XXIII INTERNATIONAL CONFERENCE ON
"MATERIAL HANDLING, CONSTRUCTIONS AND LOGISTICS"

September 18^{th} - 20^{th}, 2019

MHCL 2019

edited by
Georg Kartnig, Nenad Zrnić and Srđan Bošnjak

VIENNA UNIVERSITY OF TECHNOLOGY (TU WIEN)
Institute for Engineering Design and Product Development

together with

UNIVERSITY OF BELGRADE
Faculty of Mechanical Engineering

VIENNA, AUSTRIA, 2019

TECHNISCHE
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PREFACE

The International Conference on Material Handling, Constructions and Logistics – MHCL is the 23rd event of a series that has been started just 43 years ago, in 1976 by Professor Dr. Đorđe Zrnić. Up to now the Conference gathered together scientists and researchers from all republics (now independent states) of former Yugoslavia (Serbia, Montenegro, Croatia, Slovenia, Bosnia and Herzegovina, and Republic of North Macedonia), as well as from Algeria, Australia, Austria, Bulgaria, China, Croatia, Denmark, Germany, Greece, Hungary, Italy, Japan, Lithuania, Montenegro, Poland, Republic of Korea, Romania, Russia, Slovakia, Switzerland, The Netherlands, Turkey, USA and Vietnam working in the field of Material and Mechanical Handling, Constructions and Construction Machinery, as well as Transport Logistics. Since 2012 MHCL is jointly organized by the University of Belgrade (Faculty of Mechanical Engineering) and Vienna University of Technology (Institute for Engineering Design and Product Development).

The aim of the Conference is to be a forum to exchange views, opinions and experience on MHCL from technical viewpoints in order to track the current achievements, but also to look at to future developments. Most of the authors of contributed papers are experts in MHCL and related topics. Also, one of the main goals of the Conference is to make the scientific/research exchange between similar academic Departments and Institutes from different countries, as well as individual researcher in the field, in order for possible cooperation in applying for international programs or bilateral research and scientific projects.

This year the International Conference MHCL 2019 is held in Vienna at the Vienna University of Technology (Institute for Engineering Design and Product Development) from September 18th - 20th. The Proceedings contain 48 submitted peer-reviewed papers by authors from 13 countries (authors' countries are listed according to the alphabetical order): Austria, China, Croatia, Egypt, Germany, Greece, Italy, Japan, Montenegro, Poland, Serbia, Slovenia and The Netherlands.

The papers are grouped into three sessions A, B and C:

Session A: Hoisting and Conveying Equipment and Technologies - 15 papers

Session B: Constructions, Design Engineering, Mining Equipment and Technologies - 14 papers

Session C: Logistics and Intralogistics Systems - 19 papers

Proceedings also contain 4 invited papers presented in the Plenary Session, from respective professors and scientific and research leaders from German and Slovenian Universities. The invited lectures reflect the wide spectrum of important topics of current interest in MHCL. These Proceedings can also be considered as a kind of handbook on MHCL, and can be inspiring for researchers, graduate students and engineers specializing or addressing attention to MHCL. We truly believe that a reader will take advantage of the papers in these Proceedings with further satisfaction and motivation for her or his work.

We would like to express our sincere thanks to all members of the Scientific and Organizing Committee, Sessions chairmen and reviewers, as well as to all participants including invited speakers for coming in Vienna to present their papers. On this occasion, we are particularly indebted to all people who rendered their help for the preparation of the Conference and publication of the Proceedings.

We are grateful to the authors of the articles for their valuable contributions and for preparing their manuscripts and presentations in time.

Vienna, Austria, September 2019

Editors

Georg Kartnig, Nenad Zrnić and Srđan Bošnjak

DISTINGUISHED PERSON IN THE HISTORY OF THE MHCL CONFERENCE

Prof. Đorđe N. Zrnić, MHCL conference founder in 1976

ZRNIĆ, N. ĐORĐE, full member of the Academy of Engineering Sciences of Serbia (member of **Euro-Case), since 2000.**, was born in Belgrade in 1934. He finished high school and graduated (Dipl.-Ing.), from **F**aculty of **M**echanical **E**ngineering, **U**niversity of **B**elgrade 1959. After he was employed in "Serbia - project". Assistant on the **FME-UB** in decembar 1960, full professor 1982. He received his Dr Sc. at **FME-UB.** He was the Head of Department of Mechanization (1988 - 1999) and Dean of Faculty (1994 - 1997). Member of the Scientific Society of Serbia since 1996. He is married, wife Ljiljana, son Nenad.

