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USE OF SAFETY ANALYSIS IN INDUSTRIAL MAINTENANCE MANAGEMENT

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Abstract: The maintenance system is one of the key systems in the industry, because it ensures the continuity of work and the safety of the production systems. The maintenance system includes a set of specific activities carried out by people in various environmental conditions, with the use of appropriate equipment and within a specific organizational and management structure. Activities carried out by maintenance workers are related to the occurrence of various types of physical, chemical, biological or psychosocial risks. These dangers can lead to accidents or occupational diseases. Therefore, the task of managers within maintenance systems is to provide people working in these systems with an appropriate level of safety through the use of properly selected preventive measures. The methods of safety analysis are related to the examination of various systems in order to identify and assess the risks in these systems and to prepare the safety characteristics of these systems, which allows for the correct adjustment of preventive measures to the identified needs. The purpose of this work is to present the basic methods of Safety Analysis in terms of their possible use in the area of industrial maintenance. As part of the work, the hazards at work in maintenance were characterized, the importance of safety analysis for the identification of hazards and accident prevention was discussed, and the key methods of safety analysis were presented in terms of their possible use to improve work safety in an industrial maintenance system. The presented considerations are original. The findings of the article will be very useful for management in implementing safe maintenance systems in industry.
Keywords: maintenance management, Safety Analysis, methods

1. INTRODUCTION

Enterprises competing on the free market feel a strong pressure to reduce production costs (Wang et al., 2007), which negatively affects those aspects of operation that, in the traditional sense, do not generate added value, i.e. maintenance. At the same time, enterprises are developing towards improving manufacturing flexibility, which means that they must focus on improving the efficiency of maintenance systems (Abreu et al., 2013). In addition, the increasingly faster automation of manufacturing processes emphasizes the importance of efficient maintenance departments in enterprises and the selection of effective maintenance strategies by managers (Tsang, 2002; Ding et al., 2014). Proper, systemic maintenance management can significantly improve the efficiency, productivity and profitability of an organization (Lofsten, 1999; Liyanage et al., 2009; Kiseľáková et al., 2020; Teplická and Hurná, 2021) as well as ensure the safety of people working in various workstations (Alsyouf, 2007; Leong et al., 2012; Sheikhalishahi et al., 2016). To achieve this, managers should use the various health and safety problem-solving tools available for both immediate use and lifetime service of facilities (Parida and Chattopadhyay, 2007).

2. HAZARDS AT WORK IN MAINTENANCE

According to the European standard EN 13306 (BSI, 2010), maintenance is all activities of a technical, administrative and managerial nature that are carried out during the entire life cycle of the facility, and the purpose of which is to maintain or restore the facility to the condition in which it can carry out the planned functions, while protecting against failure or loss of these functions.

In industrial maintenance, the objects to be maintained can be workplaces, buildings, work equipment (machines, devices, installations) or means of transport. Commonly, "maintenance" is considered to be technical activities such as assembly and disassembly, replacement of spare parts, lubrication, repair, etc. However, in practice, maintenance covers a much wider range of activities, and includes numerous additional tasks, such as: selecting the right tools, selecting the right chemicals, preparing the site (e.g. by removing uninvolved staff, controlling traffic and placing signs), preparing machinery and equipment to be shut down, transport of spare parts, preparation of the necessary safety measures, etc.

The EN 13306 standard on basic maintenance terminology distinguishes between 16 basic maintenance activities (BSI, 2010): condition monitoring, compliance list, fault diagnosis, fault localization, function check-out, improvement, inspection, maintenance schedule, maintenance task preparation, modification, overhaul, rebuilding, restoration, repair, routine maintenance, and temporary repair.

Depending on the type, place and nature of the activities performed, maintenance workers may be exposed to various types of hazards, which can be broadly divided according to their specificity, into physical, chemical, biological and psychosocial hazards (Tabor, 2014; Carrillo-Castrillo et al., 2015; Niciejewska and Kiriliuk, 2020; Kapustka et al., 2020; Woźny, 2020).

