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BACKGROUND

The roots of Serbian technical civilization date as early as the time of the Nemanjics. Beginnings of engineering activities were associated to the mining and metallurgical undertakings (Novo Brdo) and to building of magnificent medieval sacral structures of the Serbian state.

After the First (1804) and second Serbian Uprising (1815) the technical tradition was renewed and Serbian joined the then current European trends. First educated engineers came in Serbia from Austro-Hungarian Empire in 1830s. At that time, the main preoccupations of engineers were railway construction, town planning, construction of sewage disposal and water supply systems, as well as creating of national defense system. At that time 1834/35 from Austrian Empire arrived first schooled engineers France Jankovic and Franz Baron Kordon who served as so called “drzavni indzilirin” or state engineers.

In Serbia in the 19th century there were a total number of about 6000 engineers engaged in various activities. In an eighty–year period from 1834-1914 the State Construction Administration (which from 1880 also included railways) employed one third of these engineers. However other ministries were also competent for some engineering affairs like, for example the Ministry of Finance was responsible for mining, or the Ministry of Education and Church Affaires was responsible for education of technical stuff. From 1838 this primarily referred to the Licej: according to “Establishment of public institutions of learning” of 1844, the Department for Philosophy included also subjects such as Pure and Practical Geometry and Higher Mathematics, and Architecture, while in 1853 a separate Natural Sciences and Technical Department was introduced in the Licej and in 1863 the Great School with Technical Faculty started operating. The first classes held at the Technical Faculty of the Great School in 1863 marked turning point in schooling of Serbian engineers.

Out of some 600 engineers, approximately one third were schooled in Serbia and one fifth of them studied abroad as “state grants students”, while about one fourth were foreigners and Serbs from “across the Danube”.

In 1868 one of preconditions which might have contributed to professional associating of engineers was the numerosity of professionals and models from abroad established half a century earlier (engineering associations in Great Britain, Germany and America) had influence on establishing professional associations in Serbia.

The Founding Assembly of the Technicians’ Society was held on the 3rd February 1868 in the premises of Great School. Engineer Emilijan Josimovic was elected for the first President of the Society. It is important to mention that this happened only a year after Turkish commander in Belgrade Ali -Riza pasha gave the town and the fortress keys to duke Mihailo Obrenovic. Shortly afterward in 1869 was established Society for Agrarian Economy that is the Serbian Agricultural Society. Association of Serbian Engineers was established in 1890 while in 1896 was established the Association of Serbian Engineers and Architects.

The first scientific magazine published by this Association in 1890 was “Srpski tehnicki list” The “Srpski tehnicki list” besides professional articles also published detailed information related to the work of the Association. The members at that time, who numbered around one hundred of them, initiated a whole series of issues and demand the same to be solved by the competent bodies. During the First World War,
two volumes of “Srpski tehnicki list” were published in Thessaloniki. The magazine was initiated by the engineers and architects who were in Thessaloniki as members of the Serbian Army. In Thessaloniki was held the General Assembly of the Association in 1918 attended by 463 engineers.

During his short stay in Belgrade, in 1892, famous scientist Nikola Tesla was elected for the first honorary member of the Association of Serbian Engineers.

Providing assets from its own incomes, bank loans, gifts and donations of its organizations-members and its individual members Association built the House of Engineers in Belgrade, Kneza Milosa 7 str in 1932/35. The House of Engineers “Nikola Tesla” in Belgrade Kneza Milosa 9-11 str was built between 1962 and 1969. In the premises of these two Houses of Engineers besides the Union of Engineers and Technicians of Serbia today perform their activities 26 republic’s professional and multidisciplinary engineering-technicians’ associations out of 41 collective members of UETS.

Besides Emilian Josimovic who was first President of the Technicians’ Society, prominent figure of that time, Rector of Licej and Great School and honorary member of the Serbian Royal Academy, to work of our Union contributed as well: Kosta Alkovic, professor at the Great School, Minister of Construction and member of Serbian Learned Society and Serbian Royal Academy, Dimitrije Stojanovic professor at the Technical Faculty, first Director of Serbian State Railways, and member of Serbian Learned Society and Serbian Royal Academy, Milos Savic, Minister of Construction and President of Belgrade Municipality, famous businessman who gave the greatest donation for the construction of House of Engineers in 1932, as well as presidents of the Serbian Academy of Sciences and Arts Josif Pancic, Jovan Zujovic, Simo Lozanic, Kirilo Savic, Aleksandar Despic, Nikola Hajdin and other famous scientists.

ACTIVITIES

The Union of Engineers and Technicians of Serbia - Savez inženjera i tehnicara Srbije is a voluntary, non-governmental, non-profit, scientific, interest, professional, non-party organization of engineers and technicians, and their organizations in the Republic of Serbia, open for cooperation with other scientific, commercial and other organizations, on the basis of mutual recognition, mutual respect and independence in work.

Union of Engineers and Technicians of Serbia and its collective member finance their own activities from their own assets.

Purposes and tasks of UETS are:

- Assembling and organizing of engineers and technicians of Serbia for the purpose of increase of their expert knowledge, providing appropriate status in the community, on the basis of their contribution to the, scientific-technological and economic and development in general of Republic of Serbia;
- Joining, strengthening and massification of basic engineering-technicians' organizations of Serbia, development of mutual cooperation as well as the cooperation with appropriate international organizations of engineers and technicians;
- Improvement of order-interest, reputation and protection of members of the engineering-technicians' organization of Serbia;
- Providing help to engineers and technicians in scientific, expert improvement and organization of appropriate forms of permanent education;
- Monitoring contemporary development of engineering and technology and pointing out the currents of events and changes in this area and providing opinions on optimality of engineering and technological solutions in investment and other enterprises;
- Caring for and development of ethics of engineering-technician profession, human rights and liberties;
- Stimulating, organization and publishing of scientific and expert papers, magazines and other publications of interest for engineering-technician organization and technical intelligence;
- Work on technical regulations (laws, regulations and standards), providing its modernity, adequacy, actuality and functionality;
- Consideration and providing expert opinions on plans, programs, analysis and other acts, which are important for the development of engineering, technology and production in the Republic of Serbia;
- Stimulating and helping the activities and initiatives, aiming to preserve the human environment and area organization, saving and rationalization of spending of all sorts of energy;
- Preparation and maintenance of the meetings with purpose of permanent education of engineers and technicians;
- Providing help in development of technology and economy whose purposes are similar to the purposes of engineering-technicians' organization;
- Organization of multidisciplinary meetings and meetings of wider social importance;
• Cooperation with appropriate expert, commercial organizations and other organizations and organs at the realization of tasks of mutual interest;
• Management of Houses of Engineers and other property of Union of Engineers and Technicians of Serbia.

Union of Engineers and Technicians of Serbia has developed cooperation with organs of local government, state ministries, Serbian Academy of Sciences and Arts, Serbian Chamber of Engineers, Engineering Academy of Serbia, Chamber of Commerce and Industry of Serbia, with numerous companies, professional associations, faculties and universities and other institutions. UETS also has developer international cooperation.

In accordance with the Law and Contract with republic ministries in the framework of UETS are organized and performed specialist‘ exams for several engineering branches.

Union of Engineers and Technicians of Serbia has several thousand individual members and 41 collective members in the Republic of Serbia: 19 republic’s professional associations (associations of architects, town planners, mechanical engineers, electrical engineers, mining and geological engineers, surveyors, agricultural engineers, chemical engineers etc) 7 republic’s multidisciplinary engineering-technicians’ associations (ecology, standardization and quality, material protection and corrosion, informatics etc) 1 provincial engineering-technicians’ association, 14 municipal and regional engineering-technicians’ associations.

Union of Engineers and Technicians of Serbia is founder of the Engineering Academy of Serbia, and collective member of the Chamber of Commerce and Industry of Serbia.

Union of Engineers and Technicians of Serbia, in a cooperation with faculties, universities, enterprises, economic and professional associations organizes various scientific meetings, professional reunions, congresses, seminars, conferences. UETS members publish their expert magazines; “KGH”; “Procesna tehnika”, “Ecologica”, “Tekstilna industrija”, “Forum”, “Sumarska industrija”, “Zastita materijala” and maintain professional reunions, seminars, conferences and congresses in branches of architecture, mechanical engineering, chemistry, electrical engineering, agriculture, forestry etc.

All activities of the Union are performed in accordance with the procedures and standards of **QMS - Quality Management System.**

Union of Engineers and Technicians of Serbia is National member of **FEANI – European Federation of National Engineering Associations** from Serbia. FEANI is a federation of professional engineers that unites national engineering associations from 32 European countries. Thus, FEANI represents the interests of over 3,5 million professional engineers in Europe. FEANI is striving for a single voice for the engineering profession in Europe and wants to affirm and develop the professional identity of engineers. Through its activities and services, especially with the attribution of the EUR ING professional title, FEANI aims to facilitate the mutual recognition of engineering qualifications in Europe and to strengthen the position, role and responsibility of engineers in society.

Union of Engineers and Technicians of Serbia is member of COPISSE – Permanent Conference of the Engineers of Southeast Europe.

Collective members of UETS are members of international professional associations and have developed international cooperation.

