Aleksandar Brkić[1], Mirjana Misita[2], Vesna Spasojević Brkić[2], Tamara Golubović[3], Neda Papić[2], Martina Perišić[2]*

CRANE STOPPAGES RISK ASSESSMENT

PROCENA RIZIKA ZASTOJA DIZALICA

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Adresa autora / Author's address:
[1)] University of Belgrade, Innovation Centre of the Faculty of Mechanical Engineering, Belgrade, Serbia
[2)] University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia [*]email: vspasojevic@mas.bg.ac.rs
[3)] University of Belgrade, Innovation Centre of the Faculty of Technology and Metallurgy, Belgrade, Serbia

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Ključne reči
- dizalica
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- zastoj
- analiza zastoja
- matrice rizika

Abstract

According to available literature, safety at work and productivity of cranes are a necessary and insufficiently researched topic. Both research directions are closely related because they depend on the number and type of stoppages that occur during operation of these construction machines. The focus of research should be on identifying the stoppages that can have fatal consequences for employees on-site, or unintended consequences in terms of production loss, means of work, or environment. In the present research, an attempt is made to create a methodology for identification, analysis, assessment, classification, and calculation of stoppage risk in cranes (classified by categories and causes). Criteria used for analysis, assessment, and calculation of stoppage risk: degree of stoppage danger, frequency of stoppage classified according to stoppage categories/causes, and downtime according to the adopted classification. Experimental research on a sample of 1,091 stoppages recorded on several cranes over a longer time interval has confirmed the hypothesis of generating a 3-criterion matrix for stoppage risk assessment sensitive enough to prioritise key crane stoppage in terms of risk. Results of experimental research indicate mechanical downtime of 16.22 %, a frequency 45.35 % in downtime, and RPN number 80, at hazard level 10. Selectively, according to the cause of stoppage, the results indicate that the hoisting brake (6.48 % downtime at hazard level 10; 2.14 % stoppage frequency) and hoist gear/tooth breakage (5.29 % downtime at hazard level 10; 3.58 % stoppage frequency) are key mechanical causes of stoppages and crane risk generators. By mitigating the given risks, it is possible to improve safety and increase productivity.

Izvod

Prema dostupnoj literaturi, bezbednost u radu i produktivnost dizalica je potrebna i nedovoljno proučena oblast. Oba pravca istraživanja su u bliskoj vezi jer zavise od broja i tipa zastoja koji se događaju u toku rada ovih mašinskih konstrukcija. Predmet istraživanja treba da bude u identifikaciji ovih zastoja, koji mogu imati fatalni ishod po zaposlene na terenu, ili nepredviđene posledice u smislu proizvodnih gubitaka, radnih sredstava, ili na okolinu. U radu je predstavljena izrada metodologije za identifikaciju, analizu, procenu, klasifikaciju i proračun rizika zastoja (sa klasifikacijom prema kategoriji i uzroku) kod dizalica. Kriterijumi upotrebljeni za analizu, procenu i proračun rizika zastoja su: stepen opasnosti zastoja, frekvencija zastoja sa klasifikacijom prema kategorijama/uzrocima zastoja, kao i vreme prekida, prema usvojenoj klasifikaciji. Eksperimentalno istraživanje na uzorku od 1091 zastoja, zabeleženih kod nekoliko dizalica tokom dužeg perioda potvrđuje hipotezu o generisanju 3-kriterijumske matrice za procenu rizika zastoja, dovoljno osetljivom, kako bi se dao prioritet ključnim zastojima kod dizalice s obzirom na rizik. Rezultati eksperimentalnog istraživanja pokazuju period mehaničkih prekida rada sa procentom 16.22 % i frekvencijom 45.35 % u vremenu prekida, sa brojem RPN od 80, pri nivou rizika 10. Selektivno, a prema uzroku zastoja, rezultati pokazuju da su: kočnice (6.48 % vreme prekida sa nivoom rizika 10; 2.14 % frekvencije zastoja), zatim otkazi prenosnika/zubaca (5.29 % vreme prekida, sa nivoom rizika 10; 3.58 % frekvencije zastoja), ključni mehanički uzročnici zastoja i generatori rizika dizalica. Ublažavanjem datih rizika, moguće je poboljšati bezbednost i povećati produktivnost.

INTRODUCTION

Cranes are a group of the most widely used materials handling devices which have historically been present for a very long time /1/. They are used for vertical lifting of loads, usually with a rope or chain, and include bridge cranes, construction cranes, portal cranes, loading bridges, etc. Today the work cannot be imagined without modern and efficient devices for lifting and transport, especially where production is done according to a certain technological procedure, and where the transfer of materials and parts of unfinished products from place to place is an integral part of the entire production process. The rapid development of the industry from the second half of the last century until today imposes the ever-faster development of cranes and other machines for lifting and transporting parts, goods, and other materials in wide industrial settings. It has long been observed that cranes operate under very different operating conditions that also applies to the drive mechanisms on the same crane, and their maintenance and inspection procedures are of great importance, /2-3/. Even after continual improvement of maintenance and inspection procedures, cranes still are machines that posess the highest risks in mining and construction sites, and often cause injuries and fatalities /4-6/. It is not surprising since human error is recognised as the most frequent cause of problems on sites where cranes operate /7-10, 24/, but crane-related safety and productivity, although recognised as important, are not enough discussed topics in the domain of industrial engineering and management /7, 11/. Medjo et al. /25/ propose the integrity of structures approach application on cranes at the hydro power plant 'Đerdap 2' and find that non-allowable indications detected at the right brace and the threaded spindle by ultrasonic tests do not influence the load carrying capacity of the equipment. Brkić et al. define the main causes of accidents involving cranes by Pareto analysis, such as construction, inadequate use, assembly/disassembly, and the transport of cranes, and prove that 80 % accidents are due to the abovementioned causes, /11/. As a proposal for further research, a detailed analysis of the role of human factor in dominant causes of accidents is given, /11, 12, 24/.

