TOWARDS A COMMON LANGUAGE BETWEEN LEAN PRODUCTION AND SAFETY MANAGEMENT

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

ABSTRACT

This paper discusses lean production objectives and design principles that can be shared by production management and safety management. It focuses on strategies to deal with variability, emphasizing two typical lean production concepts – autonomation and visual management – which can be used in safety management to detect variability. Moreover, considering the cognitive systems engineering perspective on safety as a basis, this paper discusses four guidelines for developing and monitoring procedures in the lean production approach: (a) take into account workers´ mental and physical capabilities; (b) stress workers involvement in procedures development and monitoring; (c) investigate reasons for successful performance rather than just causes of non-compliance with procedures; and (d) adopt a broader view on the meaning of deviations from procedures, which should not necessarily be seen as negative. It is proposed that similar analysis to the one carried out in this paper be undertaken to other lean production elements (e.g. how lean practices such as kaizen, supply chain management and total productive maintenance may benefit safety?). An inverse analysis is also necessary, since some elements that are usually included in safety management systems can be integrated to lean production practices.

KEY WORDS

Safety management, cognitive systems engineering, lean production, operations management.

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[1] Ph.D., Associate Professor 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: saurin@ufrgs.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@ufrgs.br

[3] Civil Engineer, MSc, PhD candidate at NORIE/UFRGS. Av. Osvaldo Aranha, 99, 3º andar, Porto Alegre, RS, Brasil. CEP 90040-020. E-mail: fabricio@cpgec.ufrgs.br

INTRODUCTION

The human impacts of lean production remain a controversial issue, despite the widespread application of this type of production system. From one hand, a number of studies have identified undesired impacts of lean production in terms of job stress, workload and loss of autonomy (Niepce and Molleman, 1998; Dankbaar, 1997). On the other hand, several studies have stressed its positive impacts, such as job enrichment and increasing participation (Jackson and Mullarkey, 2000). Nevertheless, whatever the viewpoint emphasized, the studies on this matter have been limited by a number of factors, such as: (a) most of them have been based on surveys (Sepalla and Klemola, 2004) - very little is based on in-depth analysis of actual impacts; (b) the extension to which lean production is actually implemented has not been properly assessed, so there is the risk that lean production has been portrayed either as good or bad to workers based on data collected in companies which were not in fact lean; (c) some discussions, such as the one presented by Kato and Rob (1993) seem to be biased by ideological viewpoints, without being supported by empirical data.

While it is necessary to understand the human impacts of lean production, this discussion has hindered possibilities of synergy between lean production and safety and ergonomics (from now on, refereed to just as safety in this paper). In fact, production management (either lean or not) and safety management are not necessarily in conflict and both are about dealing with similar challenges, such as variability, limited slack, resources and capacity to adjust to fit unforeseen demands (Hollnagel, 2004). In particular, within the lean production paradigm accidents are considered extreme forms of inefficiency and are to be avoided at all costs (Wokutch and VanSandt, 2000).

Moreover, basic objectives of production management and safety management depend on each other and, more importantly, they share some common design principles. This realization could help to improve communications between safety and production practitioners and researchers, as well as to integrate safety management and lean production practices. However, a primary requirement is to abstract the principles of one area and adapt them to the other. Similarities between production and safety management principles may be illustrated considering the parameters for designing safe work systems proposed by Hollnagel *et al.* (2006): buffering capacity; flexibility versus stiffness; margin (determine how closely the system is currently operating relative to performance boundaries); tolerance (how the system behaves near a boundary, whether the system degrades as pressure increases, or collapses quickly when pressure exceeds adaptive capacity). Differently from what usually occurs with safety, all of those parameters are explicitly taken into account in the design of lean systems. For instance, both sizing and strategic positioning of buffers are major decisions in lean systems, which in turn are based on demand and process reliability characteristics. Similarly, monitoring of margins is also critical for lean production and to a large extent this is made on a real-time basis through visual management.

An additional motivation to link production and safety theories is that there are opportunities to learn from each other. For instance, it would be useful to incorporate human factors principles in total productive maintenance (TPM) initiatives, one of the cornerstones of lean production. Maintenance errors have been identified as major contributing factors to accidents in complex systems and the counter-measures proposed (e.g. identify omission-prone task features during design of maintenance activities) can be extended to maintenance in manufacturing environments (Reason and Hobbs, 2003). This idea is also applicable to construction, especially concerning the maintenance of major construction equipment and refurbishments of industrial facilities.