Long-term exposure to certain types of hazards in the work environment can cause serious health problems (occupational diseases) such as asbestosis, cancer, hearing problems, skin diseases, respiratory diseases, and musculoskeletal disorders.

This may lead to an increase in the sickness absenteeism rate in a short period of time, and in a longer period of time, to the permanent disabling of the employee from performing work (Lind and Neonen, 2008; Tabor, 2014; Blaise et al., 2014; Grabara, 2019).

The type of maintenance may be different depending on the industry, the specificity of the organization or the management's policy in the field of maintenance (Kučera and Kopčanová, 2010), so the implementation of even the same tasks may take place in completely different conditions, and thus the consequences of such work they can be very different.

In addition, exposure to certain types of factors (e.g. stress) may not only lead to an occupational disease, but also in many cases may increase the frequency of accidents at work (Antti and Mats, 2011). For example, during corrective maintenance, maintenance workers are exposed, among other things, to psychosocial risks such as high skill requirements and severe time pressure. This combination of factors increases the likelihood of making a mistake that may result in a breakdown or accident. European statistics show that approximately 10-15% of all fatal accidents and 15-20% of all accidents are related to broadly understood maintenance (EASHW, 2010). Therefore, it is widely recognized that maintenance itself is a high risk activity (Kelly and McDermid, 2001; Reason and Hobbs, 2003; Pollard et al., 2014). The clearly observed relationship between maintenance activities, safety and the company's productivity (Liyanage et al., 2009) means that the effective assurance of safety during the implementation of maintenance works has a strategic dimension for the company.

3. IMPORTANCE OF SAFETY ANALYSIS FOR HAZARDS IDENTIFICATION AND ACCIDENTS PREVENTION

Safety Analysis is a documented system examination procedure to identify and assess the risks in that system and to compile the safety characteristics of the system (Harms-Ringdahl, 2013).

Many safety analysis tools have been described in the literature. The IEC / ISO 31010 (2009) standard collects 31 risk assessment techniques. The US Federal Aviation Administration manual (FAA, 2000) identifies 81 different techniques for safety analysis. J. Bell and J. Holroyd (2009) analyzed 17 different methods related to human error. S. Sklet (2004) discussed 14 and E. Hollnagel and J. Speziali (2008) characterized 21 accident investigation methods.

There are two approaches in safety analysis - proactive and reactive. The proactive approach uses qualitative and quantitative risk analysis and assessment tools. On the other hand, the reactive approach uses tools for the analysis of accidents and near misses.

The literature indicates a number of cases when it is necessary to use the safety analysis: (1) a serious accident has occurred, (2) changes to the technical equipment are planned, which may result in a deterioration of the safety level, (3) organizational changes are planned, (4) a safety problem has been detected and improvements are needed, and (5) it is necessary to verify the design of the new system before a decision is made to implement it.

4. REVIEW OF SAFETY ANALYSIS METHODS IN THE CONTEXT OF SAFE MAINTENANCE NEEDS

In terms of possible application, four main groups of safety analysis methods can be distinguished: (1) risk identification methods; (2) methods to facilitate understanding of the problem; (3) risk assessment methods; and (4) accident (and other incident) analysis methods. The first group includes tools for identifying threats - risks (Table 1). The methods from this group can be used to detect undesirable events or problems that may occur in connection with the tasks performed by maintenance workers in different systems (or at different workstations).

Table 1
Examples of Hazards (Risks) Identification Methods

Method	Comments
Energy Analysis – EA (Hammer, 1972; Haddon, 1980; Johnson, 1980)	Identifies hazardous forms of energy. Structures the system into physical volumes.
Preliminary Hazard Analysis – PHA (Hammer, 1972)	Free search for hazards (example of a coarse analysis methods).
Hazard and Operability Studies – HAZOP (CISHC, 1977; ILO, 1988; Taylor, 1994; Lees, 1996)	Identifies hazardous deviations in process installations. Structures the system into units.
Job Safety Analysis – JSA (McElroy, 1974; Heinrich et al., 1980)	Identifies hazards in work task. Structures the work procedure into different tasks.
Deviation Analysis – DA (Kjellén, 1984)	Identifies hazardous deviations in equipment and activities. Structures the system in functional blocks. Identification of deviations related to the events.
Failure Mode and Effects Analysis – FMEA (Hammer, 1972; Taylor, 1994; Aven, 2008)	Identifies failures in component or subsystems. Structures a technical system into functional blocks.
Task Analysis – TA (Kirwan and Ainsworth, 1993; Annet and Stanton, 2000)	Analysis of human tasks and identification of threats.
Action Error Method – AEM (Taylor, 1994; Kirwan, 1994; Gertman and Blackman, 1994; Stanton et al., 2005)	Identification of operator's errors in well-defined procedure in e.g. process industry (the human error methods).

