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ADVANCES IN INTEGRATION OF EQUIPMENT LOCKOUT/TAGOUT, DETERMINATION OF ACTUAL PRODUCTION CAPACITY AND PRODUCTION/MAINTENANCE PLANNING

SYLVIE NADEAU

Mechanical Engineering Department, University of Quebec, École de technologie supérieure, 1100 Notre Dame West, Montreal (Quebec), H3C 1K3, Canada. E-mail: sylvie.nadeau@etsmtl.ca (corresponding author)

JEAN-PIERRE KENNÉ

Mechanical Engineering Department, University of Quebec, École de technologie supérieure, 1100 Notre Dame West, Montreal (Quebec), H3C 1K3, Canada.

BEHNAM EMAMI-MEHRGANI

Mechanical Engineering Department, University of Quebec, École de technologie supérieure, 1100 Notre Dame West, Montreal (Quebec), H3C 1K3, Canada.

ADEL BADRI

Mechanical Engineering Department, University of Quebec, École de technologie supérieure, 1100 Notre Dame West, Montreal (Quebec), H3C 1K3, Canada.

ABSTRACT:

Individuals and groups throughout an organization are both faced with occupational health and safety (OHS) issues that arise often from deficiencies in product, process or equipment design or in operations management. If such issues are addressed appropriately, improved efficiency and productivity can result throughout the entire organization. The purpose of the present article is to review research results on the subject of integrating OHS into operational risks and to propose improvements to theoretical analytical models of manufacturing systems variability. A portfolio of analytical models for integrating equipment lockout/tag-out into the planning of production and maintenance and the calculation of production capacity is presented.

The use of Markov chains followed by solving of Hamilton-Jacoby-Bellman differential equations using numerical methods led to three findings: (i) lockout/tag-out is an activity that should be planned and organized within Materials Requirements Planning (MRP); (ii) lockout/tag-out procedures under certain conditions require suitable study and work measures; (iii) the calculation of production capacities must include estimation of parameters relevant to lockout/tag-out. Avenues to the integration of OHS risks into operational risks are proposed. Lockout/tag-out becomes an asset when the motivation for bypassing it is reduced, the payoff being reduced likelihood of workplace accidents.

Keywords: lockout/tag-out, occupational safety, production control, maintenance activities

1. INTRODUCTION

Management of OHS risks and operational risks in the same process is becoming an unavoidable necessity (Zwetsloot et al. 2007). Studies have shown that if OHS issues are addressed appropriately, improved efficiency and productivity can result throughout an entire organization (Bruseberg 2008, Morse et al. 2009, Vogt et al. 2010). Since quality, health, safety and operations management problems are all interrelated, many researchers (Dul and Neumann 2009, Caroly et al. 2010) and practitioners (Goodyear 2005) are interested in integrating all of these aspects into the design and planning stages of manufacturing systems and therefore recognize the difficulties inherent in attempting to integrate information in dispersed and complex systems (Le Coze 2005).

The literature on lockout/tag-out is focused on protective devices, compliance with standards, and on lockout procedures and programs (Hesla et al. 2012, Cawley and Homce 2007). Some researchers emphasize the necessity to plan such activities (Hill and L'Espérance 2013, Matsuoka and Muraki 2001, Dunn et al. 2000), while remaining focused on technical aspects. The principal preoccupations are electrical, fire, explosion, mechanical and chemical hazards. Some business categories (auto-body repair) appear to be applying expert recommendations or best practices correctly (Brosseau et al. 2014). Others (e.g. construction dump trucks, grain conveyors, sawmills) appear to be meeting with major difficulty (McCann and Cheng 2012, Shapiro 2011, Holcroft and Punnett 2009). The differences between the legislations and standards involved (Doherty and Gatien 2013), especially in sectors under global economic pressure (Scott and Segers 2012) raise particular challenges. Some studies (Bulzacchelli *et al.* 2008) show that in most accidents involving energy hazards, lockout was incomplete.

OHS risks increase when dangers and time constraints converge, which is the case for maintenance interventions (Papadopoulos et al. 2010). Intensification of work in a company leads to bypassing or blocking of machinery security systems to allow faster work and maintenance of higher production rates (European Agency for Safety and Health at Work 2007). The risk of human error during such activities has a direct impact on the availability of the production system and is a major source of work incidents and accidents. Protective devices are often absent or easily bypassed for reasons related to corporate/individual culture, time pressure, human error, ignorance or technological problems (Burlet-Vienney 2011). This is a significant contributor to the persistent high accident statistics in the manufacturing sector (Burlet-Vienney 2011).

