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INVESTIGATION OF THE INDUSTRIAL INJURIES STATE AT THE MACHINE-BUILDING ENTERPRISES OF THE WESTERN REGION OF UKRAINE

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Abstract. The article describes the prerequisites for creating an automated system for planning measures to prevent occupational injuries at machine-building enterprises. The results of a study of occupational injuries based on statistical data depending on the employee's experience, gender, working conditions, days of the week and month are given for the leading machine-building enterprises. The research of the influence of technical and economic indices of machine-building enterprises of the Western region of Ukraine on industrial injuries is described. It has been established that out of all significant technical and economic indicators of machine-building enterprises, only 3 factors significantly impact the level of occupational injuries: stock armament, energy armament, and occupational health and safety costs. The practical value of research results is to adjust plans to prevent injuries, taking into account situations with the highest probability of employee emergencies. Further research will develop and implement an automated system for planning injuries at the machine-building enterprise.

Keywords: frequency and severity ratios of occupational injuries, occupational health and safety, occupational injuries, queuing theory.

Introduction and Problem Statement

The introduction of a comprehensive automated planning system for occupational injuries prevention in machine-building enterprises directly relates to the development of qualitatively new methods of evaluation and planning based on the principles of system analysis and synthesis, mathematical modelling, multicriteria optimization and prediction of production processes. The development of such a system puts the task of further improvement of not only the system for assessing the traumatic security unit of the machine-building enterprise but also an optimization system for the synthesis of such measures, which would allow obtaining the maximum effect of reducing the level of injuries at the slightest economic costs [1–4].

The following factors should be taken into account for the creation of such a system:

1. The need for significant investment due to the high cost of expenses for measures related to the prevention of occupational injuries. This imposes special responsibility in choosing technical, organizational, sanitary and hygienic decisions.

2. The complexity of mathematical modelling of statistical flows of injuries and formalized communications with measures to reduce traumatic industrial safety and, as a result, unjustifiedly significant expenses as a result of admitted errors during the planning process.

3. Multi variation of alternative decisions of the organizational and technical structure of the plan for the occupational injuries protection and search for an optimal option for the needs of a particular machine-building enterprise.

Analysis of well-known methods of planning a system of measures to prevent production injuries described in literary sources [2, 5–9] showed that, firstly, these tasks are solved, as a rule, without proper integrated analysis of design decisions; secondly, there is no systemic relationship and unity in solving problems of analysis of traumatic safety departments and the synthesis of measures to reduce it; thirdly, in solving such tasks is ignored by an economic factor (labour protection costs, the change in the productivity of technological equipment and the cost of essential products). It is unacceptable in a modern market economy. As a result of these disadvantages of well-known planning methods, we can conclude the necessity and importance of developing a fundamentally new method, which would allow a systematic analysis of statistical flows of traumatic safety and system synthesis of a plan of measures to reduce it. At the same time, structural and functional relations of labour protection measures based on the unification of alternative decisions at all phases of planning should be established and investigated.

To create an automated design system for occupational injuries prevention planning, first of all it is necessary to create a database that can adequately characterize the state of the labor protection system at the manufacturing unit of the machine-building enterprise taking into account the actual conditions of operation of equipment, technical and meteorological conditions of work and qualifications of the main and auxiliary personnel, etc.

To achieve this goal, a comprehensive analysis of the causes and effects of occupational injuries in machine-building enterprises of the Western region of Ukraine should be carried out, to investigate the influence of critical factors (age, gender, time of year, etc.) on the probability of accidents. The obtained dependencies should be summarised and calculate the multifactorial regression equations of traumatic safety for operational analysis of the emergence of a dangerous situation in any manufacturing unit of the machine-building enterprise.

Main Material Presentation

Investigation of the state of industrial injuries based on statistical data

Verification of the reliability of the mean values of the frequency and severity ratios of occupational injuries was carried out by constructing a univariate series of distribution according to the root mean square deviation [10, 11]:

$$\sigma = \sqrt{\frac{\sum X_i^2}{n} - \overline{X^2}}\ , \tag{1}$$

where X_i is the value of the characteristics; $\overline{X}$ is the arithmetic mean values of the attributes; n is the number of elements.

The value of the interval of the studied parameters is taken from the condition of detecting the main feature of distribution and smoothing of random deviations. The end of the last interval is taken equal to ($\overline{X} + 3\sigma$), the beginning of the first interval is the ($\overline{X} - 3\sigma$). This construction of a number of distribution allows detecting and removing the values that vary sharply from the average values of the frequency and the severity of injuries coefficients and removing random disability data that distort statistical characteristics.

Percentage polygons of the distribution of injury frequency (K_f) and severity (K_s) rates at these enterprises are shown in Fig. 1. and 2. Distribution intervals from the mean are within three standard deviations. The difference in magnitude s is slight. Modal, the highest value of the frequency ratio M_{of}=8.13 is close to the mean value K_f=8.97. The average value is reliable.