Teaching activity. He lectured Plant Layout Design, Material Handling Systems Design, Optimization Methods in Design. He was supervisor of number of Magister Sc. and eight PhD dissertations. Iinvited speaker at the Universities in: England, France, Germany, Hungary and Sweden. He was a member of IFAC, IIE, ICAW, since 1980 on invitation, at the Europäische Konferenz der Professoren für Fördertechnik.

Scientific and research activity encompass the development of the theory and practice of designing transport and warehouses systems. He published 177 professional and scientific papers, 82 of them were in international publications and chapters in the monograph, PERGAMON Elsevier Sc 1997 and 1999. He set the theoretical basis of design of storage Large Scale System. He developed a method **T**otal **P**erformance **D**esign, for modeling these systems, and applied it in practice. The work, based on the application of the **TPD** method presented to IFORS 2002, Edingburgh (Invited section), was one of the 6 awarded works. The results were presented in monograph Manufacturing Systems: Modeling, Management and Control, Ed. P. Kopacek, PERGAMON, Elsevier Sc. 1997. He wrote 10 books, (4 first co-author, total 20 ed.). Book Design of Foundries, total 6 ed. entered in the world bibliography of foundries. In 2016, he published the book Plant layout and Technical Logistics. He received the Annual prize from Belgrade Chamb. of Com. in 1989, for the best technical improvement in the economy, for the project "Central Plant for the Maintenance of the Energy System of Belgrade" (loc. New Belgrade).

Engineering activity. He has designed 93 projects, out of which 59 have been realized in the country and abroad. He designed a series of complex, original material handling machines (especially harbor cranes) in the country and in land (Burma, Indonesia, Bangladesh. Tanzania). All these devices have been manufactured at the "GOSA" Plant, Smederevska Palanka, most of them are innovative. **Innovations**: Design of the boogie for motion of harbor cranes (7t /30.5m and 20t /30.5m), on curvilinear rails is an original solution. Construction for boom's outreach changing and level luffing with a rope in the counterweight in the column, for the crane 7t/30,5m, is an original solution. Construction of underwater sweepers with removable knives for TISA excavator (patent), projects sandblasting plants HC-2000 and SHELL-MOULDING for foundry Belgrade. Projects of the Terminal for unloading of barges and transport to the Steel Works, Automatic loading plant for two wagons, capacity of 50 t, Winches for Liesen, Duisburg, Foundries for Burma and Indonesia, Lines for assembling agricultural trailers for Russia, etc. He led the scientific project "Investigation of Contemporary Methods for Designing Complex Systems and Structures in Mechanization" (1996-2000).

CO-PRESIDENT OF THE ORGANIZING COMMITTEE

Univ.-Prof. Dipl.-Ing. Dr. techn. Georg Kartnig was born 1964 in Graz (Austria), where he attended the Akademisches Gymnasium and then the degree programme Mechanical Engineering and Business Economics at the Graz University of Technology. After his graduation in 1989, he worked as an university assistant at the Institute for Machine Elements and Conveying Systems.

In his dissertation, he dealt with the dynamic behavior and positioning precision of Automated Storage and Retrieval Systems (AS/RS). The rigorosum took place in 1993, after which Prof. Kartnig stayed at the institute in order to work on his habilitation dealing with the dynamic behaviour and the throughput optimisation of carousel storage systems. Between 1997 and 1998, he was Department Head of "Machine Development" at the company KNAPP Logistik Automation. After completing his habilitation in 1998, he returned to the TU Graz as an extraordinary professor. After Prof. Oser retired in 2008, he became Interim Head of the Institute of Technical Logistics at TU Graz. In the same year, he applied for a professorship at the Institute of Engineering Design and Logistics Engineering at the TU Vienna. In 2009, he took over the professorship at this institute and has been in charge of the research area Engineering Design, Material Handling and Ecodesign since then.