In particular, this paper adopts the cognitive systems engineering (CSE) perspective on safety. CSE is concerned with the study of how joint cognitive systems (a human machine ensemble that cannot be separated) perform, rather than cognition as a mental process (Hollnagel and Woods, 2005). The CSE view on safety was adopted due to two main factors: (a) it is particularly adequate to dynamic and complex environments such as construction sites – even though more typical applications refereed to in the literature are related to aviation, nuclear power plants and petrochemical industry; (b) it provides high-level guidelines on work system design, which makes it easier their abstraction and adaptation to different industries. The basic CSE guidelines for the design of safe and adaptive work systems have been established by Jeans Rasmussen (Rasmussen *et al*., 1994; Rasmussen, 1997), whose ideas have been further developed by a number of more recent studies (Hollnagel *et al*., 2006; Hollnagel and Woods, 2005; Hollnagel, 2004).

Also, several recent papers have discussed opportunities for applying CSE ideas in construction industry. Howell *et al*. (2002) reviewed traditional safety management best practices, which were mostly based on behavior-based approaches, and concluded that they were ineffective to make workers capable of performing at the edge of loss of control. Abdelhamid *et al*. (2003) carried out an application of signal detection theory as a mechanism to sharpen workers´ sensitivity to hazards identification – this is particularly important in the edge of loss of control. Saurin *et al*. (2005a) conducted an analysis of the frequency of errors and violations in five construction sites. Also, Saurin *et al.* (2005b) extended the discussion of Howell *et al.* (2002) on the applicability of CSE to construction safety based on empirical data. However, none of the previous studies has made in-depth conceptual discussions on the interfaces between core ideas of safety management and lean production principles and practices. In fact, this has been conducted neither for construction nor for other industries. Due to this fact, some of the examples presented in this paper are related to manufacturing settings rather than construction, since lean production is easier to be characterized in manufacturing.

It is worth noting that the adaptation of CSE ideas to safety management in practice has not yet been fully accomplished even in highly safe industries. In fact, this indicates that innovation has followed a different path for production and safety management. While industry has taken the lead in terms of lean production development since this system was created by Toyota, academic theories for safety management from CSE perspective have not yet been properly absorbed by industry. Rather than being a concern, this difference reinforces the potential for reciprocal learning between both areas.

This paper presents a discussion on the commonalities and differences between safety management and production management, emphasizing the core ideas of lean production. This discussion is focused on the role of procedures and strategies for dealing with variability, which have been extensively studied in both areas.

LEAN PRODUCTION AND CSE PERSPECTIVES ON THE ROLE OF PROCEDURES

Procedures are not only what is written, but also the unwritten and unspoken assumptions about details of work. In fact, they can be explicit, such as in the case of written procedures, or implicit, such as in the case of artifact design interface (Hollnagel, 2004).

Concerning lean production, procedures are usually developed in the context of standardization, which is one of its core ideas. According to Spear and Bowen (1999) lean production requires that all work be highly specified in terms of timing, content, sequence and outcome. The reasoning is that standardization is necessary both to reduce variability of outcomes and to establish a basis on which working practices can be checked and continuously improved. It is worth emphasizing that standardization in lean production is not fully in conflict with flexibility, since procedures are supposed to be dynamic – i.e. even though procedures are consistently complied with, improved procedures must be developed on a regular basis.

Procedures also play a major role in safety management. In fact, production procedures often include alerts on safety hazards into their content. Another frequent approach is to develop specific procedures for safety, through techniques such as Preliminary Hazard Analysis and Failure Mode and Effect Analysis.

In particular, from the CSE perspective procedures are useful since they both reduce task demands by alleviating requirements to memory, and help decision-making by providing a prepared description of what the alternative possibilities for actions are (Hollnagel, 2004). Moreover, procedures may reduce the degrees of freedom of workers and define a space of safe performance where accidents will not happen (Rasmussen *et al*., 1994). In lean production, procedures are also supposed to define a space of stable performance – in this case stability could include safety, but also other criteria such as quality and timing.