Own study based on the cited literature

The second group includes methods that facilitate the understanding of how an accident may occur when certain actions are taken, and what the various consequences of such an event may be (Table 2).

Table 2
Examples of Methods facilitating the understanding of the problem

Method	Comments
Fault Tree Analysis – FTA (Vesely et al., 1981)	Logical diagram of faults (causes) explaining the accident. Binary – a failure exists or does not.
Event Tree Analysis – ETA (CCPS, 1985; Rausand and Høyland, 2004)	Logical diagram of barriers and alternative consequences of an initiating event. Binary – a barrier works of fails.
Management Oversight and Risk Tree – MORT (Johnson, 1980; Ruuhilehto, 1993)	Logic diagram with organizational aspects.
Structured Analysis and Design Technique – SADT (Hale et al., 1997)	Analysis of safety management systems.
Safety Function Analysis – SFA (Harms-Ringdahl, 2000)	Search for safety functions and barriers. Analysis of the safety characteristics of a system. Safety functions are identified, structured and evaluated.

Own study based on the cited literature

The third group of tools are risk assessment methods (Table 3). According to the IEC / ISO 31010 (2009) standard, risk assessment is the process of comparing the results of a risk analysis with risk criteria to determine whether a risk and / or its magnitude is acceptable or tolerated.
On the other hand, according to the IEC definition (1995), risk assessment is a process in which risk tolerance has been determined (based on its analysis). The purpose of using the methods from this group is to assess whether the level of risk and the system's safety characteristics are acceptable.

Table 3
Examples of Risk Assessment Methods

Method	Comments
Direct Risk Evaluation – DRE (HSE, 2008; Harms-Ringdahl, 2001)	Judges directly whether safety measures are needed. Several factors, including regulation, are considered.
Risk Matrix – RM (Cox, 2008; Carvalho and Melo; 2013)	Classification of consequences and probability based on estimates. Acceptability based on predefined combination consequences and probability.

Own study based on the cited literature

The fourth group includes methods of analyzing accidents and other near misses (Table 4). The purpose of using these methods is to investigate undesirable events that have occurred in a specific system in order to properly select preventive measures.

Table 4
Examples of Accidents (Incidents) Investigation Methods

Method	Comments
Change Analysis – CA (Ferry, 1988, DOE, 1999)	Analysis of differences between the accident (incident) and a normal situation.
Systematic Cause Analysis Technique – SCAT (Bird and Germain, 1985; Sklet, 2004)	Identifies causes of accident using special lists.
Sequentially Timed Events Plotting – STEP (Hendrick and Benner, 1987)	A detailed method for sequence analysis. Events and actors are plotted in a time diagram following strict rules.
Cognitive Reliability and Error Analysis Method – CREAM (Hollnagel, 1998)	Analyzes human error taking into account the situation and context.
Accident Evolution and Barrier Function Method – AEB (Svenson, 1991)	Sequence of events with technical and human errors including barriers that might stop the sequence of accident (incident).
Safety Barrier Diagrams – SBD (Taylor, 1994, Duijm, 2009)	Presenting and analyze barriers to accidents.
System-Theoretic Accident Model and Processes – STAMP (Leveson, 2004)	Analyzes the accident from the point of view of information and control feedback.
Man-Technology-Organization – MTO (Evenéus and Rollenhagen, 2007)	Sequence of events with direct and undelaying causes and safety barriers.
Acci-Map (Rasmussen, 1997; Rasmussen and Svedung, 2000; Branford et al., 2009)	Combines accident sequence and organizational levels. Sequence of events at different organizational levels. The flow of decision and information between actors.