Prof. Kartnig's teaching activities cover the areas of fundamentals of engineering design, advanced engineering design, product development, materials handling and technical logistics. In these subjects, he gives lectures and supervises construction exercises and project papers. In addition, he has been involved in the lecture series "Technology and Society" for five years, in which he deals with the topics of technology and ethics as well as the responsibility of engineers. So far, Prof. Kartnig has supervised 83 diploma theses (18 more are in progress) and 5 dissertations (3 more are in progress).

His research activities focus on the calculation of the handling performance of shuttle systems, the modelling and optimisation of the dynamic behaviour of cable cars, the investigation of friction, slip and wear behaviour of wheel-rail systems of bridge and portal cranes as well as the simulation of cohesive and non-cohesive bulk-material simulation. In addition, the development of new products as well as the improvement of existing products play an important role in his research area. In these and other research fields, Prof. Kartnig has led about 30 large-scale projects, many of them funded by the Austrian Research Promotion Agency (FFG).

He published 41 contributions in international journals or conference proceedings (8 of them on the SCI list with IF) and presented 22 lectures at international conferences.

Prof. Kartnig is Chairman of the Standards Committee for Cranes and Hoists of the Austrian Standard Institute. Moreover, he is a member of the Scientific Society for Technical Logistics and of the European Conference of Materials Handling Professors. Since 2012, he has been co-organiser of the MHCL, which was held at the TU Vienna for the first time in 2015.

CO-PRESIDENT OF THE ORGANIZING COMMITTEE

Prof. Dr.-Ing. Nenad Đ. Zrnić was born in 1966 in Belgrade. He graduated from the University of Belgrade - Faculty of Mechanical Engineering (UB FME) in 1992. In 2005 he was elected Assistant Professor at the Faculty of Mechanical Engineering, in 2009 Associate Professor and in 2013 full - tenured professor and head of the Laboratory for logistics/intralogistics and eco-design. He is Corresponding member of the Academy of Engineering Sciences of Serbia since 2015. Since 1st October 2018 he is Vice Rector of the University of Belgrade for international relations, interuniversity cooperation, innovations and technology transfer.

In the period 2012-2015 he was Vice Dean for Academic Affairs at the UB FME and ECTS coordinator, 2015-2018 Vice Dean for International Cooperation and member of HERE (Higher Education Reform Experts) team. He was the president of the Executive Board of the Association of Mechanical Engineers of Serbia. He is chairman of the Organizing and Scientific Committees of international conferences: MHCL 2006, 2009, 2012 and 2017, held in Belgrade, as well as MHCL in 2015, held in Vienna in cooperation with TU Wien. He is technical expert in Eureka Eurostars program and evaluator of projects H2020 FET OPEN RIA and INNOWWIDE.

Until now he was a supervisor of over 100 MSc and Dipl-Ing. theses, 4 PhD dissertations and currently he is a supervisor of 3 ongoing PhD dissertations. He was a visiting professor at the University of Montenegro – Maritime Faculty in Kotor (2009-2011 and since 2016). He is the author of 2 university textbooks and 2 research monographs (1 in English). He is reviewer in 19 SCI journals and member of editorial board in 5 international journals.

He has excellent multi-year scientific cooperation with the TU Vienna (Institute for engineering design and technical logistics) where he spent a total of 8 months as a visiting researcher. He is a member of several international scientific societies and their bodies: Europäischen Konferenz der Professoren des Fachkreises Foerdertechnik, IFToMM Technical Committee for Transportation Machinery, IFToMM Permanent Commission for History of Mechanism and Machine Science. He was an invited lecturer at foreign universities in Italy - Brescia in 2011 and Greece - Patras, 2013 and at the CEMAT Port Forum in Hannover in 2014.