Also, CSE proposes that effective procedures should match designers and users mental models. Considering workers as users, this implies that designers should consider workers´ physical and cognitive demands from both production and safety perspectives. Lean production has no specific mechanism to take those demands into account during procedures development. As a result, cycle times, work sequences and schedules are primarily driven by production concerns. Human factors have a secondary role (if so) regarding decision-making on those issues. If workload matches workers capabilities this is likely to have occurred by chance rather than human-oriented design. This characteristic of lean production partly explains why it has been featured by a number of studies as too demanding to both workers and managers (Dankbaar, 1997).

WEAKNESSES OF PROCEDURES

Despite their widespread use, the weaknesses of procedures – mainly the written ones - are extensively discussed in CSE literature. According to Reason (1997), procedures written to ensure safe working suffer from a lack of requisite variety. There is no way in which all the possible combinations of dangers and their related accident scenarios could be anticipated. There will always be situations that are either not covered by the rules or in which they are locally inapplicable (Reason, 1997). This criticism is also valid for production procedures, even though Reason (1997) alerts to the fact that the variety of possible unsafe behaviors is very much greater than the variety of required production behaviors. However, as a reinforcement of that criticism to lean production, it should be noted that safety and production performance cannot be strictly separated, so unsafe work sooner or later will be detrimental to production behaviors. Moreover, even when they are applicable, procedures may be useless if they cannot be consulted whenever workers feel that this is necessary. This might be true, and hazardous, in manufacturing environments where work is automatically paced (e.g. by a conveyor belt) and newly hired workers cannot stop production to check information.

The shortcomings of procedures both for production and safety management are also evident when analyzed in the context of the well-known dynamic model of accident causation proposed by Rasmussen (1997), which is illustrated in Figure 1. This model assumes that non-compliance with procedures is unavoidable because of economic and workload pressures, among others. Thus, people are pushed to work near the edge of loss of control (boundary of functionally acceptable performance in Figure 1), where procedures are either no longer being complied with or are inapplicable. In addition, Wokutch and VanSandt (2000) suggest that cultural differences also have an impact on the extent to which procedures are complied with. According to those authors, compliance is much easier in Japan where one´s sense of identity is much more based upon group membership than in the United States, and conformity to social norms is highly valued.

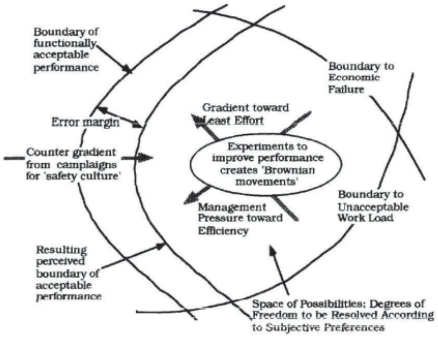

Figure 1: Activity can be characterized by Brownian movements within the work space, subject to work load and effectiveness gradients (Rasmussen et al.*, 1994).*

LEAN PRODUCTION AND CSE APPROACHES FOR DEALING WITH DEVIATIONS FROM PROCEDURES

Lean production and CSE advocate different approaches to deal with deviations from procedures, also known as human errors in safety management literature. According to Reason and Hobbs (2003), all errors involve some kind of deviation – the departure of actions from their intended course, or the departure of planned actions from an adequate path towards some desired goal, or the deviation of work behavior from appropriate operating procedures. Sometimes, these deviations involve rule violations, such as driving over the speed limit (Reason and Hobbs, 2003).

From one hand, lean production emphasizes a continuous effort to detect deviations from procedures and bring performance back to the stable zone of work. However, rather than detecting deviations, efforts are primarily driven to reduce variability and keep workers in the stable zone of work. This means that lean systems also have counter-gradients to avoid migrations, as shown in Figure 1. For instance, audits are widely used in lean factories to check whether standards have been complied with. Also, behavior-based approaches, such as incentive programs, are frequently used in lean plants as mechanisms to motivate workers to comply with standards and achieve desired outputs. In fact, Wokutch and VanSandt (2000) concluded that Toyota and all major Japanese auto companies adopt a strongly behavior-oriented approach to safety management, which is similar to the well-known DuPont model.