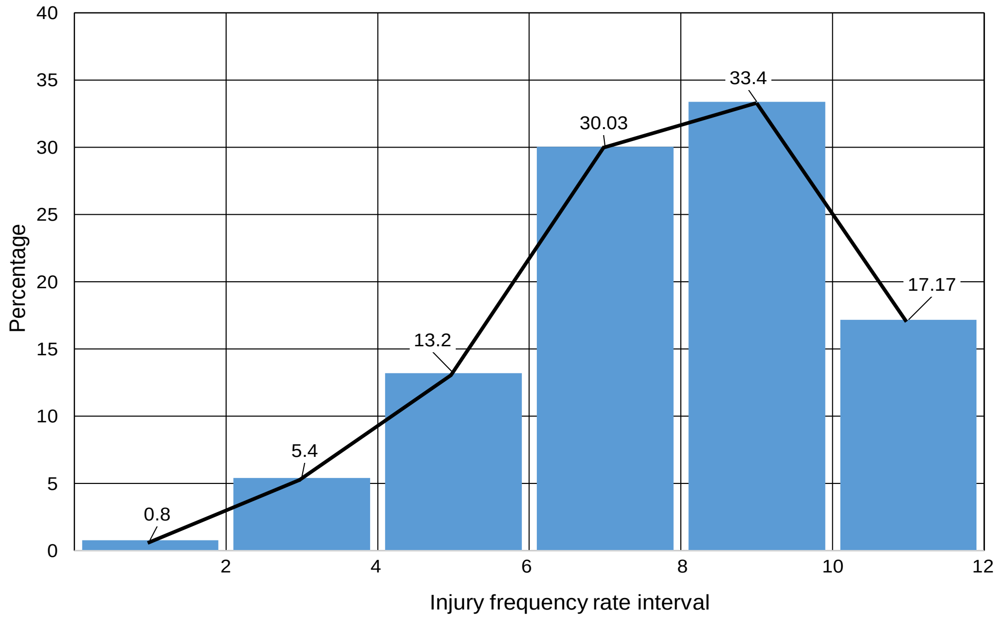

Fig. 1. Percentage polygons of the distribution of injury frequency rate

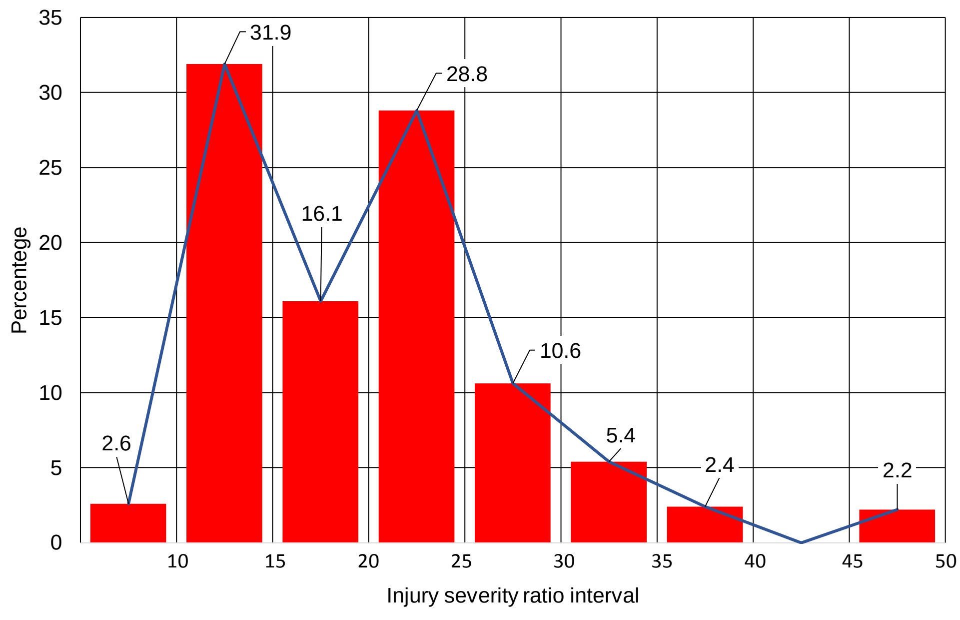

Fig. 2. Percentage polygons of the distribution of injury severity rate

To determine the distribution of accidents by gender, the work experience and age of injured are given data on cases in the last 10 years. In total, 391 cases of occupational injuries were investigated. In calculating the average values of the severity coefficient, verification of their reliability is guided by data on the days of disability. Fig. 3., Fig. 4 presents the distribution of industrial injuries in work experience and age of injured (men and women). In these figures, graphical dependencies of the severity coefficients are shown, taking into account all cases of injuries, as well as average reliable values ($\overline{K_s}$), are set taking into account cases within deviations from the average $f_{\max} = \overline{X} + 3\sigma$ and $f_{\min} = \overline{X} - 3\sigma$ where $\overline{X} = \overline{K_s}$

