International Journal of Occupational Safety and Ergonomics

ISSN: 1080-3548 (Print) 2376-9130 (Online) Journal homepage: https://www.tandfonline.com/loi/tose20

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International Journal of Occupational Safety and Ergonomics (JOSE), 2016
Vol. 22, No. 2, 186–192, http://dx.doi.org/10.1080/10803548.2015.1129154

Analysis of occupational accidents: prevention through the use of additional technical safety measures for machinery

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This article presents an analysis of results of 1035 serious and 341 minor accidents recorded by Poland's National Labour Inspectorate (PIP) in 2005–2011, in view of their prevention by means of additional safety measures applied by machinery users. Since the analysis aimed at formulating principles for the application of technical safety measures, the analysed accidents should bear additional attributes: the type of machine operation, technical safety measures and the type of events causing injuries. The analysis proved that the executed tasks and injury-causing events were closely connected and there was a relation between casualty events and technical safety measures. In the case of tasks consisting of manual feeding and collecting materials, the injuries usually occur because of the rotating motion of tools or crushing due to a closing motion. Numerous accidents also happened in the course of supporting actions, like removing pollutants, correcting material position, cleaning, etc.

Keywords: safety of machinery; occupational accident analysis; technical measures of injury prevention

1. Introduction

The accident database accumulated by the National Labour Inspectorate (PIP) shows that 23–28% of fatal and serious accidents that happened in Poland occurred due to machine operation (over 400 accidents per year, considering the years 2005–2010). Those accidents happened due to machine operation in: manufacturing processes (50% of the registered fatal and serious accidents), machinery cleaning (25% of accidents) and maintenance and repair (25% of accidents). Additionally, minor accidents, which have not been included into the PIP database, happened. Considering the total number of persons injured in industrial accidents (about 8500 persons per year) and assuming that the same fraction of persons was injured due to machine operation as the ratio considered above in view of fatal and serious accidents, one arrives at the number of 19,000–24,000 persons each year. The aforementioned data prove the significance of the problem of guaranteeing safety during machine operation.

The issue of machine operation safety should be taken into consideration by both the manufacturers and users. The manufacturers should reduce the risk of injury from machine operation by means of the following:

- Inherently safe designs
- Safeguarding and complementary protective measures
- Information for use:
  - at the machine (warning signs, signals, warning devices), and;
  - in the manual.

On the other hand, the user should reduce risk of injury by means of the following:

- application of additional (besides those introduced by the designer) technical safety measures;
- application of personal protective equipment;
- safe work procedures;
- training.

Machine manufacturers demonstrate sufficient knowledge of the principles of application of technical safety measures. The analysis presented by Latała [1] showed that the knowledge of users, especially in small and medium-sized enterprises, was rather poor. The accident figures prove that a large percentage of accidents happened because of the lack of guards or protective devices. According to the PIP, 788 accidents happened in 2010 due to technical causes, including over 280 events (36.2%) caused by the lack or improper use of protective devices. Feyer and Williamson,[2] Riihimaki et al. [3] and Pratt et al. [4] obtained similar results. This might result from both neglecting the application of additional safety measures and disassembling guards or protective devices in

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the course of machine operation. In both cases, the events appear as the result of neglecting initial inspection before being put into service for the first time, as well as neglecting periodical inspections. This results from incomplete knowledge of machinery users on the principles and possibilities of application of additional technical safety measures. This article presents the results from analysis of accidents that happened in Poland in 2005–2011, in view of their prevention by means of application of additional safety measures by the users.

2. Materials and methods

In Poland, employers are required to provide the Central Statistical Office with information about all industrial accidents involving injury or death that happened in their enterprises. The information is widely available in the form of statistical data. On the other hand, the PIP accumulates another, much wider database of accidents, which contains accident reports comprising all circumstances of the events, as well as their codes according to the European Statistics on Accidents at Work.[5] The PIP accident database was therefore employed for further considerations.

2.1. Selection of accidents to be analysed

The database of accidents made available by the PIP contains information about accidents that happened in the processing industry in 2005–2011. The database comprises over 5500 records (998 accidents in 2005, 1026 in 2006, 1067 in 2007, 1061 in 2008, 828 in 2009, 317 in 2010 and 200 in 2011). The numbers of accidents in 2010 and 2011 are lower, because the principles of collecting information have changed and only information on serious and fatal accidents that happened in those years was included.