However, Rasmussen *et al*. (1994) stress that those types of counter-pressures, either for safety or production purposes, will only be temporarily effective because its influence tends to fade away. It only works as long as the pressure that acts against the functional pressure of the work environment is maintained.

Anyway, design of lean systems recognizes that deviations from procedures are unavoidable. Once this has happened, the underlying reasons should be carefully examined. As a result of such investigation, either the procedure prescriptions are reviewed or the production system is re-planned (e.g. workers will be given better training) (Spear and Bowen, 1999).

On the other hand, CSE emphasizes variability management and proposes that design should support the natural human strategies for coping, rather than enforce a particular strategy. This implies studying what people actually do and then consider whether it is possible to support that through design (Hollnagel and Woods, 2005). The complexity of real world should be captured by design and it could be encapsulated into less strict procedures than the ones advocated by lean production. Also, Rasmussen *et al.* (1994) note that this approach allows actors to have opportunities to identify boundary characteristics and to learn coping strategies. Actors will 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 (Rasmussen *et al*., 1994). Moreover, CSE proposes that the causes of safe performance are as important to be investigated as causes of unsafe performance (Hollnagel *et al*., 2006). Successful strategies normally not prescribed in procedures could be identified and disseminated to the workforce. Such strategies could be identified, for instance, based on the investigation of near misses that provided positive feedback (i.e. when the accident did not happen either because of physical protections or effective behavior). However, this type of near miss is likely to be less frequent than the negative ones (i.e. the defenses were not effective and the accident did not happen just by chance), as pointed out by Cambraia *et al*. (2005). Those authors analyzed 122 near misses in a construction site and concluded that just 17,3% provided positive feedback.

Thus, there is a conflict between lean production and CSE approach, since natural human strategies for coping are not seen as normal behavior by lean production, but rather as undesired deviations from production performance. The lean production approach towards procedures is mostly concerned with what people should do rather than what they actually do. In fact, in general lean production gives workers the opportunity of becoming familiar with the perceived boundary of acceptable performance (which separates safe and hazard zones), but not with the boundary of functionally acceptable performance (which separates hazard and loss of control zones). Rather than allowing workers to cope within the hazard zone, the lean approach is to push them back to the safe zone as soon as the performance migration is detected. As pointed out by Rasmussen *et al.* (1994), this will have a negative impact on workers´ flexibility and skills to deal with unexpected situations. Moreover, it may encourage the enforcement of prescribed strategies when conditions have changed and the strategies have not yet been perceived as inappropriate.

DESIGN OF ERROR MARGINS

The definition of an error margin, such as the one represented in Figure 1, is necessary to allow early detection of deviations before losing control. It gives actors an opportunity to realize that they are no longer in the safe zone and need to regain control. In fact, this approach is in line with lean system design, since it establishes both a well-defined stable zone of work and an error margin. However, in opposition to what is recommended for safety, the error margin in lean production is intentionally small. For instance, according to Rother and Harris (2002), the cycle time in a typical lean environment should be defined at about 95% of the takt time – this proposal does not take into account impacts of the ratio between cycle time and takt time on workers´ health. Moreover, lean systems are designed to exacerbate the impacts of error margins deterioration. For instance, the definition of a cap (not necessarily small) for work-in-process makes workstations strictly connected. Both examples illustrate the fact that work zones and error margins are probably easier to be determined accurately for production than to safety, since the design of the production system seems to have a stronger quantitative basis.

Regardless of specific conflicts and different emphasis of lean production and CSE approaches towards procedures, there are positive examples of how lean production encompasses CSE principles to deal with human errors. In particular, this study has identified two typical lean approaches that contribute both to detect migrations and to make boundaries of safe work visible: autonomation and visual management.

APPLICABILITY OF AUTONOMATION TO SAFETY MANAGEMENT

According to Shingo (1986), autonomation means that either operators or machines are given the autonomy to stop production whenever something abnormal is detected (e.g. typically, the production of a defective piece). Autonomation equates to pre-automation (or automation with a human touch), which is the last stage before full automation. In the pre-automated stage, machines are designed to detect abnormalities, however human operators perform problem solving (Shingo, 1986). This concept was also extended to manually operated processes in the TPS, since workers were given autonomy either to ask for help or stop the assembly line when they find out a problem that they cannot manage by themselves – this includes situations when they find a bad rule or no rule situation. The underlying assumption is that by stopping production, the problem becomes visible to the operator, his colleagues and supervisors. Therefore, everybody will be forced to concentrate on eliminating the problem, which otherwise would remain unsolved. In the long-term, companies that apply the line stoppage principle will have lesser stoppages than those companies that do not apply it (Womack and Jones, 1991).