Fig. 3. Dependences ratios of injuries frequency and severity from the experience of workers in the machine-building enterprise

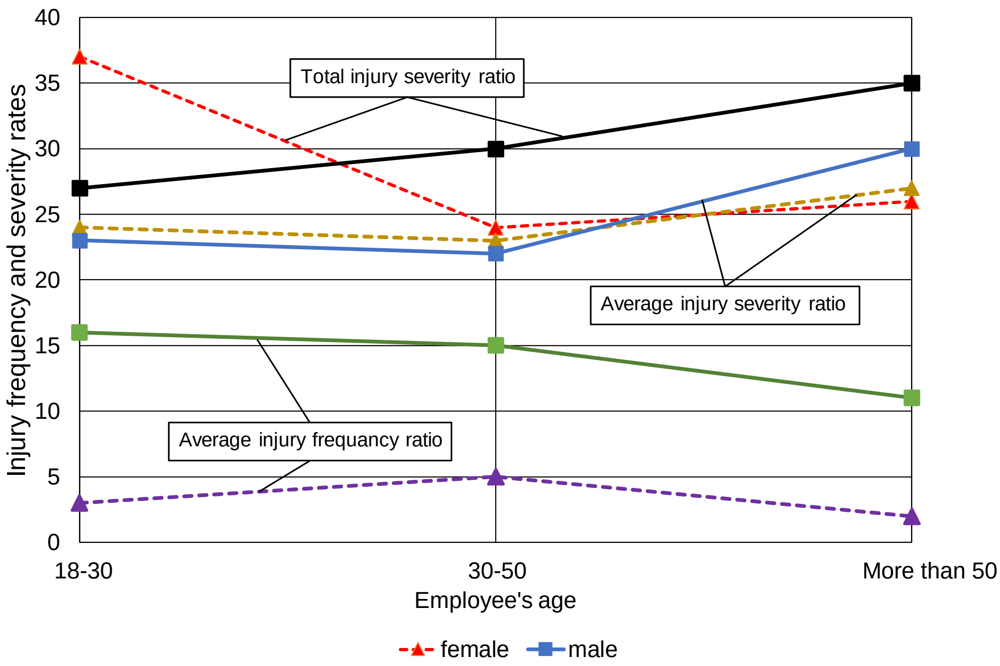

Fig. 4. Dependences of injuries frequency and severity ratios from the age of workers in the machine-building enterprise

Based on the analysis of the above statistical data, we can conclude that the coefficient of severity (K_s) of occupational injuries at a machine-building enterprise is higher for women than for men between the ages of 18 and 30 and is 36.82 for women, while for men it is only 27, 0. At the same time, the most significant difference in women between the real severity rate K_s and their average value $\overline{K_s}$ is 33 % (K_s = 36.82 and $\overline{K_s}$ = 24.14). As the wounded age, the situation is reversed. At the age of workers over

50, the severity coefficient is significantly higher than for women and reaches values: for men $\overline{K_s}$ = 37.78 and only $\overline{K_s}$ =29.17 for women. Studies have shown that work experience has no significant impact on reducing the injury rate at a machine-building enterprise. This indicator reaches its highest values during experience employment up to 1 year 31.92 for men and 41.7 for women.

Accidents with loss of working capacity from 60 to 150 days (~ 8.7 %) were excluded from data while calculating the average values of severity ratio, considering all injured men and women (Fig. 5), since such cases were beyond three mean square deviations. The most significant number of accidents occurs with loss of working capacity in the range of 2 to 22 days and reaches 47 % for men and 41.5 % for women. More severe injury with performance loss for a higher term is observed more often for men (Fig. 5). The increased level of injuries among men is due to their work's higher complexity and labour intensity than women.