The database employs the accident model developed by the European Union Statistical Office (EUROSTAT) within the project European Statistics on Accidents at Work (ESAW).[5] The database also contains descriptions of accidents. The considered PIP database contains all kinds of accidents that happen in processing industry; however, only those connected with machine operation were to be analysed. Therefore, it was necessary to preselect accidents in order to identify the applicable ones, which was done using two criteria according to the ESAW classification.

Table 1. Accident selection criterion according to the working process.

Working process	Code
Manufacturing, processing	11
Preparation, installation, assembly, disassembly, dismantling, etc.	51
Maintenance, repair, adjustment, etc.	52
Cleaning, cleaning up – by machine or manually	53

Table 2. Accident selection criterion according to the work performed.

Work performed by the injured person at the accident instant (within the group of machine operation)	Code
Starting/stopping of machinery	11
Feeding up/collecting of materials, semi-finished products, products, etc.	12
Supervising and other operations connected with the work and translation of the machine	13
Other, not mentioned or known actions within the group	14

The accident criteria are listed in Tables 1 and 2, and Table 3 presents a list of all accidents selected from the PIP database using these criteria while Tables 4 and 5 present serious and minor ones. In 2010 and 2011 only the information on fatal and serious accidents was provided, which is why the figures for those years differ substantially from the other years and there are no data for them presented in Table 5.

The data presented in Tables 3–5 prove that the numbers of fatal and serious accidents selected for further analysis were much higher than the figures for minor accidents. This indicates that the consequences of accidents due to machine operation are usually more serious than those resulting from other industrial accidents.

Table 3. General accidents selected for analysis.

	Working process					
Year	11	51	52	53	Total number of accidents selected	% of all accidents recorded
2005	306	20	29	7	362	36.27
2006	294	5	25	11	335	32.65
2007	343	10	19	6	378	35.42
2008	292	5	17	9	323	30.44
2009	220	1	10	3	234	28.26
2010	134	1	3	2	140	41.54
2011	138	2	2	2	144	49.28
Total	1727	44	105	40	1916	34.64

Table 4. Serious accidents selected for further analysis.

Year	Working process 11	51	52	53	Total number of accidents selected	% of all accidents recorded
2005	208	15	21	5	249	42.27
2006	198	5	17	9	229	39.01
2007	228	9	16	5	258	39.38
2008	210	2	13	5	230	31.20
2009	129	0	4	2	135	26.41
2010	134	1	3	2	140	41.54
2011	138	2	2	2	144	49.28
Total	1245	34	76	30	1385	38.64

Table 5. Minor accidents selected for further analysis.

Year	Working process 11	51	52	53	Total number of accidents selected	% of all accidents recorded
2005	98	5	8	2	113	27.62
2006	96	0	8	2	106	24.14
2007	115	1	3	1	120	29.12
2008	82	3	4	4	93	28.70
2009	91	1	6	1	99	31.23
Total	482	10	29	10	531	38.64

Since the analysis aimed at formulating principles for the application of technical safety measures in machinery, it was decided that the accidents would bear the following three types of additional attributes:

1. Type of machine operation
   M11 – normal operation of an automatic cycle machine (automatic feeding of material/semi-finished products, processing in continuous or automatically initiated working motion, automatic product collection);
   M12 – normal operation of a semi-automatic cycle machine (manual material/semi-finished products feeding or collection, processing in continuous or automatically initiated working motion);
   M13 – normal operation of a manual operation cycle machine (manual material/semi-finished products feeding and collection, manual initiation of working cycle);
   M2 – supporting actions performed in the course of normal machine work (e.g., waste disposal, lubrication, cleaning etc.);
   M3 – adjustment actions during which the machine motion is necessary;
   M8 – other than given above; and
   M9 – no data available.
2. Technical safety measures, which could prevent the accident
   E1 – fixed guard;
   E2 – mobile guard;
   E3 – two-hand control device;
   E4 – pressure-sensitive device;
   E5 – light curtain or beam;
   E6 – laser scanner;
   E7 – supportive tool;
   E8 – other technical measure; and
   E9 – technical measures are not enough.
3. Type of event causing injuries
   Z1 – injury due to contact with a rotating element;
   Z2 – injury due to contact with a sharp element;
   Z3 – crushing by a closing motion;
   Z4 – cutting by a closing motion;
   Z5 – hitting by a moving element;
   Z6 – grasping by a moving element; and
   Z9 – other events.