His scientific research work involves intralogistics and logistics systems, dynamics, strength, integrity and redesign of material handling, conveying and mining machines, eco-design and sustainable logistics, LCA analysis. Among the others he has published 9 chapters in books published by the world's leading publishers (Kluwer, Springer, Wiley, SPH) and 24 papers in international journals on the SCI list with IF. He presented 7 invited plenary papers at international conferences. According to data from Scopus he has got a total of 471 citations, h-index 13, out of which 281 are straight quotes, h-index 10.

He is author of 7 technical and development solutions for industrial purposes, he managed and participated in the realization of 36 projects performed for the purpose of industry, 132 elaborations of as-built design, as well as 26 studies of limited circulation and expertise. He participated in the implementation of 9 projects financed by Serbian Ministry of education, science and technological development, as well as in 13 international projects (1 is FP7 project NEWS, and in international tender he was chosen as the executor of the work package for Serbia WP3 Census of logistic and multimodal platforms in Serbia within the project WATERMODE - Transnational Network for the Promotion of the Water-Ground Multimodal Transport) in 6 among them he was a project manager (since 2017 he is project coordinator of Erasmus+ CBHE project DualEdu), He was an external expert for FP7 project Spider Plus (2013-2015). For the results of his engineering work, he was awarded with a group of authors for the Annual prize of Belgrade Chamber of Commerce for the best technical innovation in 2009.

ABOUT THE MHCL CONFERENCE ORGANIZERS

Vienna University of Technology looks back on a long tradition at the leading edge of scientific research and education: Founded in 1815 as Polytechnisches Institut (Imperial and Royal Polytechnical Institute), it was divided into 5 faculties in 1865. One year later the first freely elected rector was inaugurated. In 1872 its name changed to Technische Hochschule (College of Technology), and in 1902 the first doctorates were awarded. The institution has borne its current name – Technische Universität Wien (Vienna University of Technology) – since 1975. At the Institute for Engineering Design and Product Development the research group Engineering Design for Material Handling and Conveying Systems **(**Konstruktionslehre und Fördertechnik) is engaged with design principles in mechanical engineering and with material handling as technical as well as logistical tasks. Further key aspects of activities are: rail vehicles, ropeways and supporting structures.

The University of Belgrade is the oldest and largest University in Serbia. Technical Faculty at University of Belgrade was established in 1863, and the first subject in the field of Mechanical Engineering ("Mechanics and Science of Machines") in 1873. First subject as a forerunner of the Department of Material Handling, Constructions and Logistics (Department of Mechanization) was "Construction Machinery" established in 1897. Starting from 1907 some chapters on hoist machinery (cranes) have been lectured at the academic level. The Department of Construction Machinery and Facilities Layout was established in 1932. In 1948 was established the Department of Industrial Mechanical Engineering, renamed in 1959 to Department of Mechanization (Material Handling and Design Engineering). Up to now the members of Department of Mechanization published several hundred scientific papers in journals, books, and conference proceedings. The Department has an intensive cooperation with industry. That resulted in numerous projects and developed, designed and constructed series of complex, original and modern transporting and construction machines, devices, and systems in the country (former Yugoslavia) and abroad (Burma, Indonesia, Bangladesh, Germany, Russia, Tanzania, Greece and Azerbaijan – former USSR). All these devices have been constructed and functioning for years now and many of them are innovative.

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SERBIAN MINISTRY OF EDUCATION, SCIENCE AND TECHNOLOGICAL DEVELOPMENT

ACADEMY OF ENGINEERING SCIENCES OF SERBIA

CONTENTS

PLENARY SESSION – INVITED PAPERS

SESSION A – HOISTING AND CONVEYING EQUIPMENT AND TECHNOLOGIES

SESSION B – CONSTRUCTIONS, DESIGN ENGINEERING, MINING EQUIPMENT AND TECHNOLOGIES

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Bucket-wheel excavator gearbox failure analysis and reliability assessment

This paper presents the analysis of failure causes and reliability assessment executed for the gearbox of the bucket-wheel excavator SRs 470.20/3 "TAKRAF" (produced by "Lauhhammer", Germany), which is engaged in overburden excavation at the surface mine 'Kostolac' (in Serbia). In order to determine during which phase the error was made (during the design process, production or exploitation), failure analyses and assessments of reliability have been performed for gearbox elements through the use of Pareto analysis, FTA - Fault Tree Analysis, reliability allocation and failure intensity. For the calculation of reliability allocation and failure intensity an adequate program package was developed. Through the use of the above mentioned procedures data necessary for the identification of most important elements for the analysis regarding the maintenance process and failure prevention measures have been collected.