Own study based on the cited literature

Separately, the safety audit method Safety Audit - SA (CCPS, 2011) should be mentioned, the purpose of which is to analyze the compliance of the management system with the relevant standards.
Apart from the division of methods according to the purposes of their application, the classification taking into account the orientation of given methods is also important. Within this classification, (1) methods with technical orientation (i.e. how the system works in terms of technical equipment) have been distinguished; (2) human-oriented methods (that is, what is the contribution of the human factor to the success of the system); (3) organizational-oriented methods (that is, how organization and structure shape the outcomes of a system); and (4) combined-holistic-oriented methods.
The last methods emphasize the interactions between various elements and procedures in the work environment. In Table 5, the methods of safety analysis are classified according to their orientation.

Table 5
Classifications of safety analysis methods due to the key orientation in research

	Hazards Identification	**Methods facilitating**	**Risk Assessment**	**Accident Investigation**
Technique	EA, FMEA, HAZOP, TA	ETA, FTA	RM, DRE	STEP, AEB
Human	EA, JSA, AEM	ETA		STEP, AEB
Organization		MORT	DRE	Acci-Map
Holistic	DA, PHA	SFA		CA, DA, MTO
Holistic: Technique-Human-Organization Method acronyms are explained in Tables 1, 2, 3 and 4				

Due to the large number of developed methods, it is advisable to use specific criteria for their selection. First of all, it is necessary to decide whether the subject of the analysis is a system or an event (e.g. an accident at work). In the case of a system, the system reference model (set of elements - static model or process system - dynamic model) must also be specified.
Then check that: (1) the analytical procedure of the method is systematic and well described to always operate in a similar manner; (2) the description of the method is available and may be in books, scientific articles or on the Internet, (3) the method is fairly easy to understand and use; (4) analysis with this method can be carried out with relatively little effort; (5) the analysis can be performed even if the system (event) information is incomplete, for example, for equipment or an activity that is still in the planning stage - the analysis may then be less accurate, but will still be effective.
Indications for safety improvement measures may or may not be present in the method. But even if the method does not provide for this, there is always a need to develop such recommendations. By design, each specific method will cover only a limited part of the work environment risk panorama. In addition, the methods may have various specific uses, and advantages and disadvantages have been identified.
There are universal methods (any type of system: machine, installation, production process, workstation, etc.) and very specialized methods (for example, only for process installations). The methods presented in Tables 1, 2, 3 and 4 of this study, although they differ in purpose and orientation, can all be considered universal methods,

because since their development numerous examples of their application to various problems have been published. Therefore, in order to conduct a relatively in-depth and complete analysis, it is advisable to use 2-3 methods that will be based on complementary principles.

5. CONCLUSION

A maintenance system should be understood as a diverse set of work processes carried out by people in specific environmental conditions, using specific equipment (Caputo et al., 2013; Stadnicka et al., 2014) and within a specific organizational and management structure.

The traditional maintenance system focuses on technical equipment, while the literature on the subject indicates that it is also important to include humans (Gyekye, 2005; Crespo Márquez et al., 2009; Grabara, 2019).

Maintenance activities are necessary not only to ensure the safety and reliability of technical facilities or the company's productivity. Regular maintenance is crucial to ensuring safer and healthier working conditions, and not only in industry. Lack of maintenance or inadequate maintenance can lead to serious and irreversible consequences in the form of fatal accidents or serious health problems not only for employees, but also in the form of accidents and disasters causing serious material and environmental damage.

At the same time, maintenance processes are related to the activities performed by employees in conditions of exposure to various types of dangers that may lead to negative consequences for their health and even life. Therefore, the management tasks of maintenance systems include providing people working in these systems with an appropriate level of safety through the implementation of properly selected actions and preventive measures.

In order to properly adjust the prevention, it is necessary to correctly identify and characterize the risks in the analyzed system, and this is the purpose of the safety analysis. This goal can be achieved using the methods presented in this paper.

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