With all that has been done and with accomplished results, objectively solid conditions have been provided for further and more successful work, business operation and development of the Union of Engineers and Technicians of Serbia.
NEW MATERIALS

Original scientific papers
Ivana Dinić, Lidija Mančić, Olivera Milošević, Hydrothermal Synthesis of Optically Active Fluoride particles Doped with Rare Earth Ions in the Presence of Ethylenediaminetetraacetic acid (EDTA) ................................................................. 9

OUR CIVIL ENGINEERING

Original scientific papers
Khaled Omar Almayouf, Dejan Beljaković, Aleksandar Milajić, Methodology for Developing Probabilistic Productivity Norms in Civil Engineering .................................................................................. 17

MINING, GEOLOGY AND METALLURGY

Original scientific paper
Dragana Nišić, Dinko Knežević, Nevena Sijerković, Uroš Pantelić, Mirjana Banković, Comparative Risk Assessment of CCW Disposal in the Old and New Landfill of the Coal-Fired Power Plant Kostolac Based on the Hydrological Scenario ........................................ 25

Original scientific paper
Goran Tasev, Todor Serafimovski, Industrial Contamination of Soil Related to Some Active and Closed Mine Facilities in the Republic of Macedonia ............................................................. 33

Original scientific paper
Ivana Manasijević, Nada Štrbac, Dragana Živković, Ljubiša Balanović, Duško Minić, Dragan Manasijević, The Effect of Zinc on the Microstructure and Phase Transformations of Casting Al-Cu Alloys ..................................................................................................................................... 41

MECHANICAL ENGINEERING

Original scientific papers
Goran Cvijović, Srdan Bošnjak, Calculation Methods' Comparative Analysis of Monorail Crane Local Bending Effects ........................................................................................................ 51

Goran Vasilić, Saša Živanović, Modelling and Analysis of 2-axis Reconfigurable Parallel Mechanism MOMA with Translatory Actuated Joints ........................................................................ 59
ELECTRICAL ENGINEERING

Original scientific paper
Aleksandra Lekić, Dušan Stipanović, LMI Approach for Sliding Mode Control and Analysis of DC-DC Converters

TRAFFIC

Original scientific paper
Milan Andrejić, Milorad Kilibarda, Measuring Global Logistics Efficiency Using PCA-DEA Approach

Previous announcement
Dubravka Vuković, Railway Stations as Efficiency Decision-Making Units – Input and Output DEA Model

MANAGEMENT

Original scientific papers
Darko Božanić, Dragan Pamučar, Samed Karović, Application the MABAC Method in Support of Decision-Making on the Use of Force in a Defensive Operation
Snežana Tadić, Slobodan Zečević, Global Trends and Their Impact on City Logistics Management

QUALITY IMS, STANDARDIZATION AND METROLOGY

Original scientific paper
Marina Janušević Strižak, Sustainable Management of Drinking Water Production Plant Pollutants

Review paper
Radoje Jevtić, Fire Detectors Arrangement in Objects with Slope Roof
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Novi materijali – Nouveaux matériaux – Neue Materialien – Новые материалы


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Hydrothermal Synthesis of Optically Active Fluoride Particles Doped with Rare Earth Ions in the Presence of Ethylenediaminetetraacetic Acid (EDTA)

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Fluorescent nanoparticles have an important role in biological analyzes, and in the last 10 years they are successfully applied in a visualization and characterization of biological processes at the cellular and molecular level, as well as, in the development of fluorescent lamps, displays, plasma screens and protective labels. The great interest is directed towards the development and implementation of the light up-converters containing rare earth ions which have the ability of the intense luminescence. In this paper we described the process of EDTA assisted hydrothermal synthesis of the rare earth doped fluorides. Different structural forms of materials were obtained by changing the time of a hydrothermal reaction. Comparison of the NaYF₄:Yb³⁺/Er⁴⁺ structure, morphology and optical properties were done based on X-ray powder diffraction analysis (XRPD), scanning and transmission electron microscopy (SEM and TEM) and through measuring of the luminescence in a visible part of spectra. It was shown that the transformation from cubic to hexagonal phase is affected by the reaction time, while the up-conversion luminescence is dependent of the particles morphology and the crystal structure.

Key words: NaYF₄:Yb³⁺/Er⁴⁺, EDTA, hydrothermal synthesis, luminescence

1. INTRODUCTION

Up-conversion (UC) nanoparticles which comprise rare earth (RE) elements have been successfully applied recently in a visualization of the different biological processes at the cellular and molecular level since that they have remarkable photostability and low citotoxicity. Beside being attractive as biological markers, they are used as light sources (fluorescent lamps), in the production of displays, plasma screens and protective labels [1, 2]. Fluoride-based rare earth halides, such as YF₃ and NaYF₄ represent the most efficient hosts for doping of the optically active rare earth ions due to their high refractive index, excellent chemical stability and very low phonon energy of 350–400 cm⁻¹ [3, 4]. YF₃ crystallizes in the orthorhombic crystal arrangement (space group Pnma) while NaYF₄ may occur as cubic α (Fm-3m) or hexagonal β phase. For latter one, symmetry is still under debate and the following space groups P63/m, P-6 and P-62m have been considered as possible ones which could describe its crystal arrangement well [5]. This phase is thermodynamically more stable than cubic one, and α → β transformation occurs through increasing of the reaction temperature or with prolongation of the reaction time [6, 7]. Due to the existence of a higher number of cationic site for RE ions doping (according to the literature, depending on the space groups there are two or three possible sites for doping) β-NaYF₄ exhibits superior UC efficiency and provides long lifetime of the excited states [8]. Besides the crystal structure, the particle size, shape and purity, as well as the concentration and the homogeneous distribution of dopants also affect the up-conversion efficiency in a great measure.

Up-conversion represents a nonlinear optical process in which two or more absorbed photons are combined toward emitting a light with of higher energy. In this process absorption occurs at the longer wavelengths (NIR and IR) than emission (UV and VIS). Three basic mechanisms could contribute to efficient photon up-conversion: excited state absorption (ESA),
energy transfer (ET) and photon avalanche (PA) [9]. Due to the rich energy levels, trivalent Er, Tm, Ho, Nd and Pr were usually co-doped with Yb, which have high absorption cross section at 980 nm, in order to achieve efficient up-conversion emission. In the case of Yb3+/Er3+ pair, Er3+ ion has metastable 4I9/2 and 4I11/2 levels which are perfectly resonant with the 4F9/2 level of Yb3+ so the energy transfer from ytterbium to erbium (and then to higher energy levels of erbium) occurs enabling emission of the erbium ion upon excitation of ytterbium by the near infrared (NIR) source [10].

The synthesis of up-converting halides through co-precipitation, thermal decomposition of trifluoroacetates (in the presence of oleic acid and oleylamine) and hydro/solvothermal processing are widely explored and presented in the literature [11]. In order to control the composition, shape and size of nanoparticles organic additives such as trisodium citrate (TSC), ethylenediaminetetraacetic acid (EDTA) and cetyltrimethylammoniumbromide (CTAB) are commonly used. EDTA represents the polyamino carboxylic acid which belongs to a group of hexadentate chelating ligands capable to bind RE3+ ions [12]. It enables homogeneous nucleation of the NaYF4:Yb3+/Er3+ phase, wherein the temperature of the hydrothermal treatment, as well as, amount of EDTA and fluorides determines the crystal arrangement, shape and size of the particles. For example, the spherical particles (diameter ~ 300 nm) with a cubic crystal structure were synthesized hydrothermally from common aqueous solution of chlorides (0.05 mmol) and RE:EDTA=1:2 at T=180 ºC, while either ethanol addition or the increase of the precursor concentration enables generation the hexagonal NaYF4 microcrystals [13, 14]. Cubic α-NaYF4 nanospheres (50-100 nm) as well as hexagonal β-NaYF4 microparticles (size of around 2.5 μm) were also synthesized hydrothermally (180 ºC, 24h) when higher F/RE3+ and EDTA/RE3+ ratios were used [15]. In this case, decrease of the precursor concentration leads to the formation of YF3. Based on this, it is concluded that transformation from cubic to hexagonal phase is possible with increase of the temperature, precursor concentration or F/RE ratio, and is usually followed by a change of particles morphology [16].

This paper presents the impact of hydrothermal processing time on nucleation, growth, crystallinity and luminescence characteristics of up-converting fluoride particles synthesized in the presence of EDTA.

2. MATERIALS AND METHODS

Hydrothermal synthesis. Synthesis of up-converting NaYF4:Yb3+/Er3+ nano and microparticles were performed by EDTA assisted hydrothermal method from common nitrate precursor comprising overall concentration of RE3+ ions of 100 mmol, dopants concentration of 20 mol%, predefined surplus of NaF (F:RE3+= 7:1) and EDTA:RE3+=4. All reagents were used as obtained from Sigma Aldrich.

In a typical synthesis route, total amounts of rare earth nitrates, EDTA and NaF were separately dissolved in water and then mixed together. The resulting solution was thoroughly stirred, heated up to 60 ºC for additional 15 min, and transferred to a 100 ml Teflon lined autoclave (filling factor of 80 %). The pH value was kept at 3 with the addition of few drops of HNO2. Sealed autoclave with a reaction mixture was then slowly heated up to 200 ºC with the continual stirring (100 rpm). After cooling, the as-prepared particles were washed with water several times by centrifugation (8000 rpm, 10 min) and dried at 100 ºC for 3h. The final product was retrieved through additional thermal treatment at 500 ºC (4 h) in the argon atmosphere.

In the following text thermally treated samples obtained through hydrothermal processing during 0.5 and 2 h are labeled as sample 1 and sample 2, respectively.

X-ray powder diffraction (XRPD) patterns were obtained using Bruker D8 Discovery and Philips X’PERT diffractometers equipped with a Cu-Kα source (λ = 1.5406 Å). Powders structural data were acquired through combined La Bail and Rietveld refinement in Topas 4.2. For the β-NaYF4 hexagonal phase, trial refinements were carried out in P63/m (No.176) and P-6 (No.174) space groups, of which later provided slightly better goodness of fit, while for cubic α-NaYF4 phase Fm-3m (No.225) data from the ICSD 60257 card were used.