Keywords: *bucket-wheel excavator, bucket-wheel drive gearbox, failure analysis, reliability*

1. INTRODUCTION

Continuous technological process of excavation, transport and disposal of overburden at the surface mine is being executed through the use of the compact system which consists of the bucket-wheel excavator, rubber band conveyors and spreader. Bucket-wheel excavator SRs 470.20/3 and the excavation subsystem which consists of the electromotor (1), couplers (2, 3), drive gearbox (4), bearings (5), bucket-wheel shaft (6) and wheel (7) with buckets (8) are shown in Figure 1. Bucket-wheel excavator SRs 470.20/3 is engaged in overburden excavation at the surface mine 'Kostolac' and possesses the following technical and technological properties:

- theoretical capacity Q_t = 1688 [m^3/h],
- maximum depth of the cut L = 3 [m],
- maximum height of the cut H = 20 [m],
- drive power of the bucket-wheel N = 400 [kW],
- bucket-wheel diameter D_r = 6.3 [m],
- number of buckets and interbuckets (intercutters) z = 8
- number of interbuckets (intercutters) z_m = 8,
- number of bucket unloads n_s = 58 [min-1],
- overall drive efficiency coefficient η = 0.92,
- cutting rate V_r = 2.4 [m/s].

During the exploitation, bucket-wheel excavator is subjected to loads with changeable amplitudes-stochastic loads [1], which are caused by operating conditions, natural low-frequency oscillations [2] and the simultaneous influence of a large number of technological, metallurgical and structural parameters. Stochastic loads can cause unpredictable failures, damages and breakdowns of components and assemblies. Therefore, the behaviour of the bucket-wheel excavator in real conditions of exploitation and it`s reliability during operation cannot be predicted by engineering methods, but only through the use of methods related to Probability Theory.

Reliability of mechanical components, assemblies and subsystems is a probability that the bucket-wheel excavator will successfully perform it`s operational function within the range of allowable deviations and for the designed interval of time. Development of the reliability is fundamentally based on the comparison of specified magnitudes which characterize the operational ability.

Through the use of Pareto analysis, Fault tree analysis, reliability allocation and failure intensity for the bucket-wheel excavator gearbox the data necessary for the identification of most influential components (elements, assemblies) regarding the reliability assessment, analysis of the maintenance process and refurbishment, as well as for carrying out failure prevention measures [3] were obtained.

2. BUCKET-WHEEL DRIVE GEARBOX FAILURE ANALYSIS

Data regarding the loads on the support structures of the bucket-wheel excavator, properties of base material for components and welded joints, production technologies, structural solutions for assemblies, technical and physical characteristics of recorded breakdowns and prescribed failure prevention measures are being entered into a suitable database. Nevertheless, databases should contain the data acquired during the testing of structures that proved to be adequate.

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2.1 Resistance to excavation and operational stresses at the shaft of the bucket-wheel excavator drive

Measurement of resistance to excavation and calculation of torque at the shaft of the excavation subsystem of the bucket-wheel excavator SRs 470.20/3 in various environments has been performed through the use of the wattmeter method. On the basis of tensometric deformation measurements performed through the use of 4 XY-120-HBM gauges, stresses and torque at which the plastic deformations or initial cracks may occur at the shaft of the excavation subsystem have been calculated. Through the use of the method which refers to the comparison of load and strength by maximizing the ratio of their indicators drive factor K_A at the gear with the highest number of revolutions which is a part of the bucket-wheel drive gearbox was determined.