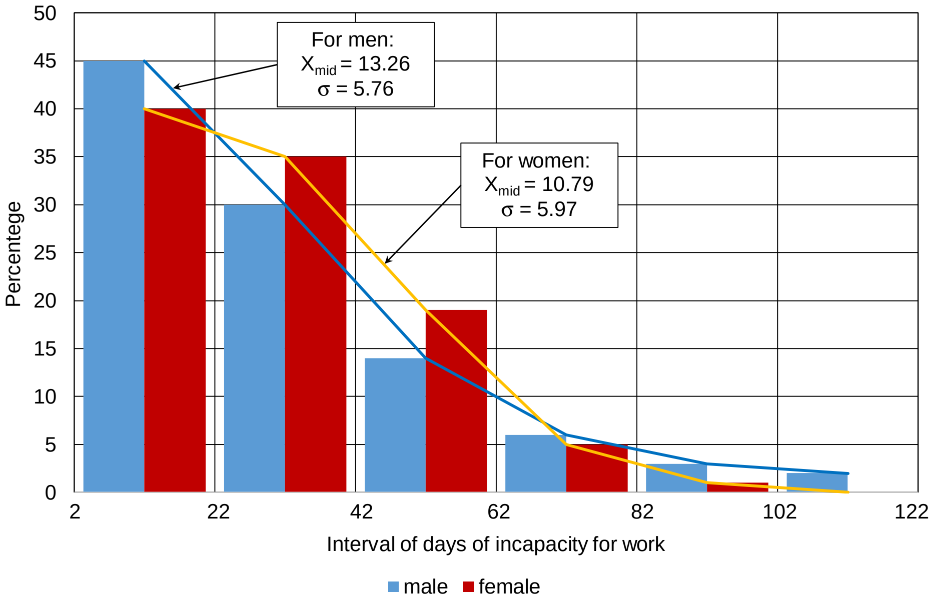

Fig. 5. Polygon of distribution of the number of days of traumatic disability by gender

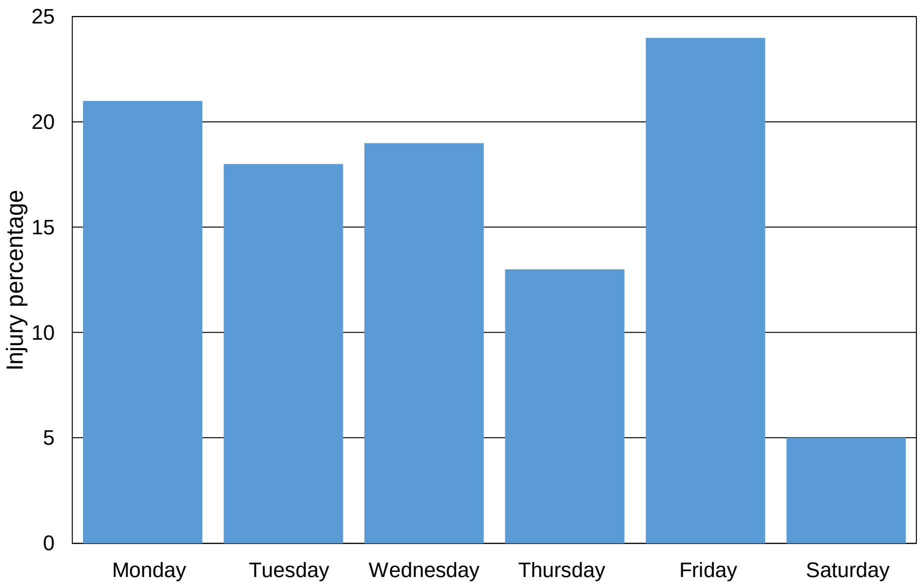

Fig. 6. Statistical distribution of accidents by working days of the week

Further studies have shown that a significant impact on injuries of machine-building enterprises has months of the year and days of the week. The increased number of accidents in January, February, and March explained by meteorological conditions for October accounts for increased intensity of workers' production and household work, leading to significant fatigue and inattention (Fig. 6, 7). The distribution of injuries by day of the week showed that most cases fall on Monday and Friday. In the third week of the month, the incidence of injuries increases significantly. It indicates the existence of nonrhyththes of enterprises. The distribution of accidents by damaged parts of the human body is shown in Fig. 8.

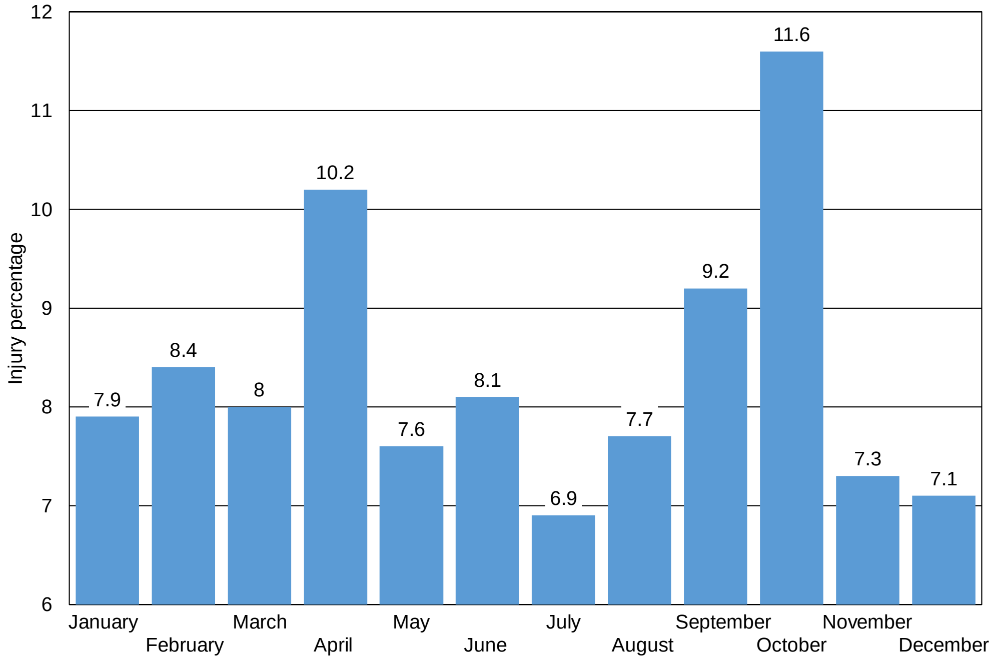

Fig. 7. Distribution of industrial injuries cases in machine-building enterprises by months of the year