The morphological features and chemical purity of the particles were investigated by means of both scanning (SEM XL 30/EDS Dx4 and FESEM/EDAX HITACHI SU-70) and transmission electron microscopy (JEOL TEM 2010).

Photoluminescence emission spectra and decay time measurements were performed on L980300J (Thorlabs) spectrometer with a scattering detector MCP-D7700:311C (Otsuka Electronics Co. LTD) and using a spectrometer system which comprises optical parametric oscillator excitation source (EKSPA LA NT 342, emission range 210–2300 nm), Cryostat (Advance Research Systems DE202-AE) equipped with Lakeshore model 331 controller, spectograph FHR 1000 (Horiba Jobin–Yvon, 300 groove/mm grating) and ICCD detector (Horiba Jobin–Yvon 3771) using 978 nm laser excitation.

3. RESULTS AND DISCUSSION

Crystal structure has proved to be one of the most affecting factor that affects growth of the particles and
their luminescence emission. As it is mentioned before, NaYF₄ could crystallize in cubic and hexagonal crystal arrangement. In a cubic phase (space group Fm-3m) with a high degree of symmetry there is only one crystal site over which Na⁺ and RE³⁺ ions are randomly distributed, whereas in the hexagonal phase two (P63/m) or three (P-6) cationic sites for Na⁺ and RE³⁺ ions accommodation exist. Diffraction patterns of the synthesized samples are presented at Figure 1.

![Figure 1 - XRPD patterns: sample 1: α-NaY₁₀.₈Yb₀.₁₇Er₀.₀₃F₄ (a); and sample 2: β-NaY₁₀.₈Yb₀.₁₇Er₀.₀₃F₄ (b)](image)

Morphology of samples obtained through transmission (TEM) and scanning electron microscopy (SEM) are shown at Figures. 2. and 3, respectively.

![Figure 2 - TEM/SAED images of sample 1: α-NaY₁₀.₈Yb₀.₁₇Er₀.₀₃F₄ (a) and chemical composition of the particles (b)](image)

As it is evident from Figure 2 (sample 1) non agglomerated, spherical particles with a size of around 50 nm were obtained. The selected area electron diffraction (SAED) rings (inset in Fig. 2a) confirm good particle crystallinity and correspond to the following d values of a cubic NaYF₄ phase: (111) 3.164 Å, (220) 1.931 Å, (311) 1.650 Å. Qualitative energy dispersive analysis implied high purity and presence of Na, Y, Yb, Er and F inside one nanoparticle (Fig. 2a), while Cu line originates from TEM grid. With the prolongation of the synthesis time formation of the micron-sized particles was observed (sample 2, Fig. 3).

Well defined hexagonal prisms with the elongated rectangular sides (average diameter of 500 nm and length of about 3 μm), represents a typical form of β NaY₁₀.₈Yb₀.₁₇Er₀.₀₃F₄ particles. Intersected elongated polyhedral conjugated in a shape of flowers were sporadically observed in the sample as a result of a mismatched closure (Fig. 3b). As it is already reported α → β phase transition is usually followed with a change of the particle morphology [17]. During the synthesis of a NaYF₄ nucleation of α phase occurs first. In a course of reaction time the nucleation of the
more thermodynamically stable hexagonal phase which is characterized by anisotropic growth begin at the surface of the spherical particles. Growth of petals is influenced further by the growth rate of distinct crystal facets determined by their relative chemical potential (which is proportional to their surface-atom ratio). Since that {100} crystal planes have a bigger density of the RE$^{3+}$ ions than {001} ones, selective adsorption of the F$^{-}$ ions over them contributes further to their anisotropic growth grow creating a hexagonal prisms with a common base.

Decreasing of the spherical base due diffusion/recrystallization, as well as a friction among petals that resemble the flower led to their separation and appearance of the individual hexagonal prisms in sample 2.

**Figure 3 - SEM images of sample 2: β-NaY$_{0.8}$Yb$_{0.17}$Er$_{0.03}$F$_4$**

Photoluminescence measurement was carried out at room temperature at the excitation wavelength of 978 nm. Observed emission peaks in up-conversion spectra presented at Fig. 4a are assigned to the following f–f electronic transitions of Er$^{3+}$ ion: $^4$H$_{9/2}$→$^4$I$_{15/2}$ (405–420 nm), $^3$H$_{11/2}$, $^4$S$_{3/2}$→$^4$I$_{11/2}$ (520–540 nm) and $^4$F$_{9/2}$→$^4$I$_{15/2}$ (640–720 nm) giving blue, green and red emission, respectively, Fig. 4b [18]. Those transitions are much more intense in the spectrum of the sample 2 (β-NaY$_{0.8}$Yb$_{0.17}$Er$_{0.03}$F$_4$) due to the better crystallinity of this sample. Intensification of the red emission in spectrum of sample 1 appears due to the rise of the non-radiative $^4$I$_{11/2}$→$^4$I$_{13/2}$ relaxation (which proceeds to the direct population of $^4$F$_{9/2}$ level) which is enhanced in the nanocrystals [19]. As a result, despite having same chemical composition synthesized samples are distinguished by different CIE chromaticity coordinates, Figure 4b. Superiority of the β-NaY$_{0.8}$Yb$_{0.17}$Er$_{0.03}$F$_4$ phase optical properties is also proven by the measurement of the decay times upon NIR excitation at λ=980 nm. All decays were well fitted with the single exponential function $I(t)=I_0\exp(-t/\tau)$, where $I_0$ is the initial emission intensity at t=0 and $\tau$ is decay in milliseconds: 0.124 (blue, $^4$H$_{9/2}$→$^4$I$_{15/2}$), 0.251 (green, $^3$H$_{11/2}$, $^4$S$_{3/2}$→$^4$I$_{11/2}$) and 0.300 (red, $^4$F$_{9/2}$→$^4$I$_{15/2}$). The obtained data were significantly better from the data reported in the literature for particles with the same composition and morphology, but obtained through assistance of KF and TSC (instead of NaF and EDTA): 0.023-0.058 (green $^4$S$_{3/2}$) and 0.121.54-0.276 (red, $^4$F$_{9/2}$→$^4$I$_{15/2}$) [20].

**Figure 4 - Up-converted spectra of NaY$_{0.8}$Yb$_{0.17}$Er$_{0.03}$F$_4$ (a) and powders CIE coordinates with the energy level diagrams of Yb$^{3+}$ and Er$^{3+}$ ions following excitation with 978 nm (b)**

4. CONCLUSION

Cubic and hexagonal NaY$_{0.8}$Yb$_{0.17}$Er$_{0.03}$F$_4$ nano and microparticles were obtained through hydrothermal synthesis in the presence of EDTA and surplus of NaF. Spherical α-NaY$_{0.8}$Yb$_{0.17}$Er$_{0.03}$F$_4$ phase with a size of around 50 nm were prepared after only 0.5 h of hydrothermal processing, while prolongation of the reaction time led to α phase dissolution and recrystallization of the micron sized β-NaY$_{0.8}$Yb$_{0.17}$Er$_{0.03}$F$_4$ phase. Although measurements of the luminescence
HYDROTHERMAL SYNTHESIS OF OPTICALLY ACTIVE FLUORIDE

indicates good up-conversion properties in both samples, increased nonradiative $^2I_{11/2} \rightarrow ^4I_{15/2}$ relaxation in nanoparticles suppresses green emission and shifts the final light output from green to red part of the visible spectrum of a NaY$_0.8$Yb$_{0.17}$Er$_{0.03}$F$_4$ phase.

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REFERENCES:


I. DINIĆ at al. HYDROTHERMAL SYNTHESIS OF OPTICALLY ACTIVE FLUORIDE TECHNICS – NEW MATERIALS (2016)


REZIME

HIDROTERMALNA SINTEZA OPTIČKI AKTIVNIH ČESTICA FLUORIDA DOPIRANIH JONIMA RETKIH ZEMALJA U PRISUSTVU ETILENDIAMINTETRASIRĆETNE KISELINE (EDTA)

Fluorescentne nanočestice imaju važnu ulogu u biomedicini jer se poslednjih nekoliko godina sa uspehom primenjuju u vizualizaciji i karakterizaciji bioloških procesa na ćelijskom i molekulskom nivou, kao i u izradi fluorescentnih lampi, displeja, plazma ekrana i zaštitnih oznaka. Najveće interesovanje usmereno je ka razvoju i primeni svetlosnih "up"- konvertora koji sadrže jone elemenata retkih zemalja i imaju sposobnost intenzivne luminescencije. U ovom radu opisan je postupak hidrotermalne sinteze fluorida dopiranih jonima elemenata retkih zemalja u prisustvu etilendiamintetrasirćetne kiseline (EDTA). Različite strukturne forme dobijene su promenom vremena hidrotermalne reakcije. Radi poređenja strukture, morfologije i optičkih karakteristika kubne i heksagonalne Na$_2$YF$_4$:Yb$^{3+}$/Er$^{3+}$ korišćene su analize rendgenske difrakcije (XRD), skenirajuće i transmisione elektronske mikroskopije (SEM i TEM), kao i merenje luminescencije u vidljivom delu spektra. Pokazano je da na transformaciju kubne u heksagonalnu fazu utiče vreme reakcije, dok je up - konvertorska luminescencija u funkciji morfologije i kristalne strukture čestica.

Ključne reči: Na$_2$YF$_4$:Yb$^{3+}$/Er$^{3+}$ EDTA, hidrotermalna sinteza, luminescencija
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Methodology for Developing Probabilistic Productivity Norms in Civil Engineering

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Successful implementation of the Critical Path Method requires availability of clearly defined duration for each activity, while the PERT method is based on personal estimation. However, due to the long duration of the construction and unpredicted delays that accompany this process, it is often difficult or almost impossible to predict exact duration of an activity, and consequently to take it for granted that the given activity will be finished on the very same day that is given in the dynamic plan of construction. The aim of presented research was to establish methodology for developing new productivity norms for construction works for planning under uncertainty.