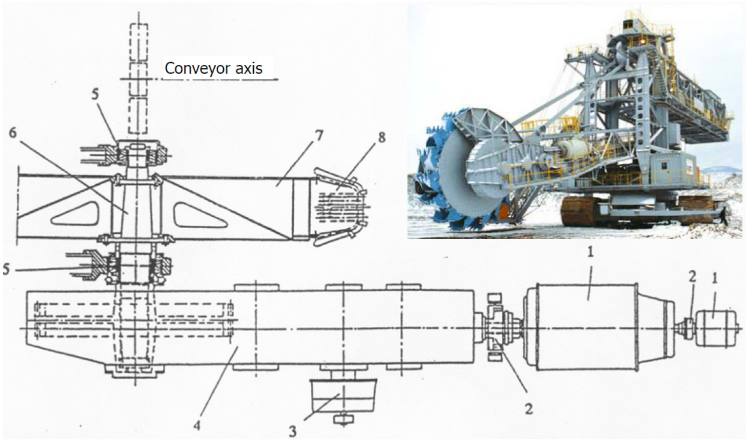

Figure 1. Appearance of the bucket-wheel excavator SRs 470.20/3 and of the excavation subsystem

2.2 Pareto Analysis

On the basis of available databases regarding the failures of the excavation subsystem the Pareto (ABC) analysis has been performed, which shows the average contribution percentage of failures of basic subsystem assemblies in correlation with the overall standstill.

2.3 Fault Tree

A fault tree presents a series of events, causes and effects which cause the failure of the specific function in relation to which the reliability of the system is being assessed. It is of utmost importance to identify the events which directly violate the considered function, as well as to identify the logical correspondence between those events. Fault Tree Analysis continues until the level of basic events which are not caused by other events is being reached by deductive analysis.

2.4 Reliability allocation and failure intensity

Most suitable for the allocation of reliability and failure intensity is the method that is based on the assessment of the relative ratio of the failure intensity of the 'weakest' element and conditionality of possibility of system failure if that element fails. Level of conditionality ranges between 0 and 1. When the failure of an element causes the failure of the whole system $E_i = 1$.

3. RESULTS

All characteristics of the production system, taking into account their role and specified goal functions, are defined as a probability that the system will successfully operate in the moment of need and perform the predefined criterion function in projected time and under existing conditions of exploitation.

3.1 Measurement results

Stresses τi, resistances to excavation per knife length k_{Li} and torques T_i at the bucket-wheel shaft of excavator SRs 470.20/3 were calculated on the basis of tensometric measurements of deformations and powers measured by wattmeter at the electromotor of the bucket-wheel drive. Results of those calculations are shown in Table 1.

Table 1. Values of stress, resistance to excavation and torque at the drive shaft of a bucket-wheel excavator

Operational environment	According to tensometric measurements				According to the power variation of the electromotor			
	Maximum value		Mean value		Maximum value		Mean value	
	T_i [kNm]	τ_i [MPa]	T_i [kNm]	τ_i [MPa]	T_i [kNm]	k_{Li} [N/cm]	T_i [kNm]	k_{Li} [N/cm]
Loose soil	178	21	132	17	275	64	183	441
Transition zone	434	51	283	31	309	75	262	618
Grey clay	576	64	376	38	511	101	326	676

3.2 Pareto Analysis

Pareto analyses that refer to contribution and cause of failure during the operation of the bucket-wheel excavator SRs 470.20/3 showed that the failures of gearbox elements cause more than 40% of failures of the excavation subsystem, Figure 2.

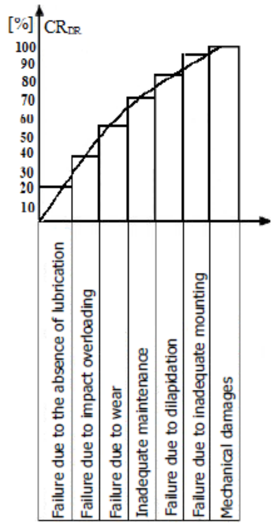

Figure 2. Pareto analyses of the contribution and causes of failure of the bucket-wheel excavator drive gearbox

3.3 Fault Tree Analysis

In Figure 3 detailed analysis of the fault tree for bucket-wheel excavator drive gearbox is shown. The cross-section of the gearbox is shown in Figure 4. Horizontal gearbox of the excavation subsystem, with nominal power N=400 kW and reduction ratio 135 transfers the power, or to put it differently reduces the number of revolutions from 980 to 7.25 min-1 by means of the hollow shaft and bucket-wheel axle.