In the aim to improve crane safety and productivity, authors usually focus on automation and innovative devices /13/. Automation of cranes began 50 years ago with ideas for feed control, and are followed by control concepts with feedback of the rope angle, such as measurements of rope angle by cardanic joint, and continue in vision-based systems directions, /13-14/. Milazzo et al. and Kim et al. introduce safety device supporting crane operations based on stereoscopic vision /15, 16/. The anti-sway control solution is examined by authors such as Smotzek et al., and Kim et al., /17, 18/. Price et al. propose multisensory system to prevent problems of blind lifts, /19/. There is for sure much more research and solutions, but data on accidents do not show decline over time and it seems that safety is not improved enough. Productivity is even less discussed /20/, and even when it is surveyed, it is usually done in the context of the delay of other tasks /21-22/. Tang et al. /23/ notice that the most probable reason for low research rate and results in the field of cranes risk is the fact that they do not work the whole shifts, and accordingly, their downtimes data are rarely collected and later on surveyed, although there is the possibility on the basis of those analyses to recognise causes of productivity and safety problems.

Research is based on the fact proposed by Tang et al. and is aimed at gaining insight into the structure of crane stoppages as well as to propose a methodology for determining the risk for the identified stoppage. The following part presents the applied methodology, based on which data are collected and analysed, followed by conclusions.

RESEARCH METHODOLOGY

The aim of this research is to examine the causes of crane stoppages, downtime, frequency of stoppages, and calculation of stoppage risk in order to gain insight into the efficiency and safety of the crane. In accordance with the goal set of the research, the initial assumptions are generated:

- causes of stoppages can be classified into categories and types,
- based on the percentage of stoppage according to defined categories and types of stoppages, it is possible to calculate the frequency of a certain stoppage,
- to calculate the risk of stoppages by categories or types. It is possible to use the calculated frequency of stoppages, downtime, and degree of danger of the observed type of stoppage.

Methodological steps of the research aimed at assessing the risk of crane stoppage relate to:

1. To calculate the risk of crane downtime, risk matrices, and the following criteria will be used: downtime, frequency of stoppages and hazard level of stoppage for stoppages classified according to defined categories, and then for stoppages according to defined types. In the research methodology, two possibilities of defining risk zones in risk matrices are considered:
   - var 1: Risk matrices have three ALARP zones: low risk, moderate risk, and high risk;
   - var 2: Risk matrices have five ALARP zones: low risk, low to moderate risk, moderate risk, moderate to high risk, high risk.
2. Hazard level scale from 1 to 10 (1 minimal, 10 maximal hazard level);
3. The scale for estimating the frequency of stoppages (by types and categories of stoppage), and the scale for estimating the downtime, represent the most important methodological setting of the research.

   The experimental part of the research should enable the correct identification of scales for estimating the frequency of stoppages (by types and categories of stoppage) as well as scales for estimating the downtime in the observed cranes. For example, if it is determined by experimental research, those individual stoppages by criterion of the frequency of occurrence are represented by less than 10 % of the share in all identified stoppages, according to the scale with categories {0-20% = L; 21-40 = LM; 41-60 = M; 61-80 = MH; 80-100 = H}, all stoppages would be classified as L (low risk) and we would not be able to identify significant stoppages.
4. Finally, after determining the scale for estimating the frequency of stoppages, the scales for estimating the downtime and for assessing the hazard level, it is possible to define risk matrices with defined ALARP zones, based on which it is possible to perform risk assessment.

EXPERIMENTAL PART OF RESEARCH

In the experimental part of research, data on crane stoppages in a period of one year is recorded. Crane operation with following characteristics is monitored: double girder bridge crane: 10 t (capacity), 29 m (span); double girder bridge crane: 16 t, 27 m; double girder bridge crane: 20 t, 16.7 m; double girder bridge crane: 20 t, 22.5 m; double girder bridge crane: 32 t, span 24 m; single girder bridge crane: 10 t, 22.5 m; single girder bridge crane: 5 t, 29 m; gantry crane: 63 t, 18 m; portal crane: 160 t. All stoppages are recorded in a database with the following structure: date of stoppage, ident number of stoppage, type of machine, cause of stoppage, downtime, category of stoppage, hazard level. The total is recorded during the observed time period 1091 stoppages. Categories of stoppages according to which stoppages are classified, are set according to types: mechanical; electrical (cause of electricity); abuse (human factor); stoppages of organisational nature; stoppages caused by external factors (earthquakes, floods, storms, etc.).

A data analysis in the recording period is performed.

Stoppage analysis by downtime categories

Stoppage frequencies

Table 1 shows percentage of stoppages by category and hazard level for observed cranes. Figure 1 shows the largest percentage in all stoppages, and according to the frequency criterion, have mechanical stoppages of 41.76 % of all recorded stoppages.

Table 1. Percentage of stoppages by category and hazard level in observed cranes.