These attributes were assigned to particular accidents based on their descriptions. If it was impossible to define the applicability of technical safety measures, the accident was withdrawn from the analysis.

2.2. *Methods*

Accident analysis usually focuses on proper identification of the most important phenomena that emerge in the course of an accident. The analysed accident models differ in both their level of detail and their scope of applicability. More general models enable a rough analysis of the phenomena only.

The STEP model presented by Heinrich [6] is the simplest example. Since the accident is represented as a series of consecutive events, it is a sequential model. Various, more detailed models (see [7]) have been based on that model. A basic drawback of the sequential models consists of the fact that they only allow one to analyse phenomena that emerge directly in the course of the accident, neglecting the indication of accident causes which, by their nature, must have emerged earlier. These causes had exerted their influence before the accident happened, thereby making it possible for the phenomena to follow. Since, first of all, the mistakes made by designers of machines and workstations are to be analysed, the sequential model is not suitable for our purposes.

A relatively large group of accident models comprises those based on the analysis of human behaviour under stress. The model of social environment effect on safety at work developed by Studenski or the Smille model (see [8]) can be referred to, as well as the Glendon and Hale model of human behaviour in danger (see [9]) and many others. In view of our needs, however, the level of technical factor effect introduced into those models is not satisfactory and, additionally, they are not detailed enough to be applied to the analysis of accidents caused by improper performance of safety functions.

Many other models have also been proposed in the literature. Until now, researchers investigating the influence that the malfunctions of the control system exert on the course of accidents have concentrated on complex systems; such as chemical processes, nuclear power plants or aeronautical systems. Toola [9] used fault tree analysis in studying the causes of potential accidents and in the examination of control actions suitable for providing protection against them, thereby reducing the probability of accidents in the process industry. Kim et al. [10] proposed a similarly complicated systematic approach to the diagnostic situation in the accident scenario in nuclear power plants. Basso et al. [11] used performance indicators as a tool for investigating accidents. Basnyat et al. [12] developed a task modelling system using the Petri-nets approach to safety investigations of computer-controlled processing. This approach was demonstrated on a fatal mining accident case study. Dźwiarek [13] proposed a model of accidents caused by the malfunction of machine control systems.

In our investigations, an accident model based on that of EUROSTAT was used. The ESAW Phase III model, developed by EUROSTAT, includes three distinctive levels or sequences:

- The circumstances just before the accident.
- The Deviation, last ‘deviant event from normality’ leading to the accident, occurring in the framework of circumstances related at the previous level.
- The Contact – Mode of Injury, which is the action that actually causes the injury as a consequence of the Deviation related at the previous level.

In the before-accident phase we deal with an employee in a working environment. The working environment means not only the place where the injured person was at the moment of the accident, but also all elements associated with their work, i.e., the action performed by the injured person and a material factor connected with it.

The Contact phase is separated from the before-accident one by the event, which represents a kind of deviation from the normal state (called Deviation). It is the last event being in opposition with the circumstances assumed as normal, which disturbs the normal course of the working process and causes the accident. Usually, a material factor is associated with the deviation. Therefore, it is the factor (tool, machine, environment element, including living organisms, etc.) that caused the disturbance (deviation) in the working process or was closely connected with the disturbance. We aimed at finding the extent to which the application of additional safety measures could prevent accidents from happening; therefore, our analyses focused on that phase of the accident.

The Contact phase comprises the event causing the injury and a material factor which is the source of the injury. It is worthwhile to pay attention to the relation between the deviation and the injury-causing event, since the injury-causing event always appears as a result of the deviation.

In general, the after-accident phase comprises the results of the accident. The basic accident classification in view of the results consists of distinguishing three types of them: minor, serious and fatal. Additionally, the model includes two other variables representing the results, i.e., the type and place of the injury. The injury type defines the accident consequences to the injured person (e.g., bone fracture, wound, burn). Together with the injury type, one should specify which part of the body suffered injury as a result of the accident.