Key words: productivity norms, dynamic plans, uncertainty

1. INTRODUCTION

In construction industry, productivity norm can be defined as time required by a skilled worker qualified for a given type of work to successfully complete specific procedure and/or sequence of work operations with satisfactory quality using appropriate tools and/or machines, in average surrounding and ambient conditions, with normal effort and fatigue.

Standard productivity norms, which have been used for decades in civil engineering for calculating and planning duration of the construction works, can be basically described as deterministic, because they are always precisely and strictly defined by an exact number. However, in realistic situations in practice, there are many cases where an activity duration cannot be presented in a precise manner, especially in construction projects.

 Durations of different activities are usually taken from the productivity norms for man-hours calculation [1], which are often too generalized and sometimes obviously not accurate. For example, productivity rates for man-hours calculation for in-situ reinforcement fixing are based only on total amount of the reinforcing steel, regardless of the pattern complexity which can greatly affect time needed for proper placing, tying and control.

 Because of that, patterns consisting of 12Ø16 and 3Ø32 bars, respectively, have exactly the same total amount of steel and consequently the same theoretical number of man-hours needed for placing and fixing, although it is obvious that such result would not be realistic, as was proven in studies [2, 3].

 Besides that, Proverbs at al. [4] have proven that productivity rates can significantly vary from country to country. All these factors can lead to an unreliable dynamic plan for a given construction project. Critical Path Method (CPM), known in practice for decades, is characterized by the fact that the duration of any activity in the network diagram is known and expressed deterministically (by one exact number).

 However, in the general dynamic plan of construction process, it would be more desirable and realistic to have the duration of any construction activity and deadline for its accomplishment expressed as an interval of a few days rather than one specific day or date [5].
The first solution of this problem has emerged in the form of the PERT method (Program Evaluation and Review Technique), based on the theory of probability, but the application of this method in practice is very limited due to the fact that existing production norms provide only average times for accomplishing different activities, while the other required data, such as optimistic and pessimistic times, have to be estimated subjectively or by using database with collected data from previous projects and/or experiences. The aim of presented study was to introduce probabilistic approach in planning by creating productivity norms that provide not only average or most likely time, but also optimistic and pessimistic time for each activity, based not on individual estimation but on realistic data obtained by the field research and illustrated by the example of times needed for laying ceramic floor and wall tiles.

2. PROBABILISTIC APPROACH

Although the CPM technique has become widely recognized as valuable tool for planning and scheduling large construction projects, this method is based on clearly determined time duration for each activity. However, due to the complexity of construction projects, their long duration and accompanied and unavoidable risks, it is often unrealistic to expect that a given activity, group of activities or the entire project will be accomplished exactly on the day given in the dynamic plan of construction. This results in an unreliable dynamic plan for construction process.

In order to create a realistic and more applicable progress schedule in the construction industry, it is often better to use the PERT method, which does not provide exact date of accomplishing given task, but the time interval in which the task will be accomplished, thus including the element of uncertainty in order to provide expected time-frame for the network chart [6].

In this approach, every activity’s duration is described by a set of three data that can be obtained by a statistical study or subjective estimation:

- $t_o$ = optimistic time – minimum possible time required to accomplish the task;
- $t_m$ = most likely time – activity duration with high probability of completing the task;
- $t_p$ = pessimistic time – maximum possible time required to accomplish the task.

These three variables are used for calculating the expected time ($t_e$), defined as most probable (average) time for accomplishing given activity:

\[
  t_e = \frac{t_o + 4t_m + t_p}{6}
\]

with standard deviation:

\[
  \sigma = \frac{t_p - t_o}{6}
\]

Although the PERT method has proven to be a reliable source for making dynamic plans, its application in engineering practice is limited by the fact that official productivity norms offer only most likely time, while optimistic and pessimistic time have to be estimated by an individual’s estimation based on experience. This paper presents methodology for developing database of norms applicable for the PERT method, in which each activity is described by its three characteristic times, namely: optimistic, most likely and pessimistic time. Further improvement of the method can be achieved by introducing the level of probability of accomplishing given task in order to enable the planner to chose between higher and lower accuracy.

3. DATA COLLECTING AND PROCESSING

Proposed methodology for developing empirical productivity norms that would be applicable in the PERT method (Figure 1) will be illustrated by the example of productivity norms for setting different types of ceramic tiles.

\[\text{Figure 1} - \text{Algorithm for obtaining probabilistic productivity norms}\]

In order to gather data for developing adequate probabilistic norms, a field research was conducted on five ongoing building sites. Research included 24 tile setters. Times needed for laying 12 different types of
tiles were measured and expressed as time necessary for laying 1 m² of tiles, i.e. min/m². Examined activities are presented in Table 1. Obtained times for each tile type were grouped into intervals of 2 minutes, where a nominal value for each interval is expressed by its mean value, and presented graphically as frequency polygon that shows number of results in each interval (Figure 2). Shape of obtained polygons indicates that the most appropriate function approximation in all cases would be the normal (Gaussian) distribution.

Empirical and calculated values for Gaussian distributions are presented in Table 2.

Table 1. Considered types of ceramic tiles

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRW 1</td>
<td>Laying ceramic floor tile 10x20 in cement mortar</td>
<td>SRW 7</td>
<td>Laying ceramic wall tile 15x15 in cement mortar with highlighted joints</td>
</tr>
<tr>
<td>SRW 2</td>
<td>Laying ceramic floor tile 10x20 with adhesive</td>
<td>SRW 8</td>
<td>Laying ceramic wall tile 10x20 in cement mortar</td>
</tr>
<tr>
<td>SRW 3</td>
<td>Laying ceramic floor tile 10x10 in cement mortar</td>
<td>SRW 9</td>
<td>Laying ceramic wall tile 10x20 in cement mortar with highlighted joints</td>
</tr>
<tr>
<td>SRW 4</td>
<td>Laying ceramic floor tile 10x10 with adhesive</td>
<td>SRW 10</td>
<td>Laying ceramic wall tile 15x15 with adhesive</td>
</tr>
<tr>
<td>SRW 5</td>
<td>Laying ceramic floor tile 20x20 in cement mortar</td>
<td>SRW 11</td>
<td>Laying ceramic wall tile 15x15 with adhesive with highlighted joints</td>
</tr>
<tr>
<td>SRW 6</td>
<td>Laying ceramic wall tile 15x15 in cement mortar</td>
<td>SRW 12</td>
<td>Laying ceramic wall tile 10x20 with adhesive</td>
</tr>
</tbody>
</table>

Table 2. Empirically obtained times and calculated values for Gaussian distributions

<table>
<thead>
<tr>
<th>ID</th>
<th>(\mu_E)</th>
<th>(\sigma_E)</th>
<th>(\mu_\Lambda)</th>
<th>(\sigma_\Lambda)</th>
<th>NP</th>
<th>DF</th>
<th>(\chi^2)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRW 1</td>
<td>98.05</td>
<td>5.48</td>
<td>98.00</td>
<td>5.15</td>
<td>9</td>
<td>5</td>
<td>2.640</td>
<td>0.95</td>
</tr>
<tr>
<td>SRW 2</td>
<td>78.22</td>
<td>6.05</td>
<td>77.90</td>
<td>3.07</td>
<td>10</td>
<td>6</td>
<td>6.560</td>
<td>0.89</td>
</tr>
<tr>
<td>SRW 3</td>
<td>105.80</td>
<td>6.63</td>
<td>105.80</td>
<td>3.66</td>
<td>11</td>
<td>7</td>
<td>1.359</td>
<td>0.98</td>
</tr>
<tr>
<td>SRW 4</td>
<td>85.84</td>
<td>6.05</td>
<td>86.15</td>
<td>2.91</td>
<td>10</td>
<td>6</td>
<td>7.300</td>
<td>0.88</td>
</tr>
<tr>
<td>SRW 5</td>
<td>90.12</td>
<td>5.48</td>
<td>90.29</td>
<td>3.86</td>
<td>9</td>
<td>5</td>
<td>2.400</td>
<td>0.92</td>
</tr>
<tr>
<td>SRW 6</td>
<td>128.14</td>
<td>6.63</td>
<td>128.00</td>
<td>4.10</td>
<td>11</td>
<td>7</td>
<td>3.30</td>
<td>0.94</td>
</tr>
<tr>
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<td>157.68</td>
<td>6.63</td>
<td>157.60</td>
<td>4.256</td>
<td>11</td>
<td>7</td>
<td>3.82</td>
<td>0.90</td>
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<tr>
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<td>6.05</td>
<td>161.44</td>
<td>5.634</td>
<td>10</td>
<td>6</td>
<td>8.79</td>
<td>0.82</td>
</tr>
<tr>
<td>SRW 9</td>
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<td>5.47</td>
<td>199.44</td>
<td>2.91</td>
<td>9</td>
<td>5</td>
<td>4.92</td>
<td>0.93</td>
</tr>
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<td>81.20</td>
<td>2.32</td>
<td>9</td>
<td>5</td>
<td>0.78</td>
<td>0.98</td>
</tr>
<tr>
<td>SRW 11</td>
<td>101.65</td>
<td>6.05</td>
<td>101.92</td>
<td>3.70</td>
<td>10</td>
<td>6</td>
<td>2.37</td>
<td>0.95</td>
</tr>
<tr>
<td>SRW 12</td>
<td>105.69</td>
<td>6.63</td>
<td>105.40</td>
<td>4.39</td>
<td>11</td>
<td>7</td>
<td>14.03</td>
<td>0.80</td>
</tr>
</tbody>
</table>

(\(\mu_E\) – mean empirical value [min/m²]; \(\sigma_E\) – standard deviation of the empirical data; \(\mu_\Lambda\) – mean value of approximation; \(\sigma_\Lambda\) – standard deviation of the approximation; NP – Number of points; DF – degrees of freedom; \(\chi^2\) – chi square; \(R^2\) – coefficient of determination)
Figure 2 - Frequency polygons and approximations
In order to estimate accuracy of adopted approximations, it is necessary to perform a significance tests that include calculating values of correlation coefficient, coefficient of determination, chi-squared and Fisher’s analysis of variance [7]. Results of performed tests are presented in Tables 3.

