Holistic Approach in Risk Reduction Processes of the Machinery Equipment

Hana Pačaiová(✉), Michaela Balážiková, Marianna Tomašková, Katarína Firmentová, Katarína Chomová, Lukáš Ďuriš, Peter Darvaši, Lukáš Salaj, and Ján Kán

Faculty of Mechanical Engineering, Technical University of Kosice, Letna 1/9, Kosice, Slovakia
{hana.pacaiova,michaela.balazikova,marianna.tomaskova}@tuke.sk, {katarina.firmentova,katarina.chomova,lukas.duris,peter.darvasi, lukas.salaj,jan.kan}@student.tuke.sk

Abstract. Safety of machinery is an area, which, at the first glance, appears as solved and sufficiently specified by regulations and harmonized standards in the EU. However, the reality is that, according to statistics, the machinery, including lifters, conveyors, and similar equipment, is a source of as much as 25% of all serious work injuries annually. Machinery condition, method of performed activities, environment in which the machine is located, are basic factors projected into hazardous event origination. This contribution, based on the status analysis protective measures of more than 100 machineries, evaluates the level of measures implemented on the equipment throughout its life cycle. Within the research, the methodology was proposed, evaluating the efficiency of protective measures on three levels: on the machinery itself; in relation to machines existing within the given operation, as well as complex level of machinery safety in an organization.

Keywords: Machinery safety · Human factors · Risk reduction

1 Introduction

Occupational health and safety during machinery use is a key area in OHS management in industrial plants [1]. The condition of machinery changes during its life cycle, so do employees and the conditions of the operation, as well. Despite numerous legislative requirements and supervision over their observance (e.g.: EC declaration of CE mark conformity), number of accidents when operating the machinery reaches up to 25% of all serious occupational injuries per year [2].

Permanently sustainable development of an organization requires holistic approach to evaluation of both goals as well as activities of corporation, including the machinery risk assessment. Monitoring and inspection are critical elements in the management of processes. Therefore, it is inevitable to identify key performance indicators (KPI) [3], which are relevant to the analyzed processes. It is possible to carry out the monitoring of the processes on various management levels, as well as from different points of view: on the managerial, operational, logistical level; from the viewpoint of finances, safety or maintenance provision [4, 5]. Holistic approach means a general view on the system.

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System properties, of the machinery in this case, depend on the properties of its parts and its functioning in the given area.

Occupational Health and Safety currently represents one of the most significant areas of social politics of the EU and developed countries of the world.

Holistic approach to dealing with OHS issue starts as early as the machinery is designed and is concluded with a feedback of the safety management during its operation.

In 1989, legal framework determining mutual relation between machinery equipment design and its safe usage in practice was created in Europe. These were two basic regulations 89/391/EEC, known as the "OHS Directive" [6] and the Directive 89/392/EEC – known as the "Machinery Directive". Requirements for construction of "safe machinery equipment" were developed and the Machinery Directive is currently known as the European Directive 2006/42/ES [7].

Condition of machinery, method of activities performed, environment in which the machine is located are basic factors projecting into creation of hazardous events. Although the unified EU market, based on more than 31 years of defined rules, expects that the approach in risk reduction process as early as by the machinery design shall be observed (or developed). However, mainly within the organizations having out-of-date machinery equipment, changes of machinery equipment are realized with insufficient consideration of the basic requirements. The next issue is education and training of technical workers [8] who have no knowledge of principles and requirements for safe designing.

Risk assessment realized as early as in the stage of machine design is an essential prerequisite for safe machinery construction, so that the residual risks were on the lowest possible level. Although modernization of old machinery provides higher effectivity and enables significant increase of productivity by means of new automated functions, but only when using the right principles of safe designing [9]. Currently, machinery safety requirements are more and more connected with programmable electronic control systems (SRP/CS). Risk estimation is a significant constituent part of risk analysis in the process of machinery development because categorization and allocation of safety requirements is based on this [10]. It is important to know how the risk estimation is carried out, because incorrect selection of the safety integrity level (SIL) or performance level (PL) may lead to multiple costs on a part of management system connected with safety [11].