The analysis was focused on the identification of characteristic features displayed by those accidents which could have been prevented using technical safety measures. The software package comprises the programming language, statistical calculation environment and result visualisation tools. It is available as a free software license. The R v. 2.13.0 [14] is used in a wide variety of research within different fields of science (e.g., biology, medicine, psychology, sociology, economy). The package provides many statistical (linear and non-linear modelling, standard statistical tests, time series analysis, classification, grouping) and graphical techniques. The R package can be extended using both additional packages and manuals written by the user. The afore-mentioned features justified the decision behind selecting the package for carrying out the analysis.

3. Results and discussion

Tables 6–9 show the numbers of accidents bearing the attributes M, E and Z. Particular lines cannot be summed

Table 6. Accidents identified for particular actions performed.

	Type of machine operation						
	M1			M2	M3	M8	M9
Consequences	M11	M12	M13				
Serious	38	82	618	201	59	37	9
Minor	14	41	210	52	8	11	5

Table 7. Accidents according to the corresponding technical safety measures.

	Technical safety measure								
Consequences	E1	E2	E3	E4	E5	E6	E7	E8	E9
Serious	458	567	153	50	214	48	424	176	14
Minor	190	165	41	9	67	20	145	82	3

Table 8. Accidents according to the type of harm-causing event.

	Type of harm-causing event						
Consequences	Z1	Z2	Z3	Z4	Z5	Z6	Z9
Serious	233	92	241	71	63	288	50
Minor	65	42	69	10	42	85	29

up, because in many cases different technical safety measures can be alternatively applied to prevent the accident (e.g., a fixed guard or a mobile guard with an interlock).

Tables 6–8 show that the most effective accident prevention can be achieved by applying additional safety measures during normal manual operation (M13) and supporting actions made when the machine is activated (M2). On the other hand, the most frequent events were injury due to contact with a moving element (Z1), crushing due to a closing motion (Z3) and trapping by a moving element (Z6). Therefore, analysis of the correlation between the executed tasks and the type of event appearing in the course of accident was carried out. We assume that the executed task is the explanatory variable while the event is the explained variable. Table 9 presents a list of tasks and events for serious accidents.

The initial hypothesis was represented by the following statement: 'There is no relation between the executed task and the cause of injury'.

Since for some events and executed tasks an expected number of accidents was < 5, the Yates correction was applied to the χ^2 test. In that case, the value of the χ^2 test was 183.988, while $p < 2.2 \times 10^{-16}$, therefore rejecting the initial hypothesis is justified. Thus, an alternative hypothesis that the executed task and the event causing the injury are closely connected is confirmed, which can be clearly seen when comparing Table 9.

Similar conclusions can be drawn from the analysis of minor accidents presented in Table 10. Similar to the serious accidents (Table 9), in the case of minor accidents (Table 10) the Yates correction was applied to the χ^2 test. In this case, the value of the χ^2 test was 106, while $p < 8.10 \times 10^{-9}$, therefore it is justified to reject the initial hypothesis and assume an alternative one – there is a relation between the executed task and the casualty event.

On account of the above, a correlation analysis was carried out between the technical safety measure attribute and the type of event. To simplify the calculation, we focused on the most frequent events, which according to Table 8 were Z1, Z3 and Z6, as well as on the most prevalent technical safety measure attributes, i.e., fixed guard, moving guard, light curtain and beam. Tables 11–13 show a close connection between the type of event and the kind of technical safety measure that stops it from happening.

For Table 9, $\chi^2 = 91.5$; $p = 1.40 \times 10^{-20}$. There is therefore a relation between the casualty event and the technical safety measure attribute.

For Table 10, $\chi^2 = 126.4$; $p = 3.60 \times 10^{-28}$. There is therefore a relation between the casualty event and the technical safety measure attribute.

For Table 11, $\chi^2 = 141.2$; $p = 2.2 \times 10^{-31}$. There is therefore a relation between the casualty event and the technical safety measure attribute.

Table 9. Table of contingency (the elements represent the number of serious accidents that happened during particular tasks of the accident event).