High values of the correlation coefficient (ranging from 0.894 to 0.989) indicate strong correlation between the empirical data and the Gaussian distribution. Values of the coefficient of determination vary from 0.80 to 0.98, which gives average variation of 0.9 between the empirical and Gaussian distribution, meaning that approximation function passes through approximately 90% points on the scatter plot, so it can be concluded that the empirical data are well represented by the Gaussian distribution [8].

It can be further observed that all calculated values \( \chi^2 \) are lower than critical values \( \chi^2_{\alpha} \), which indicates that any discrepancy between the frequencies of the empirical and Gaussian distribution can be considered as a random one.

Only two calculated value of \( F \) (SRW4 and SRW10 ) are equal to or greater than the critical values \( F_{\alpha, N1-N2-1} \), which can be considered as random error. All other values meet the criterion \( F < F_{\alpha, N1-N2-1} \), so it can be concluded that differences found between the variances have no statistical significance.

<table>
<thead>
<tr>
<th>ID</th>
<th>R^2</th>
<th>R</th>
<th>( \chi^2 )</th>
<th>DF</th>
<th>( \chi^2_{\alpha} )</th>
<th>( \sigma^2_e )</th>
<th>( \sigma^2_a )</th>
<th>F</th>
<th>( F_{\alpha, N1-N2-1} )</th>
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<tbody>
<tr>
<td>SRW 1</td>
<td>0.955</td>
<td>0.977</td>
<td>2.640</td>
<td>5</td>
<td>11.10</td>
<td>30.03</td>
<td>26.52</td>
<td>1.132</td>
<td>5.0503</td>
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<tr>
<td>SRW 2</td>
<td>0.890</td>
<td>0.943</td>
<td>6.560</td>
<td>6</td>
<td>12.60</td>
<td>36.60</td>
<td>9.42</td>
<td>3.885</td>
<td>4.2839</td>
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<tr>
<td>SRW 3</td>
<td>0.980</td>
<td>0.989</td>
<td>1.359</td>
<td>7</td>
<td>14.10</td>
<td>43.96</td>
<td>13.39</td>
<td>3.283</td>
<td>3.7870</td>
</tr>
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<td>0.880</td>
<td>0.938</td>
<td>7.300</td>
<td>6</td>
<td>12.60</td>
<td>36.60</td>
<td>8.47</td>
<td>4.321</td>
<td>4.2839</td>
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<td>SRW 5</td>
<td>0.920</td>
<td>0.959</td>
<td>2.400</td>
<td>5</td>
<td>11.10</td>
<td>30.03</td>
<td>14.90</td>
<td>2.033</td>
<td>5.0503</td>
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<tr>
<td>SRW 6</td>
<td>0.940</td>
<td>0.969</td>
<td>3.300</td>
<td>7</td>
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<td>43.96</td>
<td>16.81</td>
<td>2.615</td>
<td>3.7870</td>
</tr>
<tr>
<td>SRW 7</td>
<td>0.900</td>
<td>0.948</td>
<td>3.820</td>
<td>7</td>
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<td>21.16</td>
<td>2.077</td>
<td>3.7870</td>
</tr>
<tr>
<td>SRW 8</td>
<td>0.820</td>
<td>0.905</td>
<td>8.790</td>
<td>6</td>
<td>12.60</td>
<td>36.60</td>
<td>31.70</td>
<td>1.154</td>
<td>4.2839</td>
</tr>
<tr>
<td>SRW 9</td>
<td>0.930</td>
<td>0.964</td>
<td>4.920</td>
<td>5</td>
<td>11.10</td>
<td>29.92</td>
<td>8.47</td>
<td>3.532</td>
<td>5.0503</td>
</tr>
<tr>
<td>SRW 10</td>
<td>0.980</td>
<td>0.989</td>
<td>0.781</td>
<td>5</td>
<td>11.10</td>
<td>29.92</td>
<td>5.38</td>
<td>5.561</td>
<td>5.0503</td>
</tr>
<tr>
<td>SRW 11</td>
<td>0.950</td>
<td>0.974</td>
<td>2.370</td>
<td>6</td>
<td>12.60</td>
<td>36.60</td>
<td>13.69</td>
<td>2.673</td>
<td>4.2839</td>
</tr>
<tr>
<td>SRW 12</td>
<td>0.800</td>
<td>0.894</td>
<td>14.030</td>
<td>7</td>
<td>14.10</td>
<td>43.96</td>
<td>19.27</td>
<td>2.281</td>
<td>3.7870</td>
</tr>
</tbody>
</table>

(\( R^2 \) - coefficient of determination, \( R \) - correlation coefficient, \( \chi^2 \) - chi-squared value, \( DF \) - degrees of freedom, \( \chi^2_{\alpha} \) - critical values, \( \sigma^2_e \) - variance from the empirical data, \( \sigma^2_a \) - variance from the approximation values, \( DF \) - degrees of freedom, \( F_{\alpha, N1-N2-1} \) - critical values)

4. PROBABILISTIC PRODUCTIVITY NORMS

Based on statistical analysis, probabilistic productivity norms have been developed using probability distribution. Two cases were examined – probabilities of 68% and 96%, which are corresponding values for ±2 and 3 standard deviations around the mean value (Figure 3) [9].

Due to the so-called “three sigma rule”, it can be assumed that all probabilities out of 3σ limit (equal or greater than 99.7%) can be considered as “near certainty” [9].

Therefore, optimistic times (to) were obtained by adding one, respectively two, standard deviations to the mean time (tm = \( \mu \)), and pessimistic times (tp) are obtained by subtracting these values.

Values presented in Table 4 are optimistic, mean and pessimistic times with probability of accomplishing a given task of 68 and 96%, respectively. These values can be succesfuly implemented in the PERT method or other methods for planning for planning under uncertainty [10], so it can be talked about accomplishing the set of activities or entire project within a given time period with probability of 68 or 96%.

![Figure 3 - Probability distribution](image-url)
Table 4. Probabilistic productivity norms for probabilities of 68 and 96 %

<table>
<thead>
<tr>
<th>ID</th>
<th>Probability 68 %</th>
<th>Probability 96 %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( t_p(\mu - \sigma) )</td>
<td>( t_p(\mu + \sigma) )</td>
</tr>
<tr>
<td>SRW 1</td>
<td>92.5</td>
<td>98</td>
</tr>
<tr>
<td>SRW 2</td>
<td>74.3</td>
<td>77.9</td>
</tr>
<tr>
<td>SRW 3</td>
<td>102.14</td>
<td>105.8</td>
</tr>
<tr>
<td>SRW 4</td>
<td>83.24</td>
<td>86.15</td>
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<td>SRW 5</td>
<td>86.43</td>
<td>90.29</td>
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<td>SRW 6</td>
<td>123.9</td>
<td>128</td>
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<td>SRW 7</td>
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</tr>
<tr>
<td>SRW 12</td>
<td>101.01</td>
<td>105.4</td>
</tr>
</tbody>
</table>

5. CONCLUSION

Productivity norms commonly used for planning and scheduling construction project offer only one deterministic time for accomplishing each given activity. These data are often criticized in practice on the ground that their values are unrealistic and/or unattainable. The main downside of such norms is that they cannot be used for risks planning and scheduling under uncertainty. This paper presents methodology for developing probabilistic productivity norms based on realistic data obtained at the building sites, providing not only average time for accomplishing a given task, but the time period within which a given activity will be finished with predefined probability of accomplishment. These norms can be successfully applied in probabilistic methods for planning under uncertainty.

REMARK

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REFERENCES


REZIME

METODOLOGIJA IZRAĐE PROBABILISTIČKIH NORMATIVA U GRAĐEVINARSTVU

Za uspešnu primenu metode kritičnog puta neophodno je znati tačno trajanje svake aktivnosti, dok se PERT metoda zasniva na ličnoj proceni ili ranije prikupljenim podacima. Međutim, zbog dugog trajanja građevinskih projekata i nepredviđenih zastoja, često je teško, pa čak i gotovo nemoguće predvideti tačno trajanje svake aktivnosti i smatrati za sigurno da će određena aktivnost biti okončana baš onog dana koji je predviđen dinamičkim planom. Cilj istraživanja prikazanog u ovom radu bio je da se razvije metodologija za izradu novih normativa za građevinske radove koji bi mogli da se koriste za planiranje u uslovima neizvesnosti.

Ključne reči: normativ, dinamički planovi, neizvesnost
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Comparative Risk Assessment of CCW Disposal in the Old and New Landfill of the Coal-Fired Power Plant Kostolac Based on the Hydrological Scenario

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This paper presents a comparative risk assessment of Coal Combustion Waste Disposal in the old and new landfills in Kostolac. FMEA (Failure Modes and Effects Analysis) method is applied for risk assessment in combination with a risk matrix, which includes a detailed elaboration of potential accident scenario at the landfills and the analysis of accident effects. In this case only the hydrological scenario considered as a potential accident scenario based on massive influx of precipitation, which proved to be the cause of the largest number of accidents at industrial disposal sites. The paper analyses the environmental impacts, potential casualties and economic effects. With the use of the risk matrix it was possible to establish that both landfills belong to the so called "blue" risk zone, which is interpreted as a tolerable level of risk. Yet, the new disposal site is in an even more favourable position than the old one since it was established that the expected level of risk is lower by one degree.