2 Machinery Risk Assessment Principle

The principle of risk assessment lies in the succession of individual steps mentioned in the algorithm shown in Fig. 1.

Risk analysis begins with classification of system into elements. The aim is to describe and identify the source of unwanted event as clearly as possible, i.e., what represents threat in relation to a human; description of hazard situation – what may happen during the given activity and how. Next comes the estimation of probability and consequence, which requires selecting the appropriate methodology to match the parameters of probability and consequence (e.g.: risk matrix, risk graph). This methodology may be in a form of qualitative, semi-quantitative or quantitative approaches [12]. The next important step of this logical process is expression of the probability relation and consequence by a combination of their values, so-called risk estimation. Risk evaluation is a step that comes only after risk analysis and it basically compares the estimated risk extent (related to the identified hazard) with the "set" parameters of its acceptance (or tolerability).

Taking measures is related to such risk values, which exceed or reach an inacceptable level. It may happen that even though the estimated risk level ranges within the acceptability zone, a manager (designer, producer) will decide to take certain measures in order to reduce it. This approach is marked as ALARP (as Low as Reasonable Practicable) – represents risk reduction to the most reasonable level, i.e., effective and efficient [13]. This entire process is marked as risk reduction or also as risk control [14] and requires its re-assessment, in order to verify whether the proposed and implemented measures are really effective [15, 16].

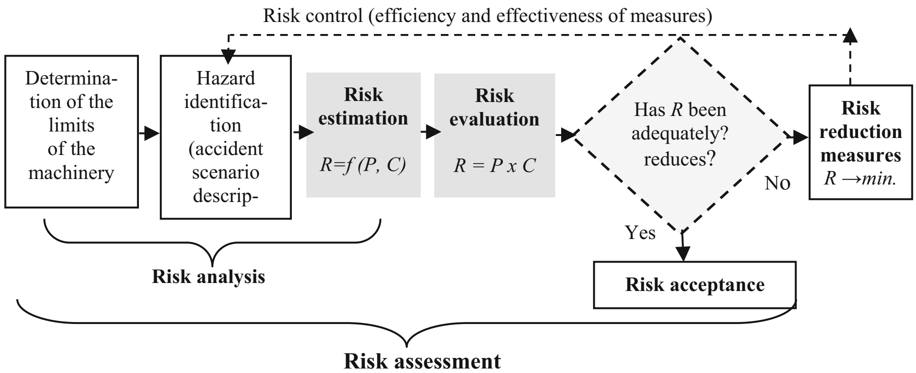

Fig. 1. Modified simplified procedure for machinery risk assessment/risk control (inspired by ISO 12100).

3 Analysis and Evaluation of the Machinery Protective Measures' Efficiency

Within the running research, experts from safety field (2 from practice and 3 from university) cooperated on the creation of the CLMS (Comprehensive Level of Machine Safety) methodology, the aim of which was, based on risk assessment results of operated machines (for the activities of operators and maintenance according to the own methodology of an organization), with regard to the phase of their operation, to analyze the status and efficiency of current measures on particular equipment, or the total efficiency level of taken protective/safety measures applied on the equipment in operations [17, 18].

Main parameters of the model were the following assumptions: there are n operation machines at each production facility; the number of safety requirements (SR) for machinery safety is m. Then the status of i^{th} requirement ($i = 1, 2, 3, \ldots, m$) is assessed on each k^{th} machine ($k = 1, 2, \ldots, n$) by means of implemented suitable safety measures.

3.1 Proposal of Methodology

Current status of safety requirements on an assessed machine is expressed by means of the so-called coefficient of current measure status $w_{k,i}$, for which holds $w_{k,i} \in \{0, 1, 2\}$**.** The $w_{k,i}$ coefficient represents a categorial variable, which can reach three possible values (see Table 1).

Table 1. Coefficient of current measure status $w_{k,i}$.