Basic assemblies of the gearbox are: input shaft (1), lubricating drive (2), slip coupler (3), wedges for the connection of the hollow shaft (4) and the bucket-wheel axle (6) and output gear with the hollow shaft (5), Figure 4.

3.4 Results of reliability allocation and failure intensity

Analysis of reliability and failure intensity of gearbox subassemblies was performed on the basis of their condition during operation, as well as their condition while the bucket-wheel excavator was at a standstill due to failure in the period from 2011–2016 [4], Table 2.

Table 2. Condition of gearbox subassemblies during operation and while at a standstill in the period from 2011–2016

Surface mine “Kostolac”	Time	Total time in operation	Total time at a standstill
Bucket-wheel drive gearbox	[h]	25200	5223

Reliability of the gearbox is being obtained through the use of the following equation:

$$R(t)=\frac{n(t)}{n} \quad (1)$$

Where:
n – total number of hours in operation and at a standstill
$n(t_r)$ = 25000 - total number of hours in operation
$n(t_0)$ = 5223 - total number of hours in standstill
n = 25200 + 5223 = 30423 [h]

$$R(30423)=\frac{25200}{30423}=0.83 \quad (2)$$

Obtained value of reliability could be considered satisfiable. Experimental researches performed on this and similar systems show that reliability of bucket-wheel gearbox subassemblies lies within the range between 0.8051 and 0.8280 (0.8051 ≤ Rbg ≤ 0.8280). It should be emphasized that the lower limit of reliability (Rbg = 0.8051) is the lowest value of reliability of the system, below which the goal function would not be accomplished. This is a referent value of reliability, used in order to determine reliability of other elements of the system. The failure intensity of the bucket-wheel drive gearbox is being obtained through the use of the following equation, on the basis of determined reliability R (30432) = 0.83:

$$\lambda(t)=-\frac{\ln R_s(t)}{n}=-\frac{\ln 0.83}{30432}=-\frac{-0.1863}{30432}=6.122\cdot e^{-6}[h] \quad (3)$$

On the basis of results of complete researches that refer to the reliability of subsystems and their elements in the period from 2011–2016 it was determined that buckets and bucket-wheel drive gearbox have the lowest reliability, while all elements of other subsystems of bucket-wheel excavator SRs 470.20/3 have much lower values of failure criticality.

4. DISCUSSION

On the basis of measurement results it can be concluded that torques and torsion stresses are within the projected range (bucket-wheel shaft material is 25CrMo4V), while the values of specific excavation resistances per knife length, for maximum measured loads, are close to the upper limit k_L=700 [kN/cm], [5].

On the basis of Pareto analyses of failures, taking into account the failure mode of the gearbox assembly shown in Figure 4b, it can be concluded that failures are, for the largest part, caused by the lack of lubrication, impact loads and wear, and to a lesser extent by inadequate maintenance, dilapidation of elements (components), inadequate mounting and the least of all by mechanical damaging.

On the basis of results of analyses that refer to reliability and failure intensity carried out for subsystems of the bucket-wheel excavator drive for the period from 2011–2016 it can be concluded that obtained value of reliability is satisfiable.

On the basis of results of analyses that refer to reliability and failure intensity carried out for subsystems of the bucket-wheel excavator drive for the period from 2011–2016 it can be concluded that obtained value of reliability is satisfiable.

5. CONCLUSION

Approach to failure analysis, carried out for the excavation subsystem of the bucket-wheel excavator SRs 470.20/3, enables the decrease of criticality, severity and effects of failure after adequate measures in the maintenance process have been taken. This approach is usable for all subsystems and all types of bucket-wheel excavators when general data necessary for the identification of most important elements for the analysis are at disposal. Data on the causes of damages and failures is valuable for the improvement of design methods, development of new technical solutions, development of testing methods in the prototype phase, improvement of properties of existing materials and technologies regarding their treatment.