Key words: coal-fired power plant Kostolac, coal combustion waste (CCW) landfill, risk assessment, FMEA method, risk matrix, hydrological scenario

1. INTRODUCTION

Industrial waste disposal sites are considered to be among the most hazardous man-made facilities. The risks related to industrial waste disposal are constantly increasing over time, Figure 1 [1].

As evidence of this, we are witnessing a large number of accidents that have been recorded in recent years [2], whereby the most frequent cause of accident was hydrology related.

Accidents at industrial waste landfills ranked 18th in the major hazard list after earthquakes, cholera, floods, etc. [3].

In Serbia CCW landfills are spatially dominant because they occupy more than 1,500 hectares of lowland terrain right next to three large rivers Danube, Sava and Morava. Therefore, it is important to assess promptly and objectively the disposal-related risks and the consequences of possible accidents [4].

![Figure 1 – Progressive increase of risks related to industrial waste disposal](image)

The Coal-Fired Power Plant Kostolac consists of two production facilities - TEKO A and B, which
participate with about 14% in the annual electricity production of Electric Power Industry of Serbia (EPS) [5]. The plant runs on lignite from Drmino Open-Pit Mine, generating large quantities of CCW, which is disposed of at nearby landfills. Currently, in TEKO A and B there are two active CCW landfills.

The CCW landfill Kostolac Central Island (SKO) has been active since the beginning of power plant operation and it is scheduled for use during next 5 years. It consists of 3 cells, A, B and C, with a total area of about 276 ha. Since May 2015, the cell B, measuring 56 ha, has the status of an operating landfill cell, and the cell C, which had previously been active, has now become an emergency backup landfill cell. The cell A is backfilled to the maximum and partly reclaimed. In the B cell there is still available space for approximately 400,000 m³ of waste. This is a typical low-landfill with a 23-m high dam. The dams are constructed from hydrocyclone-processed ash and bottom ash (CCW) applying the upstream method [6].

The second landfill has become active since 2011 and it is located within the abandoned Open-Pit Cirikovac. For this landfill it was decided to replace the slurry transportation system and to introduce transportation and disposal of thick slurry. CCW from TEKO B is disposed of at the new Cirikovac landfill, while the waste from TEKO A is still directly discharged in the form of thin-ash slurry into the SKO landfill.

Figure 2 – The position of the old and new CCW landfill in Kostolac (Source: Google Earth)

Cirikovac landfill falls into the category of depression landfills and currently it occupies 20 hectares of hydro-technically treated and hydro-isolated area, with a view to using all 130 hectares in future. It is planned to divide the landfill into 2 cells, each 20 m deep, with bulkhead dam, successively rising by 3 m, as cell backfilling progresses. However, due to the constantly active landslide on the northern slope, it was only possible to prepare the cell no. 2, which for the most part was not affected by landslide, so the cell no. 1 is currently the backup cell [7].

The position of the old and new landfill in Kostolac is shown in Figure 2. To make an accurate comparison of both landfills it is important to consider their position relative to the ground level, accepted as zero-level elevation, Figure 3.

Figure 3 - Cross section through the terrain occupied by both landfills (not to scale)

2. RISK ASSESSMENT

For risk assessment this paper applies the FMEA method (Failure Modes and Effects Analysis) combined with a risk matrix, to facilitate the interpretation of results [1].

2.1. Assessment of Accident Hydrological Scenario

The most frequently elaborated scenarios for risk assessment related to industrial waste landfills are the following: [8]:

- Normal scenarios - what would happen as a result of common, everyday activities at the landfill, or as a result of irregularities caused by poor management of the landfill?
- Seismic scenario – what would happen if the landfill were hit by an earthquake?
- Hydrological scenario – what would happen in case of massive influx of precipitation?

Accidents recorded at industrial waste landfills across Europe confirm that up to 35% of accidents occurred due to massive influx of precipitation, [9, 10, 11], which prioritizes the assessment of this type of accidents, and consequently in this paper the attention is focused exclusively to this type of scenario.

The hydrological scenario is based on the assumption that slurry could spill over the dam crown or spill through the body of the dam surrounding the landfill and cause the flooding of the surrounding area. It is common knowledge that the control of water at industrial waste landfills are of the utmost importance and that landfill management is mostly reduced to water management.

To assess the hydrological scenarios, it is necessary to consider the extreme situations that occurred in the
past when heavy rainfalls were recorded. One such extreme situation took place in May 2014, when due to heavy rainfall it was necessary to declare a state of emergency.

It was raining continuously from 14 to 16 May. Record rainfall was recorded in western Serbia ranging from 175 to 225 mm. According to the Report of the Hydro-Meteorological Institute, in Kostolac area during those three days the rainfall amounts ranged between 100 and 125 mm [12].

This heavy rainfall contributed to the rise in water level of the river Mlava, posing a direct threat to the safety of the Power Plant Kostolac-B. Both landfills, which are located along the banks of the Mlava, were potentially endangered. On the other hand, the water also threatened to overtop the dam crown of the SKO landfill, but fortunately the spill-over was avoided.

If the maximum ever recorded rainfall for Kostolac area of 113 mm is adopted as the maximum amount of precipitation [13] it is possible to carry out specific assumptions regarding potential accidents based on the hydrological scenario.

In the assessment it was considered that such scenario could be repeated under the same circumstances, at the current state of the landfill and assuming that the water inflow is not drained through the drainage system. The analysis showed that the amount of water found in the active cell at the SKO landfill would occupy half of the available storage space.

At Cirikovac landfill we have practically the same situation and the same relationship of available storage space and potential amounts of water that could be discharged into the active cell no.2. For accurate assessment it is necessary to take into account that this new landfill has an advantage over the old one, which consists in the lack of the perimeter dam that might possibly collapse in the event of accident.

The probability assessment was made by an online tool designated for such purposes: „Risk Analysis - Event Probability Assessment“ (http://www.edumine.com/xtoolkit/xmlIcon/risk01.htm), which takes into account the landfill lifespan, state and expert assessment of the likelihood of accident occurrence. Based on these parameters it provides the numerical value of the annual probability of accident occurrence, the number of expected events and the probability for exceeding these values. The panel showing events probability assessment based on the hydrological scenario for SKO landfill is given in Figure 4.

If we take into account that the state of SKO landfill can be characterized as moderate, that its remaining lifespan is 5 years, that the expert assessment of the likelihood for event occurrence according to the hydrological scenario is very low, we can conclude with a confidence level of 95% that the annual likelihood of event occurrence is approximately equal to zero, that the number of expected events during this time is 0.0013 and that the probability for exceeding the expected number of events is 5%.

Figure 4 – Panel showing event probability assessment for SKO landfill

The panel showing events probability assessment based on the hydrological scenario for Cirikovac landfill is given in Fig. 5.

If we take into account that the state of Cirikovac landfill can be characterized as good, that its remaining lifespan is 25 years, that the expert assessment of the likelihood for event occurrence according to the hydrological scenario is negligible, we can conclude with a confidence level of 95% that the annual likelihood of event occurrence is approximately equal to zero, that the number of expected events during this time is 0.0004 and that the probability for exceeding the expected number of events is 5%.

Figure 5 - Panel showing event probability assessment for Cirikovac landfill
2.2. Assessment of Potential Effects

Accident effects can be classified as follows [8]:

- environmental effects
- impact on humans (casualties),
- economic effects,
- other effects (social unrest, bad reputation, destruction of historical monuments, etc.).

The effects are assessed regardless of the landfill state, i.e. a landfill in excellent condition could potentially cause major impacts if, for example the landfill is located in the vicinity of populated areas with developed infrastructure. Because of this, for an accurate risk assessment it is important to determine the location of the landfill relative to the nearest facilities, populated areas or environmental substrates in order to assess as realistically as possible the level of endangerment and the effects therein.

The position of both landfills can be determined relative to the following reference point located in their immediate vicinity: River Danube, River Mlava, Sports Airfield Kostolac, Archaeological site Viminacium, Railway Station, Church of St. George built in 1924, Open-Pit Mine Drmno, Coal-Fired Power Plant Kostolac A and B, and other numerous energy infrastructure facilities (transmission lines, distribution lines, substations, etc.)

The area surrounding both landfills is relatively densely populated. The nearest villages with their respective population are shown in Table 1.

<table>
<thead>
<tr>
<th>Village</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kostolac</td>
<td>9,569</td>
</tr>
<tr>
<td>Pozarevac</td>
<td>44,183</td>
</tr>
<tr>
<td>Stari Kostolac</td>
<td>1,228</td>
</tr>
<tr>
<td>Petka</td>
<td>1,173</td>
</tr>
<tr>
<td>Dubravica</td>
<td>1,037</td>
</tr>
<tr>
<td>Klicevac</td>
<td>1,078</td>
</tr>
<tr>
<td>Cirikovac</td>
<td>1,278</td>
</tr>
<tr>
<td>Drmno</td>
<td>894</td>
</tr>
<tr>
<td>Ostrovo</td>
<td>646</td>
</tr>
<tr>
<td>Brdarac</td>
<td>779</td>
</tr>
<tr>
<td>Malo Bavaniste</td>
<td>332</td>
</tr>
</tbody>
</table>

So, the area surrounding the landfills has approximately 62,000 inhabitants.

Several asphalt-based roads pass through this area, among which the most important are:

- Pozarevac-Veliko Gradiste, which connects the area with the Djerdap highway,
- Pozarevac-Petrovac-Bor, which connects the area with eastern Serbia and
- Pozarevac-Vranovo, which connects the area with the highway Belgrade-Niš.