	Type of harm-causing event							
Executed task	Z1	Z2	Z3	Z4	Z5	Z6	Z9	Total for tasks
M11	3	1	8	0	2	17	7	14
M12	8	1	18	7	5	40	3	41
M13	186	74	149	51	35	103	20	213
M2	28	13	45	8	9	90	8	51
M3	6	2	12	2	6	22	9	8
M8	1	2	8	2	5	14	4	12
M9	0	0	4	1	0	3	1	6
Total for events	232	93	244	71	62	289	52	345

Table 10. Table of contingency (the elements represent the number of minor accidents that happened during particular tasks and the type of injury-causing event).

	Event							
Executed task	Z1	Z2	Z3	Z4	Z5	Z6	Z9	Total for tasks
M11	1	2	1	0	3	5	2	14
M12	3	4	4	0	3	25	2	41
M13	57	29	45	6	32	26	18	213
M2	3	6	11	4	2	23	2	51
M3	0	1	3	0	1	1	2	8
M8	1	0	1	0	2	4	4	12
M9	0	0	4	0	1	1	0	6
Total for events	65	42	69	10	44	85	30	345

Table 11. Table of contingency for a fixed guard (the elements represent the number of accidents bearing a particular casualty event attribute for the fixed guard being attributed or not, respectively).

	Type of harm–causing event			
Contingency	Z1	Z3	Z6	Total
Attributed	83	193	162	438
Not attributed	149	51	127	327
Total	232	244	289	765

Table 12. Table of contingency for a moving guard (the elements represent the number of accidents bearing a particular casualty event attribute for the moving guard being attributed or not, respectively).

	Event			
Contingency	Z1	Z3	Z6	Total
Attributed	49	175	117	341
Not attributed	183	69	172	424
Total	232	244	289	765

Table 13. Table of contingency for a light curtain or beam (the elements represent the number of accidents bearing a particular casualty event attribute for a light curtain or beam being attributed or not, respectively).

	Event			
Contingency	Z1	Z3	Z6	Total
Attributed	223	130	246	599
Not attributed	9	114	43	166
Total	232	244	289	765

This analysis indicates that the tasks of manual feeding and collecting material pose the most serious problems. In such cases, injuries are usually caused by the rotating motion of tools or a closing motion. A large number of accidents also happened in the case of supporting actions, such as removing small pollutants, correcting a material position, cleaning, etc., which were made in the vicinity of the activated automatic machine. In such a case, the operator is usually trapped by rotating cylinders.

4. Conclusions

The analysis of industrial accidents carried out in the previous section showed that the basic cause of accidents consisted of high risk of injury due to mechanical hazards. Among the hazards that were most often followed by accidents, one should mention the following:

- injuries by rotating working elements of the machine,
- trapping by rotating working elements of the machine,
- crushing by working elements of a machine that are getting closer to each other, and
- hitting or grasping by moving transmission parts.

The following two basic circumstances should be singled out in view of executed tasks and the area where the accident happened:

- The motion of a tool and other elements – the necessity to have access to the dangerous zone results from the way of feeding the material and collecting it after processing, as well as from the fact that wastes should be removed, and the tool should be changed, cleaned, adjusted, maintained, repaired, etc.
- Access to the zone of moving transmission parts – in the zone the source of hazard consists of the motion of transmission parts, and the necessity to obtain access results from the execution of cleaning, maintenance and repair tasks.

The access to the working zone may arise either frequently (over 10 times per hour) or with a medium frequency (2–10 times per hour) or seldom (once per hour at the most). The access to the working zone of moving transmission parts may arise either very seldom (once per month), or seldom or at most at medium frequency.

In the case of mechanical hazards, the safety of machine operation is based on the application of safety measures preventing or effectively reducing the possibility of accessing the dangerous zone; additionally, safety measures based on control methods and the use of protective devices can be applied.

For the machines in use, under circumstances indicating high risk due to mechanical hazards (e.g., an accident happened or a near miss) the employer is obliged to apply additional safety measures. The application of additional safety measures should follow the analysis of a series of aspects connected with the machine and the capabilities provided by the available advanced designs.

Although the presented study has been made in Poland, the analyses conducted in Germany,[15] France [16] and the USA [4] indicated that the above conclusion can also be applied in other countries.

Acknowledgements

This article was prepared based on the research task carried out for Poland's Zakład Ubezpieczeń Społecznych [Social Insurance Institution] under contract No. 6483/0/992000/1/2012.

Disclosure statement

No potential conflict of interest was reported by the authors.

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