Hazard level	Electrical	Mechanical	Abuse	Organizational	External	Total
Hazard level 1	6.72%	3.45%	0.00%	0.49%	0.00%	10.67%
Hazard level 2	25.97%	28.87%	0.00%	1.17%	0.00%	56.01%
Hazard level 3	0.00%	0.00%	9.44%	2.16%	0.00%	11.60%
Hazard level 6	1.73%	0.00%	0.00%	1.73%	0.00%	3.45%
Hazard level 7	0.86%	0.74%	0.00%	0.31%	0.00%	1.91%
Hazard level 8	0.12%	0.00%	0.00%	0.00%	0.00%	0.12%
Hazard level 10	0.00%	8.70%	4.38%	3.02%	0.12%	16.22%
Total	35.41%	41.76%	13.82%	8.88%	0.12%	100.00%

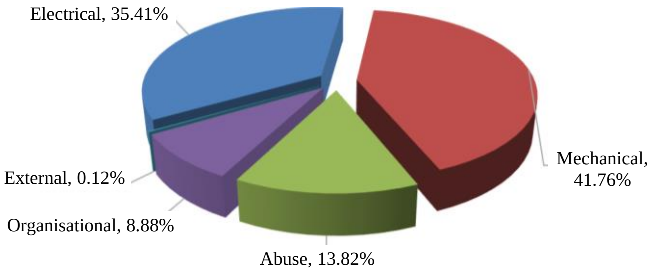

Figure 1. Structure of stoppages by categories calculated in relation to frequency of stoppages.

Figure 2 shows the structure of stoppage frequencies by stoppage categories and by hazard level. It is noticeable that most common stoppages are hazard level 2 (56.01 %, electrical and mechanical), and then there is a very important share of stoppages of hazard level 10 (16.22 %).

Downtime

In addition to frequency of occurrence, the study also recorded downtime of all stoppages. An estimated representation of individual types of stoppages, according to appropriate hazard levels in total down-time is shown in Table 2.

Figure 3 shows the structure of down-time according to hazard level and category of stoppages, by percentage. The diagram indicates the largest share (45.72 %) of total downtime of observed cranes had stoppages with hazard level 10.

Analysis indicates that according to adopted stoppage categories, the share in down-time of hazard level 10 has: mechanical stoppages (20.07 %); abuse (16.03 %); electrical (5.81 %); and organisational (3.44 %). Significant share in down-time of all stoppages have hazard level 6 stoppages.

In stoppages of hazard level 6, the largest share are mechanical (26.69 %), followed by external causes (9.12 %), and organisational (1.22 %), as in Fig. 4.

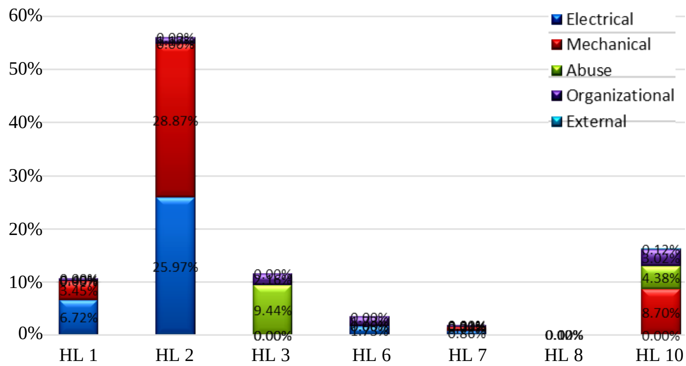

Figure 2. Structure of stoppage frequencies by hazard levels (HL) and categories of congestion.

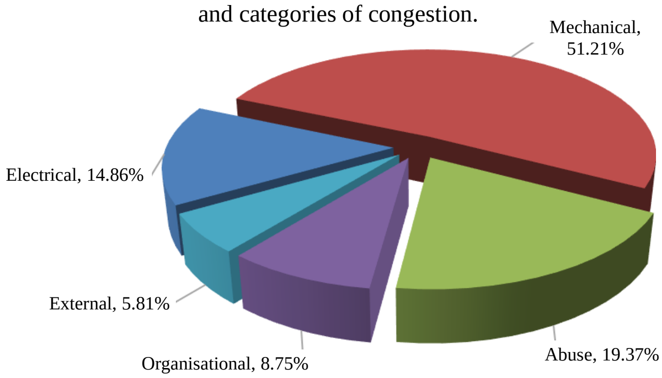

Figure 3. Structure of stoppages by categories, calculated in relation to the down-time.

Table 2. Percentage share of down-time by hazard levels and categories of stoppages.

Hazard level	Electrical	Mechanical	Abuse	Organizational	External	Total
Hazard level 1	3.18%	3.18%	0.00%	1.16%	0.00%	7.52%
Hazard level 2	9.12%	26.69%	0.00%	1.22%	0.00%	37.03%
Hazard level 3	0.00%	0.00%	3.34%	0.95%	0.00%	4.29%
Hazard level 6	1.70%	0.00%	0.00%	1.70%	0.00%	3.40%
Hazard level 7	0.75%	1.28%	0.00%	0.27%	0.00%	2.30%
Hazard level 8	0.11%	0.00%	0.00%	0.00%	0.00%	0.11%
Hazard level 10	0.00%	20.07%	16.03%	3.44%	5.81%	45.35%
Total	14.86%	51.21%	19.37%	8.75%	5.81%	100.00%

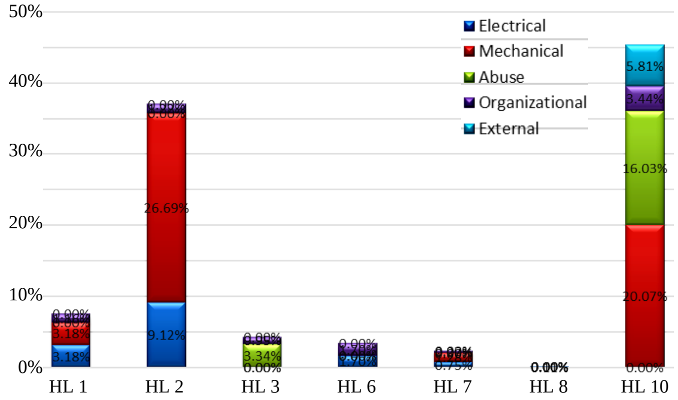

Figure 4. Down-time structure by hazard level and stoppage category.