A Standard Gauge Railway, Pozarevac-Kostolac, runs through the central part of this area, by which this area is connected with the entire country. Through the Channel, the area is connected with the Danube, and all the ports located on it.

Also, in order to assess more realistically the effects, it is necessary to estimate the amount of spilled slurry in the event of accident and the flow-out distance of the spill. Many authors have dealt with these issues, and determined that these amounts were usually up to 1/3 of deposited waste, and very rarely 2/5 of deposited waste [9, 14, 15, 16]. Essentially, in case of accident all the amounts of free water would be discharged (from the settling basin) from the landfill cell and along with it a certain amount of the deposited CCW would be released.

The assessment of effects is then reduced to the evaluation of the damage that would be caused to all reference facilities, environmental substrates or human life in the surrounding area.

Based on the numerical simulation of hydraulic consequences of accidents at SKO landfill, taken from the “Study on Hydraulic Effects in Case of Accidents at the Landfills of the CFPP Kostolac”, it was possible to determine the flood wave parameters for the event of accident at the SKO landfill [17].

Simulations, based on the reconstruction of accidental events that occurred in 2002 and in accordance with the current situation, were performed for 3 locations at the landfill.

Based on a general conclusion and for the purpose of this study it may be adopted that the dam failure would be a short-term event, and that in the worst case scenario, about 215,000 m³ to 630,000 m³ of slurry would be discharged. In any case, due to terrain configuration and the position of the facilities in landfill surroundings, the flow-out distance of spilled slurry would range from 150 to 250 m, which is not very far, and probably the entire amount would be collected in the hot-water-channel and discharged into the Danube.

This type of data is not available for Cirikovac landfill, so to estimate the amount of spilled slurry we adopted the generally accepted conclusion according to [9], which state that about 1/3 of totally deposited
waste is discharged, which in the case of Cirikovac landfill is about 66,600 m³ of slurry.

As for slurry flow-out distance, according to [18], for the height of the perimeter dam of 0 m, as is the case at the Cirikovac landfill, this distance is only 5 m.

Assessment of Environmental Effects

To assess the significance of the environmental effects we established the potential relation Source-Route-Receptor, according to [19], to help establish which environmental substrates may be endangered in the event of accidents occurring at the landfill, Fig. 6.

![Image](image)

**Figure 6 - Source–Route–Receptor in the Case of Kostolac Landfill**

The new landfill Cirikovac has a great advantage over the old SKO landfill because it is hydro-isolated preventing the contamination of groundwater, which cannot be claimed for SKO landfill.

Therefore, in the event of accident, and with reference to estimated storage capacity and the flow-out distance of spilled slurry, it can be concluded that the quality of Danube and Mlava water would be jeopardized only in case of an accident at the SKO landfill. It should be emphasized that in case of slurry discharge into the rivers it is to expect that this mixture would be multiply diluted, which would inasmuch decrease the environmental impact.

In terms of air pollution in the surroundings of the old and new landfill the most important issues are the rose of winds in this area and the waste disposal methods. In the Kostolac area, the direction of the most dominant winds is south, southeast and northwest. Therefore, when it comes to Cirikovac landfill the most endangered are the residents of the village Kle novnik, Bradarac and Petka and when it comes to SKO landfill the most endangered are the residents of the village Stari Kostolac and Drmno. The Danube is a good absorber of micro-particles emitted from landfills, so that the air pollution level in the villages across the river is very low.

In terms of ambient air quality, an important difference between the old and the new landfill is the distance from the surrounding villages. The new Cirikovac landfill is further away from the populated areas and also the applied thick-slurry disposal (solid : liquid = 1:1) enables crust formation on the surface, which considerably reduces the effects of air pollution.

Soil pollution mainly depends on the rose of winds. The winds not only spread ash particles but also cause plant drying, cover the plants with ash, (especially on slopes), pull out plant roots, etc. [20]. The effects on the quality of soil are equivalent to the effects on air quality, which means that the level of pollution is slightly higher at the SKO landfill.

**Assessment of Impacts on Humans**

The Graham method [21] was used to assess the impact on human life. This method is based on fixed mortality rates and allows easy approximation of potential casualties in the event accidents occurring at landfills according to the hydrological scenario.

When considering the number of endangered people in case of accident at both landfills, only the employees at the landfills were taken into consideration, because it was previously established that the flow-out distance of spilled slurry is not significant and that the population in the surrounding area would not be jeopardized. At each landfill the number of employees is about 10.

If we adopt that the likelihood of floods is very small, if the time for alert is from 15 to 60 minutes, and if we assume a full understanding of flood related procedures, considering that the potential casualties are the employees at the landfills, who should be acquainted with all the job-related risks and measures, the average mortality rate by Graham Method will in case of both landfills reach only 0,002, and therefore it maybe concluded that human casualties do not exist.

**Assessment of Economic and Other Effects**

A sketch showing the location of both landfills was provided in Figure 7 clearly marking the endangered facilities as to facilitate the assessment of economic and other effects.

![Image](image)

**Figure 7 – Effects in the event of potential accidents at Kostolac landfills**
Based on Figure 7, it can be easily concluded that the location of SKO landfill is much less favourable than the location of Cirikovac landfill, in terms of the vicinity of the main energy infrastructure facilities, historical monuments, archaeological sites, etc.

In the event of accident at SKO landfill the following facilities would be potentially at risk:

- Coal-Fired Power Plant Kostolac A – which implies considerable material losses, since the accident would result in temporary shutdown.
- Sports Airfield Kostolac – located in the immediate vicinity of the landfill (< 500 m) would be necessarily endangered.
- The Danube would most certainly be the first targeted, because during spillage the slurry takes on a one-dimensional flow model, and in this case it behaves like a wave moving along the river bed.
- The roads in the surrounding area might be temporarily inaccessible.
- The TPP Kostolac B Archaeological site Viminacium, although relatively close is not in great danger since the spilled slurry would have to overcome the obstacles posed by the hot-water channel and the river Mlava. The Church of St. George is not endangered due to terrain configuration.

In the event of accidents at Cirikovac landfill the number of potentially endangered facilities is much smaller and they include:

- The roads in the immediate vicinity would be temporarily impassable and
- The river Mlava directly and the Danube indirectly.

As previously established the residents of the surrounding populated areas would not be life-threatened since the slurry would not reach their villages. Therefore, it may be adopted that the destruction of dwellings and property would not take place, however a level of distress of the population could be expected and the reputation of the power plant end EPS could be compromised.

Table 2 gives the comparison of the all parameters to be taken into account when assessing the effects of potential accidents at Kostolac landfills according to the hydrological scenario. The arrows indicate the parameters with greater environmental impact. Clearly Cirikovac landfill causes less environmental impact considering all its advantages in comparison to SKO landfill.

Based on these facts it can be concluded that the overall significance of the effects in the event of accidents occurring at the SKO landfill can be characterized as moderate, while for Cirikovac landfill the overall significance can be characterized as low, in line with the effects significance rating suggested in the risk matrix, Figure 8.

### Table 2. Parameters to be taken into account when assessing the effects of potential accidents at Kostolac landfill

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>SKO</th>
<th>Cirikovac</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood wave properties</td>
<td>Amount of spilled slurry</td>
<td>Spilled slurry flow-out distance</td>
</tr>
<tr>
<td>Groundwater</td>
<td>Surface water</td>
<td>Air</td>
</tr>
<tr>
<td>Soil</td>
<td>ECONOMIC</td>
<td>TO HUMANS</td>
</tr>
<tr>
<td>Σ</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

#### 2.3. Risk Evaluation

A risk matrix, 5x5 was used for risk evaluation, as the ideal tool for the interpretation of results [1]. Based on the developed hydrological scenario, adequate occurrence probability is assigned to an accident and corresponding significance is assigned to the assumed effects and the risk evaluation was made for both old and new CCW landfills in Kostolac. The risk matrix is shown in Figure 8.

![Figure 8 – Risk matrix](image-url)

According to Figure 8 it can be concluded that both landfills are in the so called “blue zone” which is interpreted as a tolerable level of risk. The level of risk at the new Cirikovac landfill is lower by one degree.

### 3. CONCLUSION

The assessment of risks related to industrial waste disposal is carried out in order to evaluate the envi-
environmental impact of such activity, to make the population aware of inherent risks and finally to implement adequate mitigating measures.

The Coal-Fired Power Plants in Kostolac produce 14% of the total electricity generated in Serbia and considerable amounts of coal combustion waste, such as ash and bottom ash are disposed of at two currently active landfills - Kostolac Central Island (SKO) and Cirikovac.

Bearing in mind the urbanised environment, two large rivers, developed infrastructure and historical monuments that exist in this area the assessment and comparison of risks is more than necessary and desirable.

The FMEA method applied, enabled a detailed elaboration of the hydrological scenario of potential accidents and of the most frequently recorded accident scenarios that took place during the previous period.

Using the online tool Risk Analysis - Event Probability Assessment it was possible to assign the probability of occurrence to the accident scenario, while the significance of effects was based on expert assessment after detailed analysis.

Consistent with the risk matrix the Cirikovac landfill is in a more favourable position than SKO landfill since the expected level of risk is lower by one degree.

This demonstrates that the decision of the plant management to use the space of the abandoned open pit for coal combustion waste disposal was justified.