Although several companies, either lean or not, claim that they apply the same principle to safety, the extension is not likely to be so straightforward. Previous research on production and safety trade-off decisions indicates that the decision to value production over safety is implicit and unrecognized (Hollnagel *et al*., 2006). The result is that individuals and organizations act much riskier than they would ever desire. A sacrifice judgment is especially difficult because the hindsight view will indicate that the sacrifice or relaxation of pressures may have been unnecessary since nothing happened (Hollnagel *et al*., 2006). Thus, the extension of autonomation to safety should imply that production should be stopped before an undesired outcome (i.e. an accident or a near miss) has happened. By contrast, typical production problems dealt with by autonomation in lean factories, such as delays, defective items or machinery breakdowns, imply that some undesired outcome has already happened. Also, those types of production problems are usually less ambiguous than safety hazards.

Hollnagel *et al*. (2006) consider that it is necessary to develop explicit guidance on how to help people make the sacrifice judgment under uncertainty, to maintain a desired level of risk acceptance or risk averseness. For example, which indicators reveal a safety and production trade-off sliding out of balance as pressure rises to achieve acute production and efficiency goals (Hollangel *et al*., 2006). Indicators´ results should be preferably available on a real-time basis so they would be more useful to enable predictions on the changing shape of risks. While this may be feasible in some highly automated industries (e.g. petrochemical, nuclear power plants), it is still hard to implement in labor-intensive settings such as construction. For this type of working environment, a more realistic strategy seems to be giving the autonomy not to work whenever workers feel in danger. Of course, empirical studies are necessary to assess the effectiveness of this proposal. This is not to suggest that indicators are not useful in construction sites to assess the safety and production trade-off. The criticism is that the wide range of available indicators is not devised to inform workers on safety performance, but rather to inform managers, usually through written reports that present indicators results. This implies a time lag for decision-making on sacrifice judgments.

It is worth noting that indicators based on observations of behavior and site conditions, such as the Percentage of Safe Work Packages (PSW), which was proposed by Saurin *et al.* (2004), are not enough to serve as a basis to implement autonomation. Even though sacrifice judgments can be made based on the observations, the decision to stop work is usually made by the observer, rather than the workers being observed. Moreover, this approach provides intermittent feedback to workers on their safety performance – i.e. just when the observations take place. Regardless of this, a useful approach to assess the balance between production and accident prevention might be to devise indicators that compare safety and production performance. For instance, there could be an indicator relating the well-known Percentage of Plans Completed (PPC) proposed by Ballard (2000) and PSW. Similarly, another indicator could relate defects and incidents.

APPLICABILITY OF VISUAL MANAGEMENT TO SAFETY MANAGEMENT

Visual management is another key approach of lean production that is used for detecting deviations from standards. Visual devices, such as borders on the floor, and overt display of results of performance indicators, are common mechanisms adopted by lean factories to allow real-time comparison between actual and expected performance. For instance, display of output rates for workers indicates whether they are ahead or behind the schedule. Similarly, kanban cards point out visually when time to replenish stocks has come. A major strength of visual devices like those is that they are usually targeted to a wide range of users – i.e. the information is promptly available to anyone to whom it may be of concern, not only to managers in their offices (Greif, 1991).

The extension of visual management to safety purposes (e.g. safety signs, visual demarcations and boards in which accident rates are posted) is more common than the extension of the concept of autonomation. In line to what is proposed by lean production, safety information provided by visual devices allows identification of boundaries for safe performance and comparison between current and expected performance. The identification of this gap allows that potentially destabilizing disturbances be detected early and, as a result, the smaller the resulting adjustments are likely to be (Hollangel and Woods, 2005).