Stoppage analysis by type of stoppage

Stoppage frequencies

By analysing recorded data it is found that the highest frequency of occurrences has stoppages of the type ‘crane limit switch’ (21.84 %); followed by ‘two step trolley limit switch’ (20.48 %); ‘hoisting brake" (6.48 %); ‘hook safety latch’ (6.05 %), etc., as in Fig. 5.

Analysis of the frequency of stoppages by stoppage type and hazard level shows that all stoppages originating from the type ‘crane limit switch’ (21,84 %) and ‘two step trolley limit switch’ (20.48 %) are of the same hazard level 2, while stoppages of the type ‘hoisting brake’ (6.48 %) are hazard level 10, as in Fig. 6.

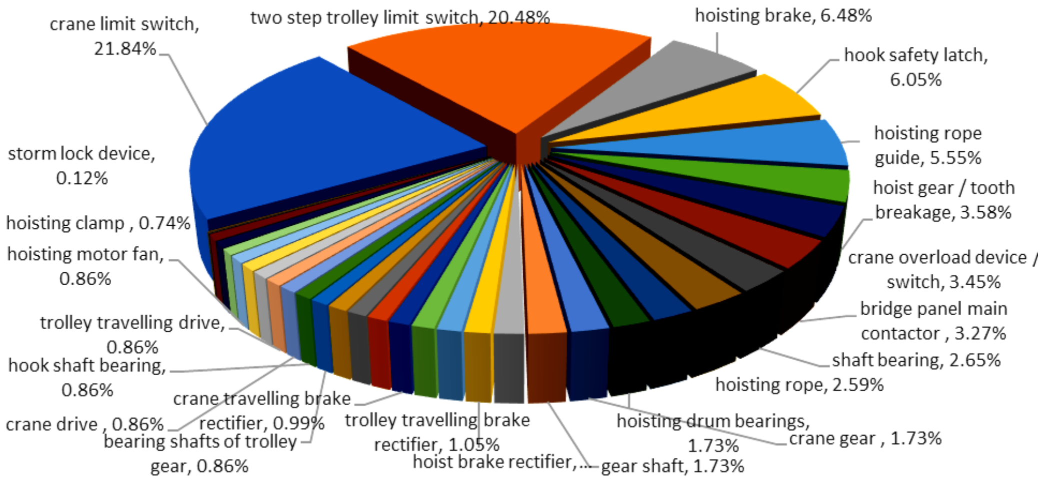

Figure 5. Percentage share structure of stoppage frequencies by stoppage type.

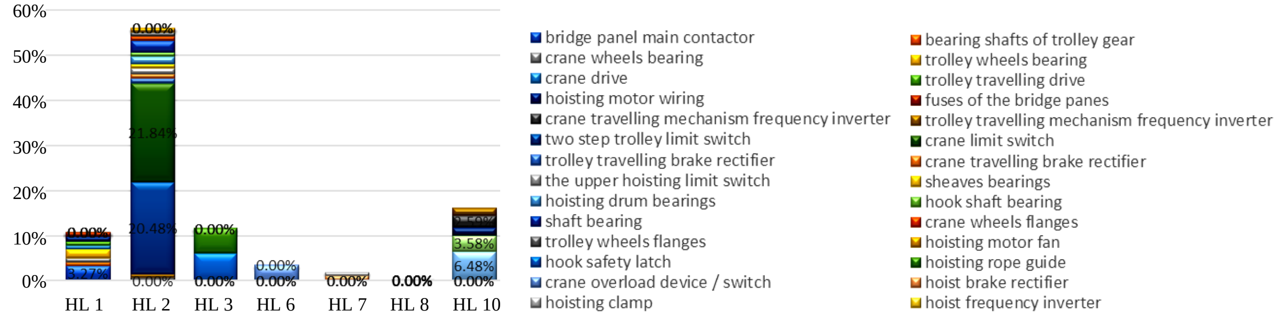

Figure 6. Percentage share structure of the frequency of stoppage occurrence by stoppage type and hazard level.

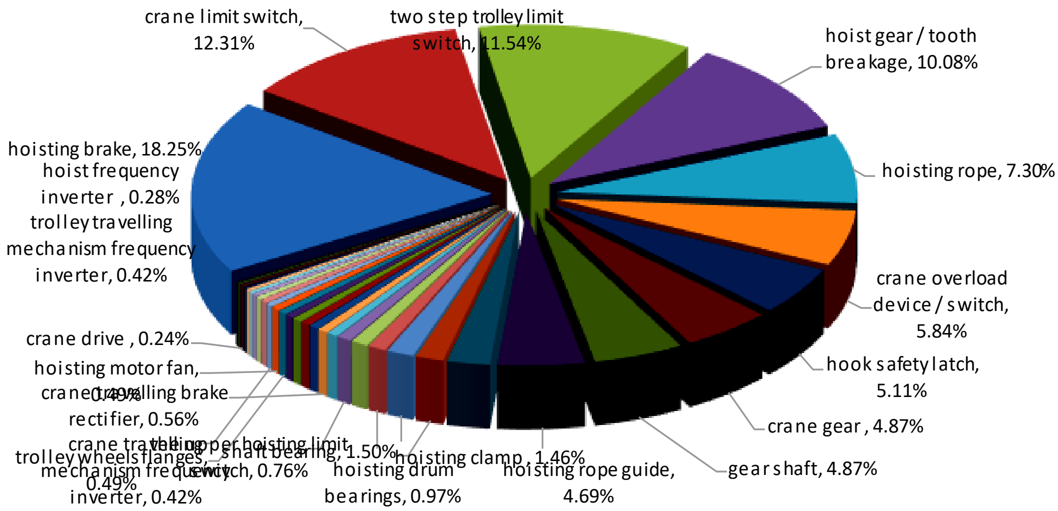

Figure 7. Percentage share structure of down-time, according to stoppage type.