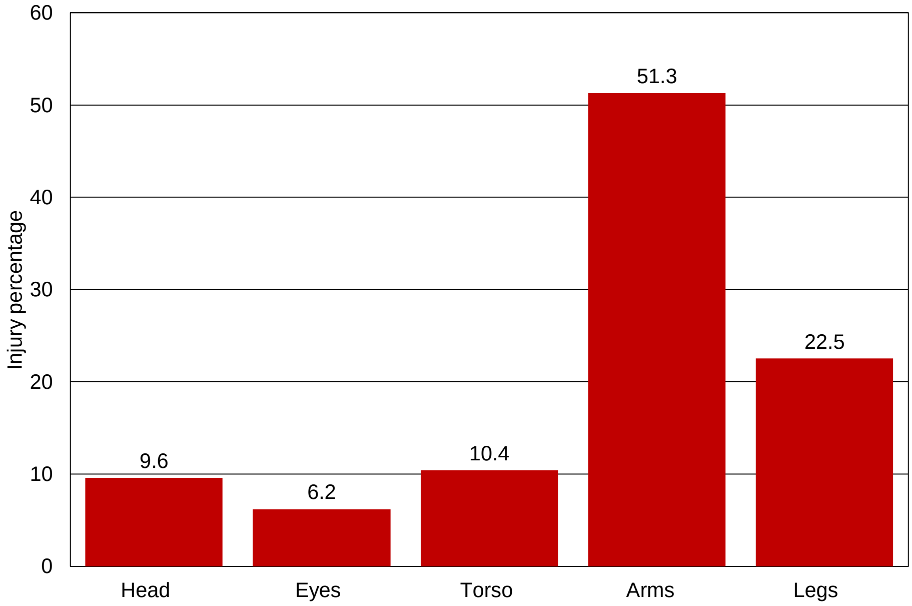

Fig. 8. Diagram of the distribution of traumatic cases by anthropometric features

The leading causes of injuries are detected, and the classification of occupational injuries (Table 1, Table 2) is revealed. The most dangerous professions in the mechanical workshop of the machine-building enterprise is mechanical and assembly work (9.8 % of the total number of injured), stamper (6.5%), electric welders (6.4 %), a turner (4.7 %) and metalsmith (4.5 %).

Table 1

Distribution of accidents by primary reasons

The name of the reasons	Statistic percentage
Technical and technological	
Constructive disadvantages of equipment	2,5
The imperfection of the technological process	16,4
Organizational	
Use of faulty machines and mechanisms	7,3
Conscious violation of the technological process by the worker	7,6
Lack of fencing of hazardous zones	1,9
Violation of operating rules of vehicles	2,6
Lack of means of mechanization and automation of the technological process	4,3
Violation of road traffic rules by shopping vehicles	1,1
Unsatisfactory organization of production	6,0
Unsatisfactory maintenance and organization of jobs	11,6
Unsatisfactory state of buildings and structures	6,0
Disadvantages in teaching safe labour techniques	7,0
Non-use of personal protective equipment	2,8
Violation of labour discipline	11,1
The use of workers not by occupation	0,9
Alcohol intoxication	1,5
Work without instructing	6,2
Insufficient supervision by the head of the unit	1,7
Others	1,4

Table 2

Distribution of accidents by types of events

Type of event	Statistic percentage
Falling objects	33,8
Shock action of moving and rotating parts of equipment	30,2
Man falling from a dangerous height	15,3
Affecting action from flying parts of tools, etc.	6,5
Road accident	5,3
The action of extreme temperature	2,0
Electric shock	0,6
The action of harmful or hazardous substances	0,5
Others	2,2

The verification sequence is as follows:

1. According to the Sturges’ rule, the number of intervals K to quantify a random flow of injury [10–12] is determined:

$$K = 1 + 3{,}3 \cdot \lg M \, , \qquad (2)$$

where M is the total number of cases of occupational injuries in the past 10 years at the mechanical engineering enterprise.

2. Optimum quantization interval Δ of random size t_w is calculated as:

$$\Delta = \frac{t_{w\max} - t_{w\min}}{K}, \quad (3)$$

where $t_{w\ max}$, $t_{w\ min}$ is the maximum and minimum duration with the disabling the worker as a result of occupational injuries.