However, signs, which are probably the most frequent application of visual management to safety, are vulnerable in many ways. Hollnagel (2004) lists several shortcomings of signs, such as: although the resource needs are low for each sign, they may be significant if many signs are to be used; the robustness is mostly low since signs depend on how they are interpreted; they are not well suited for safety critical tasks because there is only limited control over how they are interpreted; they depend a great deal on the humans who use them.

Moreover, visual management has to face some particular challenges when it is applied for safety: (a) as hazards are numerous, dynamic and spatially dispersed in the factory or site, it is virtually impossible to design visual devices to tackle all hazards; (b) differently from some metrics of production performance (e.g. output rates and machinery downtime), data on safety performance cannot be collected and displayed in a fully automatic fashion – although IT may be of help, someone must walk around to collect and interpret the data; (c) while several hazards are visible by their nature (e.g. a hole in the floor), many others – especially those not related to physical hazards – can not be easily and visually discriminated (e.g. interference among teams, workers´ fatigue). This makes it more difficult to cover by visual management all the invisible attributes of the process related to safety that need to become visible (Greif, 1991).

Regardless of this, a specific type of visual device, the fail-safes or *poka-yokes*, are widely known to be very useful to deal with human errors. The use of such devices is consistent with the CSE principle of designing for simplicity of functioning. When trying to use an artifact, the strongest rule is *what you see, is what you do* (Hollnagel and Woods, 2005).

Poka-yokes contribute to make the boundaries of performance error-tolerant, which is a major principle both of safe work system design (Rasmussen *et al*., 1994) and also of lean production. Concerning purposes of quality control, the use of *poka-yokes* has been widely disseminated in the manufacturing industry, especially in the context of lean production initiatives (e.g. Patel *et al*., 2001; Shingo, 1986). For instance, Shimbun (1988) provide 240 illustrated practical examples. Concerning purposes of safety, *poka-yokes* usually take the form of safeguards and personal protective equipment (PPE) and are adopted mostly because of regulations requirements. In fact, safeguards and PPE *poka-yokes* normally have a wider set of functions than the ones designed for quality control.

From one hand, safeguards and PPE usually protect workers from a wide range of hazards and absorb several possible errors – e.g. a hard hat protects a construction worker´s head from being stuck by a falling object, from insulation and can also be used for identifying workers and posting safety slogans. On the other hand, typical quality control *poka-yokes* are usually devised to tackle one specific type of human error that is detrimental to quality – e.g. design a piece so it matches another one only in the right way. However, the most distinctive characteristic of safeguards and PPE is that they do not *prevent* errors from happening, but they rather *mitigate* the consequences of errors. In lean production language, PPE and safeguards do not comply with the principle of source inspection. It is worth emphasizing that many quality control *poka-yokes* also have this characteristic - e.g. to install an air compressor to blow empty boxes off a conveyor belt to detect unfilled boxes (Shimbun, 1988).

Considering the role of safeguards and PPE, there are opportunities for both practitioners and researchers to develop safety *poka-yokes* that have a major preventive role and that are directly linked to specific types of human errors. Nevertheless, at least three basic issues will have to be dealt with to develop such devices:

- As mentioned before, the variety of possible behaviors that lead to defective production is much smaller than the variety of possible unsafe behaviors. While this explains why the wide set of functions of safeguards and PPE is necessary, it makes it more difficult to identify specific types of errors which can be prevented by *poka-yokes*. Of course, the establishment of priorities can be dealt with well known techniques such as risk analysis;

- There is a lack of data available on the frequency and types of human errors involved in accidents and near misses. This information is essential for devising *poka-yokes*. Wiegmann and Shappell (2003) comment that this is a gap even in industries that are considered to be highly safe, such as aviation. In construction, Saurin *et al.* (2005b) have made a pilot study on the types of human errors in five sites in Brazil. However, as the errors were not linked to specific hazards and construction activities, they could not provide an adequate basis for devising *poka-yokes;*

- As it has been done in the development of quality *poka-yokes,* empirical studies are also necessary for devising safety *poka-yokes,*. For instance, data should be collected in different industries to document existing safety *poka-yokes*, showing their links to the errors they are supposed to tackle. It is also necessary to evaluate the applicability of existing classifications for quality *poka-yokes*, such as the one proposed by Shingo (1996) (e.g. shutdown versus alarm function).