Downtime

By analysis of the down-time according to stoppage type and hazard level, we obtain the data according to which the highest percentage of stoppages of hazard level 2 in which stoppage type ‘hook shaft bearing’ has the highest percentage (18.25 %), as in Fig. 7.

According to Fig. 8, of stoppages of hazard level 10, the most common is ‘gear shaft’, with percentage share in total down-time 5.29 %. In the case of stoppages of hazard level 7, the highest percentage share in total downtime was the stoppage of the type "hoist brake rectifier" with 10.07%.

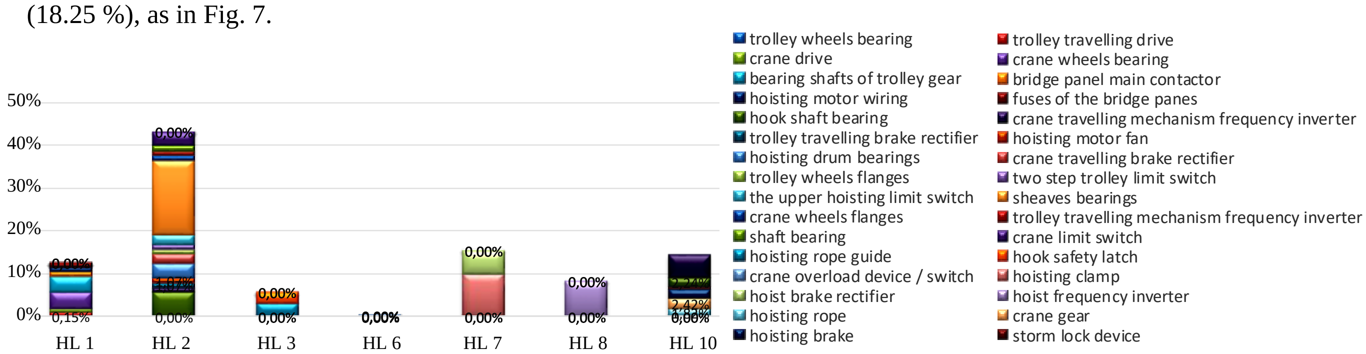

Figure 8. Percentage share structure of the down-time, according to stoppage type and hazard level.

RISK ASSESMENT

Risk assessment by down-time categories

Table 3 shows data obtained according to stoppage categories and hazard level. The data are recalculated to represent the percentage of each category of stoppages in total stoppage frequencies (Fr) and down-times (Ti).

To assess the risk according to the criteria of frequency and down-time, a five-point scale (L, LM, M, MH, H) is adopted, and recalculation of obtained values on the percentage of adopted stoppage categories is performed, as in Table 4. The assumption is adopted that stoppages according to defined categories that make up more than 30 % of total stoppages, according to the criterion of frequency or the criterion of down-time, are considered critical, i.e. they have a maximal score of 5.

Table 3. Percentage share of downtime by hazard levels and categories of stoppages, Fr and Ti.

Hazard level	Electrical		Mechanical		Abuse		Organisational		External		Total	
	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti
Hazard level 1	6.72%	3.18%	3.45%	3.18%	0.00%	0.00%	0.49%	1.16%	0.00%	0.00%	10.67%	0.00%
Hazard level 2	25.97%	9.12%	28.87%	26.69%	0.00%	0.00%	1.17%	1.22%	0.00%	0.00%	56.01%	37.03%
Hazard level 3	0.00%	0.00%	0.00%	0.00%	9.44%	3.34%	2.16%	0.95%	0.00%	0.00%	11.60%	4.29%
Hazard level 6	1.73%	1.70%	0.00%	0.00%	0.00%	0.00%	1.73%	1.70%	0.00%	0.00%	3.45%	3.40%
Hazard level 7	0.86%	0.75%	0.74%	1.28%	0.00%	0.00%	0.31%	0.27%	0.00%	0.00%	1.91%	2.30%
Hazard level 8	0.12%	0.11%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.12%	0.11%
Hazard level 10	0.00%	0.00%	8.70%	20.07%	4.38%	16.03%	3.02%	3.44%	0.12%	5.81%	16.22%	45.35%

Table 4. Scales for Ti and Fr.

Assessment	L [%]	LM [%]	M [%]	MH [%]	H [%]
Time in down-time (Ti)	0-6	6-12	12-18	18-24	30 -
Frequency (Fr)	0-6	6-12	12-18	18-24	30 -
Assessment	1	2	3	4	5

Finally, to assess the risk according to the criterion of down-time frequency, according to hazard levels, the following matrix is adopted (Table 5).

Table 5. Risk assessment matrix.