Lockout/tag-out are activities that must be planned and organized in order to minimize the motivation to circumvent them. The aim of this paper is to summarize the findings of research on progress being made towards the acceptance of equipment lockout/tag-out activities for consideration in the same economic and business framework as activities such as planning of production and maintenance and determination of effective production capacity. We also propose modifications to measures of manufacturing system variability that should facilitate the integration of lockout/tag-out.

This review is organised as follows: In Section 2, we provide a synthesis of the current knowledge and developments in this subject area. Section 3 presents a broad outline of the various facets of the problem as studied up to the present. In Section 4, implications of the published results for lockout/tag-out are presented. We provide a conclusion in Section 5.

2. LOCKOUT/TAG-OUT-PRODUCTION-MAINTENANCE MODELS

Zwetsloot et al. (2007) note that safety is often separated from maintenance in business operations. They observed in a process industry case study that the procedures, databases and personnel associated with these two functions were independent. Their analysis revealed that some of the maintenance database information was relevant to safety, while safety engineers themselves did not consider analysis of the maintenance database to be necessary. These researchers noted in their conclusion that the perception of databases and information for one function as irrelevant to the other was inherent in the mental models of the respective experts (Cox et al. 2003, Johnson-Laird 2005).

In the literature, lockout/tag-out procedures are integrated into production planning and design of manufacturing systems using a control theory based on mathematical models. This integration includes two aspects: production plan management and production capacity management. In the models thus developed, manufacturing systems consist of a single machine producing a single type of part or two non-identical machines in passive redundancy producing a single type of part. Redundancy is described as passive when resting elements are put into service only as the need arises, meaning that among a group of elements, only a subgroup is in service at a given moment. This implies that some elements are on standby or in process (Basile and Dehombreux 2002). The system is subject to random failures and repairs and deteriorates with machine age as a function of total output since the previous repair or servicing.

Three decision-aid tools thus emerge from as many different models, based on the following hypotheses:

Hypothesis 1 (Model 1): Lockout/tag-out is an activity included in preventive and corrective maintenance (Charlot et al. 2006).

Hypothesis 2 (Model 2): Lockout/tag-out is a complete activity in its own right, associated with preventive and corrective maintenance (Badiane 2010).

Hypothesis 3 (Model 3): Lockout/tag-out is an activity included in a system's corrective maintenance in passive redundancy (Emami-Mehrgani et al. 2013).

The aim of model 1 is to integrate lockout/tag-out into production plan management. Preventive maintenance activities have been considered and two types of corrective maintenance (or repairs) have been differentiated: repairs with lockout/tag-out associated with accident prevention, and repairs without lockout/tag-out. The manufacturing system considered consists of a single machine producing a single type of part. Such a machine is available when it is operational, and unavailable when it is under repair without lockout/tag-out, under lockout/tag-out for preventive maintenance, or under repair and locked. Modelling using a four-state non-homogenous Markov chain has been proposed (Charlot et al. 2006). The choice of the non-homogenous Markov chain takes into consideration the increasing probability of machine failure due to age or use. Numerical solutions for this system may be obtained by solving Hamilton-Jacoby-Bellman (HJB) differential equations.

The aim of model 2 is also to integrate lockout/ tag-out into management of the production plan. The aim of the study by Badiane (2010) was to determine an optimal production policy that minimizes the production cost while taking safety into account through lockout/tag-out during machine preventive maintenance and repair activities. This model differs from model 1 in that it considers lockout/tag-out as a separate mode of the machine to eliminate the risk of powering during operations on the machine. This leads to a five-state rather than four-state non-homogenous Markov chain. The tools used are the same as in model 1. Numerical solutions for the system may be obtained again by solving Hamilton-Jacoby-Bellman (HJB) differential equations. The principal finding of this study provided the basis for proposing that lockout/tag-out must be considered as an activity that can be planned entirely within the planning of production rather than jointly with maintenance activities.

The aim of model 3 is to integrate mean time to lockout/tag-out into management of production capacity (Emami-Mehrgani et al. 2013). This model considers the manufacturing system as consisting of three non-identical machines (two machines with passive redundancy plus one in series with these) producing one type of part. The objective of this study was twofold: (1) to minimise work-in-process and finished products inventory costs and (2) to respect the essential space–time through intervention on the machine that is shut down. This essential space-time is released thanks to the passive redundancy system, thus reducing the motivation to circumvent lockout/tag-out procedures. In this model, mean time to lockout/tag-out is integrated into repair time. A homogenous Markov chain is used, which was assumed to be eight-state. It should be noted that only two modes were considered for each machine (operational or under repair). A more realistic model of industrial activity is contemplated in model 3, a combined approach based on analytical formalism, simulation modelling, design of experiments and response surface is proposed. A numerical example and sensitivity analysis are provided to illustrate the usefulness of the proposed approach.