Ideally, the development of *poka-yokes* (whatever their purpose) should be integrated into process and product design. It would be of invaluable usefulness if all major construction technologies were designed by their suppliers considering means to eliminate or reduce their intrinsic safety hazards. The necessary safeguards and other *poka-yokes* should be considered as part of the technology design and the remaining hazards should be formally communicated to contractors. Nowadays, tasks of both designing safeguards and identifying hazards are usually carried out by contractors, which learn about the safe use of technologies painfully by trial and error.

Also, design for X (DFx) techniques, which have been used as mechanisms to eliminate waste as early as in the design stage, may be applied to the design of safety *poka-yokes* and, more generally speaking, to the consideration of safety and ergonomic issues into design. Helander and Furtado (1992) suggest that many principles of design for automated assembly – DFA - (e.g. minimize the number of components and parts, facilitate orientation of parts) apply equally well to manual assembly. Helander and Willen (1999) have even proposed the term design for human assembly (DHA) to make reference to a set of principles of DFA that can be extended for safety and ergonomic purposes. However, studies on the actual impact of such principles on workers´ health have not yet been performed (Helander and Furtado, 1992) and the DHA principles have not yet resulted in widespread and structured methods with a focus on operators´ well being.

Last but not least, it should be recognized that an unfortunate limitation of *poka-yokes* is that they are hard to be devised for the upstream managerial processes in which failures in decision-making (i.e. errors and violations of designers and managers during planning) create the conditions for hazards and defects.

CONCLUSIONS

This paper has identified opportunities for synergy between production and safety management in the lean production paradigm. From one hand, CSE theory indicates that lean production approach on procedures development should be questioned. In particular, production procedures should consider the following guidelines: **(a)** to take into account workers´ mental and physical capabilities, which does not only mean to design adequate work stations from a micro-ergonomic perspective (this is fairly common in lean shop-floors) – rather, work organization should be privileged to produce fulfilling jobs; **(b)** to stress workers involvement in procedures development and monitoring, in order to reduce the mismatch between operators and designers mental models; **(c)** successful performance – either for safety or other criteria – is as important to be understood as deviations from procedures; **(d)** to adopt a broader view on the meaning of deviations from procedures, incorporating the idea of managing variability rather than just reducing it. It would be beneficial since lean production allowed workers to cope with deviations, rather than being pushed back to the stable zone as soon as the migration of performance is detected. Moreover, procedures should take for granted that determined types of deviations are going to happen. Thus, design should be able to absorb specific behaviors that could be considered as normal. This guideline is particularly relevant for construction, in which cycle times are usually long and it is much more difficult to standardize work than in repetitive manufacturing environments. Although product and process standardization have been research issues in construction for a while, little has been made to assess the extent to which workers´ behavior is valid to be standardized.

On the other hand, some lean production methods may contribute for the development of mechanisms to detect migrations from safe performance. The extension of autonomation to safety means that workers should be granted autonomy to stop production whenever they feel in danger. *Poka-yokes* for safety purposes should go beyond PPE and safeguards. It is needed to develop devices with a major preventive role that can be linked to specific and serious types of errors. In construction safety, initial efforts should focus on registering and classifying existing devices. This could also provide a basis for regulations improvement.

Overall, it must be emphasized that lean production and safety management must be systematically integrated. Although there might be short-term benefits of lean production on safety (e.g. as a result of a cleaner and better planned working environment), full exploration of those gains needs a deeper understanding on what are the similarities and differences between both theories. In this respect, it would be useful to undertake a similar analysis to the one carried out in this paper to other lean production elements (e.g. how lean practices such as kaizen, supply chain management and cellular manufacturing may benefit safety?). Of course, an inverse analysis is also necessary, since some elements that are usually included in safety management systems (e.g. incident analysis, safety audits, safety metrics) can be integrated and improve lean production practices.

Moreover, as lean systems have gradually matured in construction and elsewhere, it has come the time to investigate whether there has been correlation between safety and production performance. Based on the ideas set upon in this paper, the proposition is made that the integration between traditional safety and lean techniques will improve safety until a plateau similar to the one that has been already achieved by leading companies. In particular, it seems that an opportunity for a significant breakthrough in construction lies in devising innovative approaches to systematically integrate safety and lean based on CSE theory.

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