Fr*		1					2					3					4					5				
Ti		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Hazard level	1	1	2	3	4	5	2	4	6	8	10	3	6	9	12	15	4	8	12	16	20	5	10	15	20	25
	2	2	4	6	8	10	4	8	12	16	20	6	12	18	24	30	8	16	24	32	40	10	20	30	40	50
	3	3	6	9	12	15	6	12	18	24	30	9	18	27	36	45	12	24	36	48	60	15	30	45	60	75
	4	4	8	12	16	20	8	16	24	32	40	12	24	36	48	60	16	32	48	64	80	20	40	60	80	100
	5	5	10	15	20	25	10	20	30	40	50	15	30	45	60	75	20	40	60	80	100	25	50	75	100	125
	6	6	12	18	24	30	12	24	36	48	60	18	36	54	72	90	24	48	72	96	120	30	60	90	120	150
	7	7	14	21	28	35	14	28	42	56	70	21	42	63	84	105	28	56	84	112	140	35	70	105	140	175
	8	8	16	24	32	40	16	32	48	64	80	24	48	72	96	120	32	64	96	128	160	40	80	120	160	200
	9	9	18	27	36	45	18	36	54	72	90	27	54	81	108	135	36	72	108	144	180	45	90	135	180	225
	10	10	20	30	40	50	20	40	60	80	100	30	60	90	120	150	40	80	120	160	200	50	100	150	200	250

Ti – Down-time

Based on the presented risk matrix and the table with scales for Ti and Fr, a new table can be formed in which the calculation of risk priority number (RPN) is performed.

According to the obtained results and Table 6, it is noticed that mechanical stoppages of hazard level 10 are the most pronounced from the aspect of risk. Their value according to RPN is a ‘high to critical’ (MH) value. Organisational and external stoppages are not important in terms of analysis of stoppages in the observed cranes. Abuse by employees has a partial impact on the occurrence of stoppages in the observed cranes. It is recommended that preventive maintenance reduce the share of mechanical stoppages, not in terms of unpredictable mechanical adverse events, but in down-time. The organisation of the maintenance function is the primary aspect from the point of view of increasing the productivity of the observed cranes.

Table 6. RPN calculation according to stoppage category and hazard level.

Hazard level	Electrical	Mechanical	Abuse	Orgaanisational	External
Hazard level 1	2	1	1	1	1
Hazard level 2	20	50	2	2	2
Hazard level 3	3	3	6	3	3
Hazard level 6	6	6	6	6	6
Hazard level 7	7	7	7	7	7
Hazard level 8	8	8	8	8	8
Hazard level 10	10	80	30	10	10

Table 7. Assessment Ti and Fr according to stoppage type.

	Hazard level 1		Hazard level 2		Hazard level 3		Hazard level 6		Hazard level 7		Hazard level 8		Hazard level 10	
Row Labels	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr
hoist frequency inverter	1	1	1	1	1	1	1	1	1	1	1	2	1	1
crane travelling mechanism frequency inverter	1	1	1	1	1	1	1	1	1	1	1	1	1	1
trolley travelling mechanism frequency inverter	1	1	1	1	1	1	1	1	1	1	1	1	1	1
two step trolley limit switch	1	1	5	1	1	1	1	1	1	1	1	1	1	1
crane limit switch	1	1	5	1	1	1	1	1	1	1	1	1	1	1
hoist brake rectifier	1	1	1	1	1	1	1	1	1	2	1	1	1	1
trolley travelling brake rectifier	1	1	1	1	1	1	1	1	1	1	1	1	1	1
crane travelling brake rectifier	1	1	1	1	1	1	1	1	1	1	1	1	1	1
hoisting brake	1	1	1	1	1	1	1	1	1	1	1	1	2	1
bridge panel main contactor	1	1	1	1	1	1	1	1	1	1	1	1	1	1
the upper hoisting limit switch	1	1	1	1	1	1	1	1	1	1	1	1	1	1
bearing shafts of trolley gear	1	1	1	1	1	1	1	1	1	1	1	1	1	1
sheaves bearings	1	1	1	4	1	1	1	1	1	1	1	1	1	1
hoisting drum bearings	1	1	1	1	1	1	1	1	1	1	1	1	1	1
hook shaft bearing	1	1	1	2	1	1	1	1	1	1	1	1	1	1
crane wheels bearing	1	1	1	1	1	1	1	1	1	1	1	1	1	1
trolley wheels bearing	1	1	1	1	1	1	1	1	1	1	1	1	1	1
shaft bearing	1	1	1	1	1	1	1	1	1	1	1	1	1	1
crane drive	1	1	1	1	1	1	1	1	1	1	1	1	1	1
trolley travelling drive	1	1	1	1	1	1	1	1	1	1	1	1	1	1
hoisting motor wiring	1	1	1	1	1	1	1	1	1	1	1	1	1	1
crane wheels flanges	1	1	1	1	1	1	1	1	1	1	1	1	1	1
trolley wheels flanges	1	1	1	1	1	1	1	1	1	1	1	1	1	1
hook safety latch	1	1	1	1	2	1	1	1	1	1	1	1	1	1
fuses of the bridge panes	1	1	1	1	1	1	1	1	1	1	1	1	1	1
hoist gear / tooth breakage	1	1	1	1	1	1	1	1	1	1	1	1	1	2
crane gear	1	1	1	1	1	1	1	1	1	1	1	1	1	1
storm lock device	1	1	1	1	1	1	1	1	1	1	1	1	1	1
hoisting clamp	1	1	1	1	1	1	1	1	1	3	1	1	1	1
crane overload device / switch	1	1	1	1	1	1	1	1	1	1	1	1	1	1
hoisting rope	1	1	1	1	1	1	1	1	1	1	1	1	1	1
hoisting motor fan	1	1	1	1	1	1	1	1	1	1	1	1	1	1
hoisting rope guide	1	1	1	1	2	1	1	1	1	1	1	1	1	1
gear shaft	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Risk assessment by type of stoppage

To estimate the RPN by type of stoppages, it is necessary to introduce a new scale, because the scale set for the assessment by stoppage category is too wide for stoppages by type.

The calculation of RNP number is performed by taking the values from the previous table and marking the fields according to the set risk matrix (Table 8).