3. RESEARCH TRENDS

Lockout/tag-out is required during corrective and preventive maintenance activities, unlocking, installation/uninstallation of production equipment, adjustment or development of production equipment, inspection and predictive maintenance or long-term production shutdowns (Burlet-Vienney 2011). It is practiced improperly primarily due to ignorance, misunderstanding or erroneous application of the procedure, unsuitable or unusable procedure for the context, collective influences counteracting application of the procedure, deficient safety culture in the company, and disregard of lockout/tag-out rules by the operator (Burlet-Vienney 2011).

Up to the present, mathematical functions have been used to model lockout/tag-out in manufacturing systems. The models have been solved using HJB differential equations, numerical analysis or simulations. Their focus is on lockout/tag-out during corrective and preventive maintenance activities and their aim is to resolve in part the bypassing of procedures (due to temporal and monetary imperatives) and to minimize downtime.

4. IMPLICATIONS AND CURRENT CHALLENGES

Solving the integration problems corresponding to models 1, 2 and 3 for optimal conditions allows determination of the structure of production, maintenance and lockout/tag-out policies in a dynamic context with uncertainty due to random failure and repair of machinery. Using sensitivity analysis to characterize the policies thus obtained shows that they are extensions of critical threshold policies. Stock levels commonly called production thresholds are defined for these policies: 1 = below the threshold, 2 = above the threshold and 3 = at or close to the threshold, to which the responses are respectively produce at the maximal rate, stop producing, and produce at the demand rate. Knowledge of the value of a production threshold is equivalent to knowledge of the associated policy. The decision aid tools associated with these policies allow continuous control of the manufacturing system based on system state feedback (machinery status and stock level according to the machine age).

4.1 Integration of logout/tag-out into manufacturing systems at the planning stage

The production coordination tool most widely used in operations management, allowing task scheduling and inventory management as a function of demand, is known as the Materials Requirements Planning (MRP) system. A production plan is constructed from a database of available resources and standard times and costs, among other things. These resources include equipment and maintenance indicators (reliability, maintenance costs, etc.).

Using model 1, Charlot et al. (2006) showed that integration of lockout/tag-out operations into the management of the production plan decreases production costs by increasing machine availability and minimizing the possibility of circumvention.

Model 2 developed by Badiane (2010) suggests building up an inventory of product in process in anticipation of downtime imposed by lockout/tag-out and optimizing lockout/tag-out procedures based on study (optimization of cost and effectiveness of procedures) and measurement (standard times) of work without compromising occupational health and safety imperatives. A space-time minimizing the risks of circumventing the lockout/tag-out procedure is thus created. Badiane (2010) provides a concrete basis for including a quantity that takes into consideration lockout/tag-out in the integrated planning of production. In view of the way the MRP system works and in order to define managerial interventions that are as close as possible to the source of OHS issues and hence more effective as preventive measures, it is suggested that the additional units to be produced be included in the forecasts set forth in the production master plan.

Using model 3 (Emami-Mehrgani et al. 2013), it is possible to embed mean time to lockout/tag-out in a production line with a passive redundancy system. This allows reduction of total production costs including inventory, shortage and maintenance costs while increasing the level of worker safety. In other words the production line becomes less vulnerable to variations in inventory, shortage and production costs, this due to meeting demand constantly. Furthermore, embedding a passive redundancy system in the production line releases the essential space-time during interventions on the machines that are shut down. This essential space-time has the effect of reducing the motivation to bypass lockout/tag-out procedures.

4.2 Integration of logout/tagout into manufacturing systems at the design stage

Production system design is based on Little’s law (Hopp and Spearman 2008). This law links throughput with cycle time and the number of products in process under normal conditions of system utilisation and is expressed as follows:

$$WIP = TH*CT \tag{1}$$

Where

WIP is work in process, the number of products in the queue between two workstations

TH is throughput, the number of products processed per unit time by the workstation

CT is the cycle time, that is, the time interval between two consecutive products exiting from the workstation

The actual maximal capacity of any production system is influenced by so-called natural randomness, due to differences between operators, machines and materials, stochastic failure, run set-up, quality problems, variations in production flow and so on. Workplace accidents and work-related illness can also be considered as random production factors. Stochastic failure associated with production equipment reliability is the principal source of variation in the majority of production systems and is thus always taken into account by engineers during the design of the production system.

Emami-Mehrgani *et al.* (2013) integrated mean time to lockout/tag-out into management of production capacity. Their results suggest using passive redundancy as means of creating a space-time that minimizes the risk of circumventing the lockout/tag-out procedure. Since this redundancy is subject to production capacity calculations based on estimated impact of randomness including that associated with stochastic failure, introducing lockout/tag-out time directly is a valid approach.