3. The average value of technological equipment downtime as a result of injuries is determined by the equation [1]:

$$\overline{t_w} = \frac{\sum_{k=1}^{K}\left(t_{wm} \cdot \alpha_{mk} \cdot n_k\right)}{M}, \quad (4)$$

where t_{wm} is the duration of disability of the worker as a result of m-th case of occupational injuries; n_k is the number of accidents of defined degree of severity, combined in one interval $\Delta_k; \alpha_{mk} = 1$; if the m-th accident while working can be attributed to the k-th interval of quantization; $\alpha_{mk} = 0$, in return.

4. Selective dispersion is calculated by the equation [11]:

$$S = \sqrt{\frac{1}{n-1} \cdot \sum_{k=1}^{K}\left(t_{wm} - \overline{t_w}\right)^2}. \quad (5)$$

5. Probability of accidental value of injury duration r times in the k-th quantization interval [13]:

$$\mathrm{P_M(l)} = \frac{\mathrm{a^r}}{\mathrm{r!}} \cdot \mathrm{e^{-a}}, \quad (6)$$

where a is the average incidence of accidental t_{mn} value in the k-th range:

$$a = \frac{\sum_{k=1}^{K}(n_k \cdot r_k)}{\sum_{k=1}^{K}(n_k)}, \quad (7)$$

$$r_k = k - 1. \quad (8)$$

6. The theoretical number of accidents when $t_{нm}$-th value was included into some interval k:

$$n_k^* = P_k \cdot \sum_{k=1}^{K} n_k, \quad (9)$$

where P_k is the probability of causing a random value in the interval k, this value is calculated by the equation (6).

7. Calculation χ^2 – Criteria:

$$\chi_w^2 = \sum_{k=1}^{K}\left(\frac{\left(n_k - n_k^*\right)^2}{n_k^*}\right). \quad (10)$$

8. By calculating the value and selecting the level of significance α= 0.05 [10, 14], we can find the critical value of Pearson's criterion $\chi_k{}^2$ If $\chi_w{}^2 \le \chi_k{}^2$, then the hypothesis about the exposer nature of the distribution of random values of the duration of disability due to industrial injuries is faithful.

Based on the research results in 10 years of work of leading machine-building enterprises of the Western region of Ukraine, the following allocation of disability due to occupational injuries (Table 3) was obtained.

Table 3

Results of calculation of injuries statistical flows

Interval of disability days		$\overline{t_{wk}}$	n_k	r_k	$n_k \cdot r_k$	$P_M(r)$	n_k^*
from	to						
2	22	12	169	0	0	0,4	156
23	42	32	128	1	128	0,361	142,4
43	62	52	65	2	130	0,165	64,8
63	82	72	21	3	63	0,05	19,6
83	102	92	5	4	20	0,011	4,5
103	122	112	1 } 8	5	5	0,002	0,8 } 5,6
123	142	132	2	6	12	0,0001	0,3
total			**391**		**358**		

For the preliminary confirmation of the adoption of the hypothesis of the Poissonian nature of the distribution of the duration of disability, the average values of technological equipment downtime (4) and selective dispersion (5) are calculated:

$$\overline{t_w} = \frac{12 \cdot 169 + 32 \cdot 128 + ... + 132 \cdot 2}{391} = 30,3;$$

$$S = \sqrt{\frac{1}{391-1}\left((30,3-12)^2 + (30,3-32)^2 + ... + (30,3-132)^2\right)} = 23,3.$$

Since S given access are not significantly different, we can pre-accept the hypothesis as a basis and align empirical distribution. The results of the calculation are given in Table. 4. The value of $P_M(r)$ is determined by the equation (6). Based on a built landfill of empirical distribution, we calculated the theoretical and empirical frequencies of the accidents distribution (Table 4). Comparing calculated indicators with statistical results (Fig. 5), we use Pearson's coordination criterion χ^2.

Table 4

Results of Pearson's criterion calculation

Empirical frequencies n_k	Theoretical frequencies n_k^*	$\left\|n_k - n_k^*\right\|$	$\left\|n_k - n_k^*\right\|_2$	χ^2
169	156	13	169	1,08
128	142,4	14,4	207,4	1,45
65	64,8	0,2	0,04	0,006
21	19,6	2,4	5,8	0,3
5 1 } 8 2	4,5 0,8 } 5,6 0,3	2,4	5,76	1,02
Total				**3,86**

The number of degrees of freedom *t* = 5-1 = 4. Choosing the level of significance α = 0.05, we can find the critical value of the Pearson's criterion $\chi_k^2 = 9,5$. Since χ_w^2 =3.86 < χ_k^2 =9.5, then the hypothesis about the expositional nature of the distribution of random values of the duration of disability due to occupational injuries is faithful.

It should be noted that the tests of this hypothesis were repeatedly carried out in the works [8], and in all described in these literary sources of cases, a positive result was obtained. In all investigated organizational management systems, the duration of disability due to occupational injuries is allocated by the exporting law at the level of significance 0.01-0.05 with different parameter values μ, which depends on a specific production.