Coefficient $\boldsymbol{w_{k,i}}$	Explanation
$w_{k,i} = 0$	Measures for the fulfillment of i^{th} requirement on k^{th} machine are not introduced
$w_{k,i} = 1$	Measures for the fulfillment of i^{th} requirement on k^{th} machine are introduced but not followed
$w_{k,i} = 2$	Measures for the fulfillment of i^{th} requirement on k^{th} machine are introduced and fully followed

Level of measures efficiency Δ_k expresses the fulfilment of safety requirements by means of realised measures on k^{th} machine and is expressed by the relation:

$$\Delta_\mathrm{k} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{w}_{\mathrm{k,i}}}{\mathrm{S}_{\mathrm{MAX}}} \times 100\%. \tag{1}$$

Where n represents the number of machines, m the number of safety requirements and $w_{k,i}$ is the coefficient of current measures status of k^{th} machine by i^{th} safety requirement.

S_{MAX} variable represents the coefficient of maximum reached efficiency of all measures on a given machine and is determined by the relation:

$$\mathrm{S}_{\mathrm{MAX}} = \mathrm{w}_{\mathrm{max}}\mathrm{m}. \tag{2}$$

Where m is the number of safety requirements (SR) and w_{max} is the maximum value of measures evaluation, in our case $w_{max} = 2$.

Total efficiency level of measures Δ in the given operation is expressed by the relation:

$$\Delta = \frac{\sum_{\mathrm{k}=1}^{\mathrm{n}} \Delta_\mathrm{k}}{\mathrm{n}} \times 100\%. \tag{3}$$

Where Δ_k is the level of protective measures efficiency on machines in the case of k^{th} machine and n is the total number of machines located in the given operation.

Total level of measures efficiency of machinery protective devices Δ in the given operation takes on values from the interval $\langle 0, 100 \rangle$.

For a complex safety level of a given operation conditioned by the status of introduced measures on machinery, the following evaluation levels were suggested – see Table 2:

Table 2. Levels of measures efficiency of an operation Δ.

Coefficient Δ	Level of measures
$0\% < \Delta < 29\%$	Low
$30\% < \Delta < 49\%$	Negligible
$50\% < \Delta < 69\%$	Middle
$70\% < \Delta < 89\%$	High
$90\% < \Delta$	Very high

If a production organization has p operations, then the complex level of safety measures efficiency $\bar{\bar{\Delta}}$ would be possible to be expressed by the relation:

$$\bar{\bar{\Delta}} = \frac{\sum_{j=1}^{p} \Delta_j}{p} \times 100\%,\ j = 1, 2, \ldots, p. \tag{4}$$

Where p is the number of operations (in our case 3) and Δ_j is the level of measures efficiency in the case of j^{th} operation, for which holds the relation:

$$\Delta_j = \frac{\sum_{k=1}^{n} \Delta_{k,j}}{n} \times 100\%,\ k = 1, 2, \ldots, nj = 1, 2, \ldots, p. \tag{5}$$

Where $\Delta_{(k,j)}$ is the level of measures efficiency in the case of k^{th} machine in the j^{th} operation and n is the total number of machines within the given operation.

3.2 Results of Applied Methodology

The aim of suggested and applied methodology in order to assess the safety level of machines in a phase of their use was to inspect the status of the machinery that was operated in a given organization from 1 to more than 30 years. Within the particular operations (3 operations for the production of plastic components, marked I, II, III), there were new as well as older machines, such as automatic or semi-automatic assembly workstations, with one or maximum two control places (loading of components, checking and unloading of ready products). For the research purposes, a questionnaire, stemming from the requirements from the Directive on machinery, which consisted of 19 safety requirements, was created.

The experimental research was carried out in several parts:

- risk assessment of each machine based on unified methodology in accordance with ISO 12100 (risk matrix – own methodology of an organization),
- status evaluation of already established (current) safety measures for each machine according to determined safety requirements (SR1–SR19) by means of the coefficient of current measures status,
- evaluation of the efficiency level of such measures (with regard to the outcomes from risk assessment) for each machine and for each operation,

- evaluation of complex efficiency level of introduced protection/safety measures for the whole organization. evaluation of complex efficiency level of introduced protection/safety measures for the whole organization.

