. Due to this fact, the analysis presented in this paper is not concerned with rigidly identifying what of the boundaries defined by Rasmussen is made visible by the SPC model.

Also, for practical purposes in this study, for any of the boundary types defined by Rasmussen, there are two basic boundary forms: (a) a physical boundary, such as safety signals; (b) an abstract boundary, such as work methods defined as safe either by regulations or planners.

Figure 4 presents the elements of the model that have a significant role to implement those mechanisms. It was assumed that when the boundaries become visible, safety awareness increases for both workers and mangers and, as a result, they tend to be more prone to respect them. The elements not included in Figure 4 were considered not to have a major role in the reduction of human error, such as the monthly evaluation meetings and the reactive performance indicators.

Elements of the SPC model	To ensure visibility of boundaries	To make the production system error-tolerant	To ensure that boundaries are respected
Safety planning*	X	X	X
Near miss reporting	X		X
Training sessions	X		X
PSW indicator	X		X
Participatory cycle	X		X
Planning and control diffusion**	X		X

Notes:

* It includes both the planning meetings and their output (i.e. the safety plans).

** It includes the bulletin boards in which safety warnings were posted.

Figure 4: Elements of the SPC model that contribute to reduce human errors through three design mechanisms proposed by Rasmussen *et al.* (1994).

As shown in Figure 4, safety planning is the only element that contributes to all three mechanisms. Concerning the visibility of boundaries, the safety plans, which are formalized through the preliminary hazard analysis, establish objective criteria to define whether it is safe to work or not. Thus, deviations from the safety plans, which are detected mostly through performance measures, should be considered as warnings that boundaries of safe work have been crossed. Moreover, safeguards planning, such as guardrails and fences, make visible physical barriers beyond which work is unsafe. Of course, safeguards and personal protective equipment also make the work system error-tolerant to some extent. However, as a means to make the work system even more error-tolerant, human factors should be taken into account to a greater extent in safety planning. For instance, physically demanding activities should not be scheduled at the end of afternoon, since fatigue is likely to increase the risk of accidents.

The formal documentation and dissemination of near misses contributes to make workers aware that they are working unsafely – i.e. it helps them to identify the boundaries. Although a near miss means that the boundary of safe work has been crossed, there is still a chance to regain control and work safely by identifying the near miss and eliminating its cause. As proposed by Reason (1997), near misses were classified according to the feedback they provided: (a) positive feedback: when the accident did not happen because the defenses were effective (e.g. someone's face was struck against an steel rebar, but there was no injury because they were using safety glasses); (b) negative feedback: the defenses were not effective and the accident did not happen just by chance (e.g. an object fell down from a high floor very close to a person working at the ground level because there were no safety nets or platforms installed). A near miss type "a" could be used to reinforce safe behavior and safe work practices.

Training sessions in general help workers both to identify and respect the boundaries. In the empirical studies, immediately prior to the beginning of a new activity workers were usually trained by a safety specialist. This kind of training was assumed to be the last opportunity to remind workers on the hazards involved in their tasks. However, some shortcomings were detected. For instance, no evaluation on the effectiveness of training was carried out and the individual differences on risk perception were ignored.

As an improvement undertaken in site D, workers received some training sessions focused on near misses. The ultimate aim was to make workers more sensitive to hazard identification. The definition of a near miss was presented and illustrated using actual examples, and its role as proactive data was explained. In addition, procedures to report them were established – workers were asked to report near misses from the previous day during regular training meetings that were held every morning. Near miss reporting has increased dramatically after that these training sessions have begun. While no more than thirty near misses were reported in sites A, B and C, more than one hundred and ten were reported in site D – of course, this increase in the number of near misses might be explained by the higher accident rate on this site.

Regarding other performance measures, the PSW indicator provides a major opportunity to check the status of the boundaries (e.g. crossed, not crossed or not defined) and to reinforce the respect for them. Different from traditional behavior observation programs reported in the literature, such as the one proposed by DuPont (2000), the unit of analysis in PSW collection is the work package, rather than the worker. Behavior observation programs focus on observing people working and their main objective is to identify both unsafe and safe acts. By contrast, the use of the PSW measure requires a wider scope of analysis, since the objective is to make an overall safety assessment of the work packages being undertaken. This assessment includes both operations performed by workers and the processes (e.g. moving materials) involved.