The studies were conducted based on a regression analysis of statistical data brought to section 2 given article. A complete regression analysis of data was guided by Ferster's functional analysis [10]. The calculations were conducted on the MathCAD. The influence of 8 leading technical and economic indicators was determined: stock armament, energy armament, level of mechanization, production cost, labour protection costs, profitability, productivity, level of stock recovery on the indicator of the frequency of injuries at the machine-building enterprise.

The generalized Kolmogorov criterion [11] was used to test the hypothesis that the distribution of the values of technical and economic indicators is consistent with the customary distribution law:

$$\lambda = \frac{\left| m_{\Sigma} - m_{\Sigma}^{T} \right|_{\max}}{N} \cdot \sqrt{N} , \tag{12}$$

where $m_{\sum}$ is the empirical incidence of injuries; $m_{\sum}^{T}$ is the accumulated theoretical incidence of injuries; *N* is the volume of statistical representative votes for the values of technical and economic indicators of machine-building production for *m* years retrospective

Theoretical frequencies of cases of injuries m^T were determined by the normalized Laplace function Z (T) with the argument T [10]:

$$t = \frac{x_i - \overline{x}}{S} , \tag{13}$$

where $x_i, \overline{x}$ is the current and average values of the random technical and economic indicators, respectively; *S* is the average quadratic deviation.

Theoretical frequencies were determined by the equation [11,12]:

$$m^{T} = z_t \cdot \left(\frac{x_i - \overline{x}}{S} \right) \cdot \frac{N \cdot \Delta}{S} , \tag{14}$$

where Δ is the width of the random variable interval;

$$\Delta = \frac{R}{K} = \frac{x_{\max} - x_{\min}}{K} , \tag{15}$$

where *K* is the number of quantization intervals (2).

We calculate P(l) based on determining the value of the coefficient l according to the probability table [17]. If the value P(l)>0.05 is obtained due to calculations, then the hypothesis of the customary law of distribution of random variables is faithful. Dependent value - frequency of occupational injuries ratio K_f we designate as *Y* and essential technical and economic characteristics as $X_k, (k = \overline{1, m})$. Since random and secondary factors can not be excluded from experimental data at the initial analysis stage, the dependence acquires a stochastic nature, an unambiguous functional connection. With the regression function quantitatively estimated the averaged relationship between the investigated variables $\hat{y} = f(X_1, X_2, ...X_m)$.

Conditionally, we assume that given values of some technical and economic indicators on the injury frequency rate *Y*, no other systematically acting factors substantial impact the value of this parameter. That is, the effect of these factors and randomness is accounted for by the random variable. The relationship between the injury frequency rate and technical and economic data was determined based on an empirical regression plot obtained using the MatLab software package. Further investigation was carried out in the sequence described below.

1. To assess the intensity of correlation between the injury frequency rate and technical and economic data X_K, the pair correlation coefficient should use. The correlation coefficient, which was less

than 0.5, was excluded from the access as insignificant. As a result, for creating a general regression model, the following indicators are selected: stock armament (X_1), energy armament (X_2), labour protection costs (X_3) and the resulting injury frequency rate *Y*.

2. The next step is to check the significance of each regression parameter. It means, the hypothesis $\frac{H}{b_k} \rangle 0$ or $b_k \langle 0$ was put forward. That is, it is necessary to analyze whether there is a significant positive (direct) or negative (inverse) dependence of the rate of injuries Y from the variable technical and economic indicator. When checking the significance of the estimates of the parameters that are included in the regression equation, statistics have been used by *t*-distribution with number of freedom $f = n - m - 1$ [10, 11]:

$$t = \frac{b_k}{S_{bk}}, \tag{16}$$

where S_{bk} is the standard deviation of the parameter assessment; b_k is the coefficient of factor included in regression; *n* is the number of values of the indicator for the period under investigation; *m* is the number of dependent factors in the regression equation.

3. The value of the indicator *t*, calculated according to the equation (16), is necessary to compare with the critical values $t_{f,\alpha}$ derived from Student's distribution tables, at a given significance level a and the number of freedom level *f*. If $(t - t_{kpb})$ is significantly more from zero, it can be concluded that regression *b* is a significant positive dependence. In return, the regression coefficient *b* reflects the negative dependence of this technical and economic factor on the rate of traumatism.

4. In the case of multifactor regression, to simplify the analysis of the results, it is expedient to convert the regression coefficients in standardized parameters by the equation [10]:

$$b_k^{©} = \frac{S_k}{S_y} \cdot b_k . \tag{17}$$

5. Determination of a multifactorial correlation coefficient that will be an indicator of the accuracy of the regression function is carried out to establish the adequacy of the selected technical and economic indicators that determine the quantitative variation of the dependent rate of injuries. In the case where the multifactor correlation coefficient is close to 1, the variation of the dependent variable is almost entirely determined by changes in explaining variables.