Each i^{th} safety requirement of the assessed j^{th} machine was assigned the coefficient of current measures status $w_{k,i}$. The assigned value (0, 1 or 2) was the result of a consensus of 5 reviewers with the aim to decrease the uncertainty rate at subjective deciding (mainly when assessing the safety status of older machines).

From the results of the evaluation of the status of measures of implemented in operation I it is obvious that safety requirements SR1, SR4, SR5, SR11, SR14, SR16 and SR19 are fulfilled on all machines. Requirements SR 17 and SR 18 are not fulfilled on none of the machines, i.e. the requirements for the application of devices for hazardous energy isolation and application of LOTO (Lockout, Tagout) means for machinery [18] were not fulfilled.

The analysis of evaluation shows that in operation I, there is no machinery that would meet all safety requirements. Each machine met on average only 52% of requirements, where measures were implemented and followed. For almost 39% of requirements, safety measures were only introduced but not followed.

For each k^{th} machinery equipment, requirement fulfilment efficiency Δ_k is determined according to the relation (1). Total level of measures efficiency Δ in operation I (marked Δ_I) is determined according to the relation (3). The average value of the total efficiency of current measures in the operation I is $\Delta_I = 69.66\%$.

Three criteria were analyzed and evaluated in a similar way (Δ_k, Δ) in two other operations: operation II (20 machines) and operation III (23 machines). The basic figures of total efficiency of current measures Δ in individual operations are shown in Table 3.

Table 3. Figures of total efficiency of measures Δ in operations [%].

Operation	Number	Average	max	min	Rv	s	IS – 95%
I	17	69.66	78.95	63.16	15.79	4.57	(67.24, 72.02)
II	20	75.66	78.95	47.37	31.58	6.77	(72.49, 78.83)
III	23	53.89	81.58	52.63	28.95	6.03	(51.28, 56.50)
Δ	60	65.61	81.58	47.37	34.21	11.25	(48.66, 68.52)

The analysis shows that the total evaluation of current applied safety measures in operation I reaches the value of 69.66% of total efficiency rate, which represents the *middle efficiency level* of current safety measures.

Operation II reaches the value of 75.66% of total efficiency rate, which represents *high efficiency level* of measures. On each machine of the operation II, there were on average only 62% such requirements, where measures were introduced and followed. For almost 27% of the requirements, measures were only introduced but not followed.

Operation III reaches only 53.89% of total efficiency level, which means almost lower borderline of the middle level of measures efficiency. On each machine of the operation

III were on average only 18% of such requirements, where the measures were introduced and followed. For almost 71% of the requirements, measures were only introduced but not thoroughly followed.

To evaluate the status of machinery safety in the entire organization, a complex efficiency level of introduced measures $\bar{\bar{\Delta}}$ (4) was determined, according to safety requirements SR1–SR19. Based on the results of applied CLMS methodology of introduced safety measures on machines and by means of the evaluation of total efficiency level in the entire organization, it is possible to state that the value of complex efficiency level $\bar{\bar{\Delta}}$ is on the value of 65.61%, which means middle efficiency level.

4 Conclusions

The proposed and in practice verified CMLS methodology has proved that even despite the fact that the machinery safety is managed already at its design by a producer, and throughout its operation by an operator, regular evaluation of efficiency of introduced measures shall point at its insufficiencies related to the entire organization [19, 20]. By analysis of status of implemented safety measures of operated machinery, which, already during the process of their procurement, must meet current requirements of EU directives, weaknesses of management of their safety at the operator itself were "uncovered".

Development of protective devices implemented on machinery equipment (so-called integrated safety) is very fast and they are normally applied in complex module solutions already (e.g., robots). However, with older machines, responsibility for the level of protective measures is on the shoulders of the operator [21, 22].

It is possible to extend the CLMS methodology, which is also a subject of further research consisting of more detailed examination of implemented types of protective devices in relation to the machinery equipment age and level of its maintenance.

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