In order to have an even greater impact on human error control, the PSW indicator included feedback to the workforce, based on lessons learned from the behavior observation programs. Similarly to what is proposed by the DuPont program, there was an interaction between the observer and the worker being observed. They usually had a conversation either to discuss why the task has been performed unsafely or to reinforce positive work practices (DuPont, 2000).

The participatory cycle is also a means of implementing the design mechanisms proposed by Rasmussen *et al.* (1994), namely visibility of the boundaries and their respect. When workers present their complaints in both the interviews and in the feedback meetings, everyone is informed about safety problems that otherwise would not be known. Also, the interviews appeared to have a therapeutic effect since workers have an opportunity to express their feelings on their jobs without the fear of being disciplined. This was assured both by the top management support for the interviews and by the fact that the interviewer was not a member of the site management staff.

Concerning planning and control diffusion, process transparency is a principle that helped the SPC model to be more effective in terms of making the boundaries of safe work visible. It can be defined as the ability of a production process (or its parts) to communicate with people (Formoso *et al.*, 2002).

In this study, bulletin boards were the main type of visual device adopted. Their main objective was to help workers to keep in mind safe work procedures. They were used to post safety planning information that should be used by workers to undertake their tasks. For instance, near the circular saw there was a message warning workers to remove all nails and residuals of cement from pieces of wood before they were cut. According to Galsworth (1997), this type of device can be classified as a visual indicator, which is the most passive form of visual device. The information is simply displayed, and compliance or adherence to its context is voluntary (Galsworth, 1997). In other words, the worker might identify the boundary of safe work but not respect it. Therefore, the SPC model should also incorporate visual devices that exert a greater degree of control, such as visual guarantees, also known as poka-yoke devices (e.g. electronic circuits that prevent movement of lifts when the door is open). Even though visual guarantees make the boundaries visible, these boundaries might not be always respected, since fraud or vandalism can still happen. Moreover, the reliability of the safety equipment is key to define the level of safety (e.g. the electronic circuits of the lifts can fail). These possibilities can be seen as residual risks that are retained by the contractor.

Considering the SPC model as a whole, its continuous implementation is likely to reinforce safety culture and, as a result, encouraging the respect for boundaries of safe work. In fact, the systematic integration of safety issues into routine production management activities tends to counter the organizational pressures (e.g. time and cost) on managers, which otherwise would lead them to adaptive behavior and improper decision-making, carrying out non-intentional errors and violations.

CONCLUSIONS

This paper discussed the impact of a safety planning and control (SPC) model on human error control. This model encompasses some safety management best practices reported in the literature. Based on data from four empirical studies in which the model was devised and tested, the conclusion was made that six of its elements (safety planning, near miss reporting, training sessions, PSW indicator, participatory cycle and planning and control diffusion) have a relevant contribution to make both the boundaries to failures visible and respected. Safety planning was also considered useful to make the work system error-tolerant, by planning safeguards and personal protective equipment.

In particular, PSW indicator and near miss reporting were very useful tools both to identify the most frequent types of human errors and to assess the effectiveness of the model. In the four sites investigated, non-intentional errors of both workers and managers had a minor role in the total of safety failures (on average, 1,7% of the total failures). Regarding workers, this might be due to the fact that construction work is usually more physically demanding rather than mentally demanding. However, this is likely not to be true in high-risk work packages. In fact, further investigation is needed in different construction scenarios to assess both physical and mental workload and their impact on human errors. This will be a valuable input for the consideration of human factors in safety and production planning.

Moreover, PSW and near miss reporting pointed out a high incidence of boundary violations (on average, 40% of the total failures in the four sites investigated), mostly by workers. A reason for this drawback is the fact that, by emphasizing safety planning and control, the model focused on managers′ respect for the boundaries of safe work rather than workers′. Thus, the little effectiveness to deal with violations is likely to be the main drawback of the model regarding human error control. Besides, considering that the respect for the boundaries depends to a great extent on their visibility, so far the model does not have proper means to make the boundaries highly visible.