The statistical indicator t was used to check the significance of the correlation coefficient [12]:

$$|t| = \frac{r \cdot \sqrt{n-2}}{\sqrt{1-r^2}} . \tag{18}$$

The calculated value of the correlation indicator was compared with the critical value determined by Student's tables at a given level of significance α with $(f = n - 2)$ degrees of freedom. If $t \rangle t_{f,\alpha}$ we conclude a significant connection between the variables, the hypothesis about communication is not accepted in the opposite case.

6. In this study, the determination coefficient is calculated by the equation [11]:

$$B_{y.1..m} = \frac{b_1 \cdot \sum_{i=1}^{I} \left[(x1_i - \overline{x}) \cdot (y_i - \overline{y}) \right] + ... + b_m \cdot \sum_{i=1}^{I} \left[(xm_i - \overline{x}) \cdot (y_i - \overline{y}) \right]}{\sum_{i=1}^{I} (y_i - \overline{y})^2} \tag{19}$$

or

$$B_{y.1..m} = R^2_{y.1..m} . \tag{20}$$

As a result of the calculation of this indicator, it can be concluded how the change in the rate of occupational injury depends on the variation of technical and economic indicators of mechanical engineering production.

The research results showed that there is a clearly expressed correlation dependence of the incidence of injuries from the feasibility studies. Multifactor regression equations of leading machine-building enterprises of the Western region of Ukraine are obtained. The results are listed in Table 5. Based on the verification of the reliability of this model, it was found that the technical and economic indicators used are sufficiently adequately describing the regression dependence of occupational injuries from the leading technical and economic indicators of mechanical engineering enterprises. There is an inverse correlation dependence; that is, with the growth of the magnitude of the prominent factors (X_1, X_2, X_3), the value of the resulting index (Y) decreases. The correlation coefficients, both pair and multifactorial, are contained within 0.8–0.9; there is a significant influence of technical and economic indicators on the rate of occupational injury.

Table 5

Calculated data of the regression equation of injury danger of the leading machine-building enterprises of the Western region of Ukraine

Estimated value	Designation	Leading machine-building enterprises			For all enterprises
		LCCE	LWS	LLPP	
Regression equation		Y=13.708- -0.099X1 - -0.58X2 - -0.003X3	Y=6.765- -0.00096X1- -0.242X2 - -0.00046X3	Y=7.844- -0.325X1 + +0.717X2 - -0.005X3	Y=2.384- -0.568X1 + +1.511X2 + +0.008X3
Pair correlation coefficients	r_{y1}	- 0.79	- 0.89	- 0.92	- 0.91
	r_{y2}	- 0.91	-0.97	- 0.81	- 0.84
	r_{y3}	- 0.87	-0.93	- 0.91	- 0.87
Multifactor correlation coefficients	*R*	0.89	0.894	0.802	0.957
Student's t-test	*t*	12.38	5.23	3.55	8.728
Determination coefficient	*B*	0.808	0.799	0.895	0.911
The value of statistics	*F*	7.02	6.6	14.2	8.927

Analyzing the correlation dependence of the injury frequency rate from cost for the industrial safety measures ($Y = F(X3)$) proves that labour protection costs do not always bring a significant result. At some point, the costs cease to be effective. Increasing financial investments does not improve the system’s state, and the indicator of injuries practically does not change. That is why one of the most important tasks is to determine a scientifically justified amount of costs for industrial safety measures and to provide such conditions for operation of enterprises at which their technical and economic indicators would correspond to the maximum guarantee of exclusion of occupational accidents and conditions that cause occupational diseases at a given machine-building enterprise.

Conclusions

1. The study results indicate that injuries in the machine-building enterprises of the Western region of Ukraine decreased, but the severity of injuries remains too high. The high percentage of injuries for organizational reasons indicates the imperfection of work management to prevent occupational injuries. It is necessary to make changes in the labour protection management system at the level of economic interest in implementing all requirements relating to the safe execution of official duties.

2. It has been established that from all significant technical and economic indicators of machine-building enterprises to the level of occupational injury, significant influence has only 3 factors: stock armament, energy armament and labour protection costs. A new method of regression analysis of the state of occupational injuries is proposed.

3. The obtained equations describe the tendency to influence the values of technical and economic indicators on the frequency of occupational injuries, characteristic of the machine-building enterprises of the Western region of Ukraine. It has been found that the used indicators are sufficiently adequately describing the regression dependence of the criteria of occupational injuries from the leading technical and economic indicators of enterprises. There is an inverse correlation dependence; with the growth of the magnitude of the determining factors (X_1, X_2, X_3), the value of the resulting index (Y) decreases. The correlation coefficients, both pair and multifactorial, are contained within 0.8–0.9, there is a significant influence of technical and economic indicators on the occupational injuries rates.

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