Analysis of results indicates that the highest risks are present in:

- hoisting brake (6.48 % Ti at hazard level 10, 2.14 % Fr),
- hoist gear/tooth breakage (5.29 % Ti at hazard level 10, 3.58 % Fr),
- hoisting clamp (0.74 % Fr, 10.7 % Ti at hazard level 7).

All identified risks are not critical and do not require urgent preventive measures, but for all identified risks down-time is the factor that contributes most to the size of the RNP number, which indicates that the identified risks have the greatest impact on labour costs. By reducing the duration of generalised risks, the efficiency of the observed cranes can be increased.

Table 8. RPN calculation according to stoppage type and hazard level.

	Hazard level 1	Hazard level 2	Hazard level 3	Hazard level 6	Hazard level 7	Hazard level 8	Hazard level 10
Row Labels	1	2	3	4	7	8	10
hoist frequency inverter	1	2	3	6	7	16	10
crane travelling mechanism frequency inverter	1	2	3	6	7	8	10
trolley travelling mechanism frequency inverter	1	2	3	6	7	8	10
two step trolley limit switch	1	10	3	6	7	8	10
crane limit switch	1	10	3	6	7	8	10
hoist brake rectifier	1	2	3	6	14	8	10
trolley travelling brake rectifier	1	2	3	6	7	8	10
crane travelling brake rectifier	1	2	3	6	7	8	10
hoisting brake	1	2	3	6	7	8	20
bridge panel main contactor	1	2	3	6	7	8	10
the upper hoisting limit switch	1	2	3	6	7	8	10
bearing shafts of trolley gear	1	2	3	6	7	8	10
sheaves bearings	1	8	3	6	7	8	10
hoisting drum bearings	1	2	3	6	7	8	10
hook shaft bearing	1	4	3	6	7	8	10
crane wheels bearing	1	2	3	6	7	8	10
trolley wheels bearing	1	2	3	6	7	8	10
shaft bearing	1	2	3	6	7	8	10
crane drive	1	2	3	6	7	8	10
trolley travelling drive	1	2	3	6	7	8	10
hoisting motor wiring	1	2	3	6	7	8	10
crane wheels flanges	1	2	3	6	7	8	10
trolley wheels flanges	1	2	3	6	7	8	10
hook safety latch	1	2	6	6	7	8	10
fuses of the bridge panes	1	2	3	6	7	8	10
hoist gear / tooth breakage	1	2	3	6	7	8	20
crane gear	1	2	3	6	7	8	10
storm lock device	1	2	3	6	7	8	10
hoisting clamp	1	2	3	6	21	8	10
crane overload device / switch	1	2	3	6	7	8	10
hoisting rope	1	2	3	6	7	8	10
hoisting motor fan	1	2	3	6	7	8	10
hoisting rope guide	1	2	6	6	7	8	10
gear shaft	1	2	3	6	7	8	10

CONCLUSIONS

Analysis of results indicates that the highest risks are present in regard to different levels of total stoppage frequencies and times in down-times in a manner to include: hoisting brake (6.48 % Ti at hazard level 10, 2.14 % Fr); hoist gear/tooth breakage (5.29 % Ti at hazard level 10, 3.58 % Fr); and hoisting clamp (0.74 % Fr, 10.7 % Ti at hazard level 7).

All identified risks are not critical and do not require urgent preventive measures, but for all identified risks the down-time is the factor that contributes most to the size of RNP number, which indicates that identified risks have the greatest impact on labour costs. By reducing the duration of generalised risks, the efficiency of the observed cranes can be increased.

By modelling such scales when generating a risk matrix, a degree of detail is provided in which adequate conclusions can be drawn without a three-dimensional matrix representing an overly extensive structure. Also during the experimental research, ALARP zones are determined for the mentioned scales. Specifically for each stoppage with a percentage share in the frequency of occurrence as well as a percentage share in the total down-time greater than 30 % is considered high risk for construction machinery, such are cranes. The risk of cranes failures has consequences in the size of the impact on the safety and health of workers, the environment, business losses, as well as equipment itself.

Specifically, for the observed cranes, in the experimental part of research, a database of 1091 stoppages is formed, classified into categories (mechanical, organisational, external, electrical, and abuse), and then classified by cause of stoppage. Results of research indicate that mechanical stoppages are most significant from the risk aspect, and according to the causes of stoppages from the risk aspect, the most significant are the hoisting brake, hoist gear/tooth breakage, and hoisting clamp. An important conclusion is that there are no organisational, or patterns of machine abuse. Preventive measures for specific construction machines relate to adequate preventive maintenance of identified elements in the coming period, in order to improve crane safety and productivity.

REFERENCES

1. Sawodny, O., Aschemann, H., Lahres, S., Hofer, E.P. (1999), *A material handling and logistic system using an automated crane*, IFAC Proc. Vol. 32(2): 998-1003. doi: 10.1016/S1474-6670(17)56168-6
2. Zhou, W., Zhao, T., Liu, W., Tang, J. (2018), *Tower crane safety on construction sites: A complex sociotechnical system perspective*, Safety Sci. 109: 95-108. doi: 10.1016/j.ssci.2018.05.001