Even though improvement in the existing mechanisms might contribute to make the model more behavior-oriented, a broader set of measures is necessary to achieve excellence in dealing with human errors and, in particular, violations. Such measures are beyond the scope of the SPC model and they might include, for instance, safety education for both workers and managers and large-scale implementation of process transparency principles.

Additional research is necessary to clarify the nature and frequency of the different types of human errors that have high impact in construction safety. Such data can be used to assess whether current safety management best practices are adequate to human error control. This investigation might also help to devise more effective tools to reduce errors in construction.

REFERENCES

BALLARD, G. (2000), *The Last Planner System of Production Control,* PhD thesis, School of Civil Engineering, The University of Birmingham, UK.

DuPONT SAFETY RESOURCES (2000), *Stop for supervision*. Introduction: the STOP system (unit 1), E.I. du Pont de Nemours and Company, Wilmington.

FORMOSO, C.T.; SANTOS, A.; POWELL, J. (2002), An exploratory study on the applicability of process transparency in construction sites, *Journal of Construction Research*, Vol. 3 n. 1, pp. 35-54.

GALSWORTH, G. (1997), *Visual systems*: harnessing the power of the visual workplace, American Management Association, New York, 320 p.

HARPER, R.; KOEHN, E. (1998), Managing industrial construction safety in southeast Texas, *Journal of Construction Engineering and Management*, Vol. 124 n. 6, pp. 452-457.

HINZE, J. (2002), *Making zero injuries a reality,* Construction Industry Institute (Report 160), Gainesville, 110 p.

HINZE, J. (1998), *Construction Planning and Scheduling,* Prentice-Hall, Upper Saddle River, NJ, 326 p.

HOWELL, G.; BALLARD, G.; ABDELHAMID, T.; MITROPOULOS, P. (2002), Working near the edge: a new approach to construction safety, In: ANNUAL CONFERENCE ON LEAN CONSTRUCTION, 10., Gramado, *Proceedings*...Universidade Federal do Rio Grande do Sul, Porto Alegre, pp. 49-60.

JASELSKIS, E.; ANDERSON, S.; RUSSEL, J. (1996), Strategies for achieving excellence in construction safety performance, *Journal of Construction Engineering and Management*, Vol. 122 n. 1, pp. 61-70.

KARTAM, N. (1997), Integrating safety and health performance into construction CPM, *Journal of Construction Engineering and Management*, Vol. 123 n. 2, pp. 121-126.

LAUFER, A.; TUCKER, R. (1987), Is construction planning really doing its job? A critical examination of focus, role and process, *Construction Management and Economics*, Vol. 5, pp. 243-266.

LAWTON, R.; PARKER, D. (1998), Individual differences in accident liability: a review and integrative approach, *Human Factors*, Vol. 40 n. 4, pp. 655-671.

MOHAMED, S. (2003), Scorecard approach to benchmarking organizational safety culture in construction, *Journal of Construction Engineering and Management*, Vol. 129 n. 1, pp. 80-88.

RASMUSSEN, J. (1997), Risk management in a dynamic society: a modeling problem, *Safety Science,* Vol. 27 n.2/3, pp.183-213.

RASMUSSEN, J.; PEJTERSEN, A.; GOODSTEIN, L. (1994), *Cognitive systems engineering,* John Wiley & Sons, New York, 378 p.

REASON, J. (1997), *Managing the risks of organizational accidents*. Ashgate, Burlington, 252 p.

SANDERS, M.; McCORMICK, E. (1993), *Human factors in engineering and design,* McGraw-Hill, New York, 7.ed.

SAURIN, T.A.; FORMOSO, C.T.; GUIMARÃES, L.B.M. (2004), Safety and production: an integrated planning and control model, *Construction Management and Economics,* Vol. 22 n. 2., pp. 159-169.

SURAJI, A.; DUFF, R.; PECKITT, S. (2001), Development of causal model of construction accident causation, *Journal of Construction Engineering and Management*, Vol. 127 n. 4, pp. 337-344.

WICKENS, C.D.; GORDON, S.E.; LIU, Y. (1998), *An introduction to human factors engineering,* Addison-Wesley, New York.