The equations for estimating the variations produced by stochastic failure (Hopp and Spearman 2008) thus become:

$$te = to/A \quad (2)$$

$$\delta e^2 = (\delta o/A)^2 + (((mr + mc)^2 + (\delta c + \delta r)^2)(1\text{-}A)to)/A(mr + mc) \quad (3)$$

$$ce^2 = \delta e^2/te^2 = co^2 + A(1\text{-}A)(mr + mc)/to + (cc + cr)^2A(1\text{-}A)(mr + mc)/to \quad (4)$$

Where

to and te are average time components associated respectively with natural and effective randomness

A is equipment availability

δo, δe, δr, δc are standard deviations respectively for natural randomness, effective randomness, repairs and lockout/tag-out

mr is the mean time to repair and mc is the mean time to lockout/tag-out

co, ce, cr, cc are coefficients of variation for natural randomness, effective randomness, repairs and lockout/tag-out.

4.3 Challenges

Analytical models are inexpensive and their validation and use are simple compared to other approaches, thanks to the limited number of parameters and hypotheses required. Such models may be very helpful in support of results obtained using numerical methods and because of the flexibility they offer when changing variables and simulating results. However, the policies produced must be robust, meaning that they respond well to uncertainties, for example due to human error (Emami-Mehrgani *et al.* 2013), and adapt to the rapidly changing conditions under which businesses operate. Field validations of the different models remain to be carried out.

When a system is modeled using a Markov chain (homogeneous or non-homogeneous) its future is determined only by its present situation. Given that the manufacturing system environment is stochastic, modelling thereof requires assumptions. Many evaluations are possible and each has a certain probability of being accurate. The term “Markov property” refers to the memory-less property of a stochastic process, meaning that the manufacturing system should follow an exponential distribution of breakdowns and repairs. As a remedy to this problem, Emami-Mehrgani *et al.* (2013) used a combined approach, which is based on a combination of analytical formalism, simulation modeling, design of experiments and response surface methodology. Other models and approaches must be considered in order to identify the most appropriate technique.

Lockout/tag-out can be considered as an activity that can be planned entirely within the planning of production, rather than in conjunction with maintenance activity. However, including additional units at the beginning of integrated production planning provides only a partial solution that must be completed by integration of logout/tag-out into manufacturing systems at the design stage. However, the structure of businesses, their size, competitive positioning (industrial sector and branding), culture of continuous improvement and innovation strategy all have a decisive impact on management system integration decisions (Jorgensen et al. 2006, Salomone 2008). It is therefore important to examine and clarify the most important characteristics of the business when adopting a management tool (Rocha 2010).

Research results in this field draw inspiration from the concept of corporate social responsibility as presented by Zwetsloot et al. (2010) and Montero et al. (2009) and from the central message of the Brundtland Commission on social, economic and environmental integration as well as worker participation in sustainable development (Lund 2004). They draw attention to the opportunity to achieve better integration of OHS into the week-to-week management processes of businesses using novel approaches that address their principal preoccupations, namely corporate image and better control over business risks. In keeping with the recommendation of Baril-Gingras et al. (2010) to consider voluntary measures as being insufficient to ensure adequate organization of the workplace and thereby eliminate accidents and health hazards, these research results can help businesses go beyond the regulatory system and thus complement legislation already in effect. Since integration of OHS into operational risk management is still an emerging field of research, evaluative studies remain rare. Monitoring and auditing of the performance of these technological tools in preventing workplace accidents and occupational illness remain essential.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Sustainability of work and production assumes that the demands of staying competitive are balanced judiciously with those of preventing workplace accidents and occupational illness. Solutions have been proposed for integrating lockout/tag-out activities into planning and production (MRP), maintenance and determination of actual production capacity (estimation of production variations due to stochastic failure). The published studies of lockout/tag-out highlight the necessity of identifying both operational and OHS risks before any manufacturing system planning or designing activity. The proposed tools constitute voluntary measures that complement the applicable standards and legislation as well as the development of appropriate lockout/tag-out procedures and protective devices. They can help to minimize the motivation to bypass lockout/tag-out to meet the pressures of production and maintenance. The robustness of the tools thus developed nevertheless remains a preoccupation, as does determining the characteristics of businesses likely to implement with diligence the recommendations arising from their application.

Businesses now face complex risk integration challenges that require an interdisciplinary approach. Planning and designing a sustainable manufacturing system is a perfect storm of technical challenges and social commitment in which ergonomics experts, engineers and managers must play the major professional roles.

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