3. Iung, B., Morel, G., Léger, J.B. (2003), *Proactive maintenance strategy for harbour crane operation improvement*, Robotica, 21(3): 313-324. doi: 10.1017/S0263574702004824
4. Spasojević-Brkić, V.K., Milazzo, M.F., Brkić, A., Maneski, T. (2015), *Emerging risks in smart process industry cranes survey: SAF€RA research project SPRINCE*, Serb. J Manag. 10(2): 247-254. doi: 10.5937/sjm10-8834
5. Raviv, G., Fishbain, B., Shapira, A. (2017), *Analyzing risk factors in crane-related near-miss and accident reports*, Safety Sci. 91: 192-205. doi: 10.1016/j.ssci.2016.08.022
6. Neitzel, R.L., Seixas, N.S., Ren, K.K. (2001), *A review of crane safety in the construction industry*, Appl. Occup. Environ. Hyg. 16(12): 1106-1117. doi: 10.1080/10473220127411
7. Zhang, C., Tang, P., Yilmaz, A., et al. (2016), *Automatic crane-related workflow control for nuclear plant outages through computer vision and simulation*, In: Proc. 33rd Int. Symp. Automation and Robotics in Construction (ISARC), IAARC Publ., Vol.33, pp.889-897. doi: 10.22260/ISARC2016/0107
8. Mandal, S., Singh, K., Behera, R.K., et al. (2015), *Human error identification and risk prioritization in overhead crane operations using HTA, SHERPA and fuzzy VIKOR method*, Exp. Syst. Appl. 42(20): 7195-7206. doi: 10.1016/j.eswa.2015.05.033
9. Park, J.H., Park, T.J., Lim, H.K., Seo, E.H. (2007), *Analysis of crane accidents by using a man-machine system model*, J Korean Soc. Safety, 22(2): 59-66.
10. Spasojević Brkić, V.K., Klarin, M.M., Brkić, A.Dj. (2015), *Ergonomic design of crane cabin interior: The path to improved safety*, Safety Sci. 73: 43-51. doi: 10.1016/j.ssci.2014.11.010
11. Brkić, A.Đ., Misita, M.Ž., Spasojević-Brkić, V.K., Perišić, M.B. (2020), *Pareto analysis application in research of crane related accidents*, Tehnika, 75(2): 238-244. doi: 10.5937/tehnika2002238B
12. Milazzo, M.F., Ancione, G., Spasojevic-Brkic, V.S., Vališ, D. (2017), *Investigation of crane operation safety by analysing main accident causes*, In: Walls, Revie, Bedford (Eds.): Risk, Reliability and Safety: Innovating Theory and Practice, pp.74-80. 2017 Taylor & Francis Group, London, ISBN 978-1-138-0 2997-2
13. Zavodni, O., Nojpert, J., Arnold, E. (2009), *Actual trends in crane automation: Directions for the future*, FME Trans. 37(4): 167-174.
14. Hu, S., Fang, Y., Bai, Y. (2021), *Automation and optimization in crane lift planning: A critical review*, Adv. Eng. Inform. 49: 101346. doi.org/10.1016/j.aei.2021.101346
15. Milazzo, M.F., Ancione, G., Consolo, G. (2021), *Human factors modelling approach: Application to a safety device supporting crane operations in major hazard industries*, Sustainability, 13 (4): 2304. doi: 10.3390/su13042304
16. Kim, S., Choi, S., Won, S., Jeong, H. (2004), *The coil recognition system for an unmanned crane using stereo vision*, In: 30th Annual Conf. IEEE Ind. Electronics Soc. 2004. IECON 2004, Vol.2, pp.1235-1239. IEEE. doi: 10.1109/IECON.2004.1431752
17. Kim, Y.S., Seo, H.S., Sul, S.K. (2001), *A new anti-sway control scheme for trolley crane system*, In: Conf. Record of the 2001 IEEE Industry Appl. Conf., 36th IAS Annual Meeting (Cat. No. 01CH37248), Vol.4, pp.548-552. IEEE.
18. Smoczek, J., Szpytko, J., Hyla, P. (2013), *The anti-sway crane control system with using dynamic vision system*, Solid State Phen. 198: 589-593. doi: 10.4028/www.scientific.net/SSP.198.589
19. Price, L.C., Chen, J., Park, J., Cho, Y.K. (2021), *Multisensor-driven real-time crane monitoring system for blind lift operations: Lessons learned from a case study*, Automation in Construction, 124: 103552.
20. Lee, U.K., Kang, K.I., Kim, G.H., Cho, H.H. (2006), *Improving tower crane productivity using wireless technology*, Comp.-Aided Civ. Infrastr. Eng. 21(8): 594-604. doi: 10.1111/j.1467-8667.2006.00459.x
21. Daganzo, C.F. (1989), *Crane productivity and ship delay in ports*, Transportation Research Record, 1251, p.9.
22. Goodchild, A.V., Daganzo, C.F. (2007), *Crane double cycling in container ports: Planning methods and evaluation*, Transp. Res. Part B: Methodol. 41(8): 875-891. doi: 10.1016/j.trb.2007.02.006
23. Tang, P., Zhang, C., Yilmaz, A., et al. (2016), *Automatic imagery data analysis for diagnosing human factors in the outage of a nuclear plant*, In: V.G. Duffy (Ed.), Digital Human Modeling: Applications in Health, Safety, Ergonomics and Risk Management - 7th Int. Conf. DHM 2016 and Held as Part of HCI Int. 2016, Proc., pp. 604-615. (Lecture Notes in Comp. Sci. (including subseries Lecture Notes in Artif. Intell. and Lecture Notes in Bioinform.); Vol. 9745). Springer Verlag. doi: 10.1007/978-3-319-40247-5_61
24. Brkić, A., Maneski, T., Spasojević Brkić, V., Golubović, T. (2015), *Industrial safety improvement of crane cabins*, Struct. Integ. Life, 15(2): 95-102.
25. Međo, B., Arsić, M., Rakin, M., et al. (2018), *Integrity assessment of vital beam components that enable conjoint operation of two bridge cranes*, Struct. Integ. Life, 18(1): 53-59.