ACKNOWLEDGMENT

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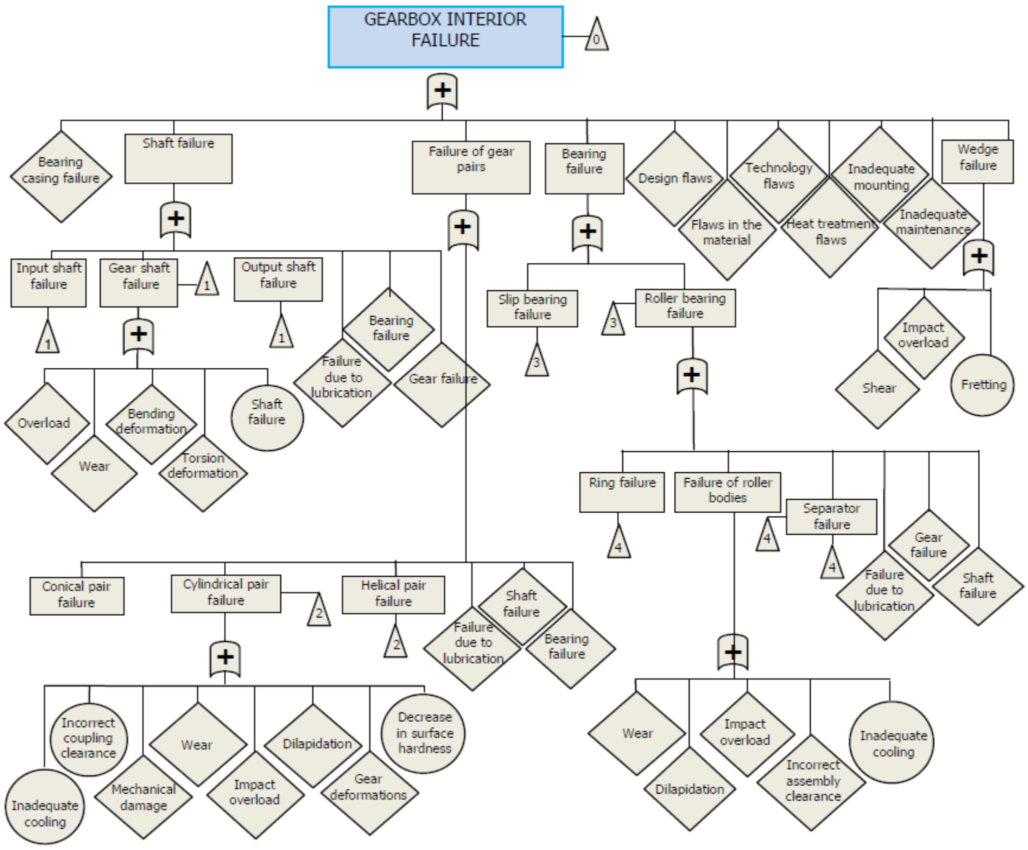

Figure 3. Fault tree analysis that refers to the bucket-wheel excavator drive gearbox

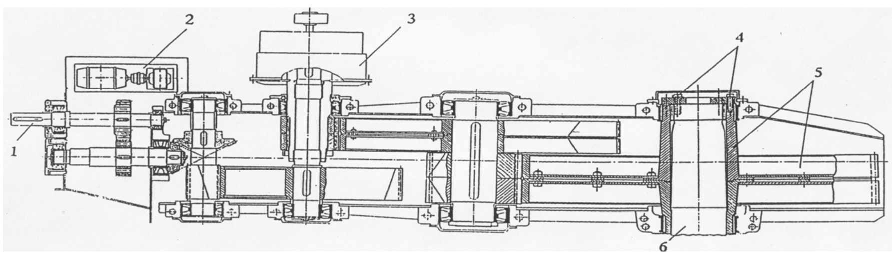

Figure 4. Schematic appearance of the bucket-wheel excavator drive gearbox cross-section