4. ACKNOWLEDGEMENT

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REMARK

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**REZIME**

**UPOREDNA PROCENA RIZIKA EKSPLOATACIJE STARE I NOVE DEPONIJE PEPELA I ŠLJAKE TERMOELEKTRANA KOSTOLAC, PO HIDROLOŠKOM SCENARIJU**

U ovom radu data je uporedna procena rizika eksploatacije stare i nove deponije pepela i šljake u Kostolcu. Procena rizika je vršena prema FMEA (Failure Modes and Effects Analysis) metodi u kombinaciji sa matricom rizika, koja podrazumeva detaljnu razradu scenarija potencijalne havarije na deponiji i analizu posledica koje bi ta havarija izazvala. Kao scenario potencijalne havarije uzet je u obzir isključivo hidrološki scenario koji se bazira na prilivu velikih količina atmosferskih padavina, uzročniku najvećeg broja havarija na deponijama industrijskog otpada ikada zabeleženih. Analizirane su ekološke posledice, potencijalni ljudski gubici i ekonomske posledice. Prema matrici rizika ustanovljeno je da se obe deponije nalaze u „plavoj” zoni rizika, koje se tumače kao tolerantan nivo rizika, ali se nova deponija ipak nalazi u povoljnijoj poziciji od stare deponije jer je očekivani nivo rizika niži za jedan stepen.

**Ključne reči:** Termoelektrana Kostolac, deponija pepela i šljake, procena rizika, FMEA metoda, matrica rizika, hidrološki scenario
Industrial Contamination of Soil Related to Some Active and Closed Mine Facilities in the Republic of Macedonia

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Several industrial pollution sources at the territory of the Republic of Macedonia, were studied, one Pb-Zn mine with mill, one copper mine with mill and copper leaching facility, as well as one former Pb-Zn smelting facility near the city of Veles and one Fe-Ni smelting facility near the city of Kavadarci. The concentrations of heavy metals at Veles hot-spot were in the range: 20±1823 mg kg⁻¹ Pb, 29±2395 mg kg⁻¹ Zn, 28±65 mg kg⁻¹ Cd, 27±82 mg kg⁻¹ Cu, 39±164 mg kg⁻¹ Ni, 508±938 mg kg⁻¹ Mn and 1.6±3.8% Fe, all of them being above Dutch standard optimal values. The vicinity of the Feni plant displayed concentrations of heavy metals as follows: 16±31 mg kg⁻¹ Pb, 117±286 mg kg⁻¹ Zn, 13±24 mg kg⁻¹ Co, 42±119 mg kg⁻¹ Cu, 158±292 mg kg⁻¹ Ni, 119±236 mg kg⁻¹ Cr and 2.24±3.79% Fe. Airborne dust measurements around the Zletovo mine displayed multiplexed above standard values, with an exception of nickel, there enrichment factors ranged from mediate ones such were those for copper of 20.8, cadmium of 28.7, arsenic of 32.5 up to high ones for zinc with 341.7 and lead 925. Soil samples around the Zletovo mine displayed: 19.3±76.9 g kg⁻¹ As, 643±28000 mg kg⁻¹ Fe, 42.3±529.66 mg kg⁻¹ Mn, 138±3240 mg kg⁻¹ Pb and 13.1±225 mg kg⁻¹ Zn. Finally around the Bucim copper mine the results displayed the following findings: 13.1±225 mg kg⁻¹ As, 0.67±17.9 mg kg⁻¹ Cd, 30.1±171 mg kg⁻¹ Cr, 17.8±1734 mg kg⁻¹ Cu, 9.8±69.4 mg kg⁻¹ Ni, 46±3456 mg kg⁻¹ Pb, 88±3438 mg kg⁻¹ Zn, 169±998 mg kg⁻¹ Mn, 0.73±5.02% Fe.

Key words: heavy metals, contamination, mines, anthropogenic, R. Macedonia

1. INTRODUCTION

As major polluted localities, confirmed even with our latest results, are the areas around the former Pb-Zn smelting plant located at the Veles city limits, active ferro-nickel plant located in the well known wine region of Kavadarci, active lead and zinc mines with their respective tailing dams in Eastern Macedonia (Zletovo) and active open pit of the Buchim copper mine with large waste dump and tailing dam (Figure 1).

Preventive measures are a must where mine and mine related plant are processing and produce significant environmental influx, so understanding the environmental impact of these processes is crucial. Metal mining has traditionally been an important part of the economy of the Republic of Macedonia and recently increased in importance due to governmental efforts to stimulate mining through renewed exploration and development, though the country relies on its agriculture and must safeguard its soil and water resources. Pollution from active and past mining related processing represents significant problem in some parts of the country. The problem continuously is solved at active mines/plants while the problem is harder to solve at those with ceased production (Veles former Pb-Zn smelting plant etc.).

2. MATERIAL AND METHODS

The process of sampling was carried out over a prolonged period (2004-2014). Soil surface samples (0-5 cm depth) were collected at several localities pointed earlier as potential so-called “hot spots” in regards to heavy metal pollution (Figure 1).

Samples were located using the Global Positioning System, topographic maps (1:25 000) and TrackMaker software. Each sample represents composite material collected at the central sampling point accompanied with at least four points collected around a central one within radius of 1 m towards N, E, S and W directions.
Each sample (~0.5 kg) was prepared for analysis and analyzed using emission spectrometry with inductively coupled plasma (ICP-AES) at the Institute of Chemistry, Faculty of Natural Sciences, University “Sts. Cyril and Methodius” Skopje, R. Macedonia. Random order of samples and standards submission to laboratory assured unbiased treatment and precision less than 5%.

2.1. Results and discussion

The Veles smelting plant: It used to be the largest Pb-Zn facility in former Yugoslavia with capacity for producing 65000 t of zinc and 45000 t of lead annually and entire production was exported.

The anthropogenic impact in that particular part of the Veles basin has been studied at two regions around former Pb-Zn smelting plant during the 2008, Bashino Selo (village to the north of the smelting plant) and area to south of the smelting plant close to the city.

Within the first area were sampled two parallel sections and one section normal to them while at the second area were sampled only two parallel sections (30 m distances between each sample, Figure 2).

Concentrations of elements were: 20÷1823 mg·kg⁻¹ Pb, 29÷2395 mg·kg⁻¹ Zn, 28÷65 mg·kg⁻¹ Cd, 27÷82 mg·kg⁻¹ Cu, 39÷164 mg·kg⁻¹ Ni, 508÷938 mg·kg⁻¹ Mn and 1.6÷3.8% Fe. All of them being quite above the reference values (Table 1 and Figure 3).

### Table 1. Concentrations of metals in soil samples around the former smelting plant in the vicinity of Veles.

<table>
<thead>
<tr>
<th>Element</th>
<th>n</th>
<th>Median</th>
<th>min</th>
<th>max</th>
<th>Dutch list standard optimal</th>
<th>Dutch list standard action</th>
<th>above standard</th>
<th>below standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb (mg kg⁻¹)</td>
<td>15</td>
<td>1190</td>
<td>20</td>
<td>1823</td>
<td>85</td>
<td>530</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>Zn (mg kg⁻¹)</td>
<td>15</td>
<td>1778</td>
<td>29</td>
<td>2395</td>
<td>140</td>
<td>720</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>Cd (mg kg⁻¹)</td>
<td>15</td>
<td>42</td>
<td>26</td>
<td>65</td>
<td>0.8</td>
<td>12</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Cu (mg kg⁻¹)</td>
<td>15</td>
<td>60</td>
<td>27</td>
<td>82</td>
<td>36</td>
<td>190</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Ni (mg kg⁻¹)</td>
<td>15</td>
<td>116</td>
<td>39</td>
<td>164</td>
<td>35</td>
<td>210</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>Fe (%)</td>
<td>15</td>
<td>3.2</td>
<td>1.6</td>
<td>3.8</td>
<td>1.8</td>
<td>-</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Mn (mg kg⁻¹)</td>
<td>15</td>
<td>841</td>
<td>508</td>
<td>938</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
If an average of Pb in World soils is 35 mg kg\(^{-1}\) [1], in European topsoil 33 mg kg\(^{-1}\) [2] and in topsoil for entire study area 220 mg kg\(^{-1}\) [3], it was found that in studied area the Pb average is 34-times higher than in the World, 36.1-times higher than European and 5.41-times higher than Macedonian (this region) averages. In regards to zinc where the average in World soils is 90 mg kg\(^{-1}\) [3], European topsoil 68 mg kg\(^{-1}\) [2] and an average in topsoil for the study area is 280 mg kg\(^{-1}\) [3], it was found that in the studied area an average concentration of Zn is 19.7-times higher than World average, 26.1-times higher than European and 6.35-times higher than Macedonian average (for this region).

Similar to the previous two heavy metals (Pb, Zn) we analyzed cadmium geochemistry (World average 0.35 mg kg\(^{-1}\) Cd [1], European average 0.12 mg kg\(^{-1}\) Cd [2], an average for the entire study area 7.7 mg kg\(^{-1}\) Cd [3]), and we found that an average concentration of Cd was 120-times higher than the World average, 350-times higher than the European average and higher than Macedonian average (for this region) for 5.45-times.

In the very same manner copper had 2-times higher concentration than the World average of 30 mg kg\(^{-1}\) Cu, 3.53-times higher than European average (17 mg kg\(^{-1}\) Cu) and 1.36-times higher than Macedonian average (44 mg kg\(^{-1}\) Cu), which matches findings by other researchers that very same year [3].

The group that comprises of Cd, Pb and Zn, as chemical elements that have been introduced into the environment through the anthropogenic activities [4], have shown the highest values in soils around the Veles smelting plant. That was expected even at the beginning of the study, but tremendously high values exceeded expectations. These findings illustratively are displayed at Figure 3.

Also, after detailed study it was determined that values from respective sampling points were spatially dependent. Namely, as can be seen from the plots and sampling location map, the lowest values were determined at topographically higher places than those for lower ones. This clarifies the correlation between pollution and smoke dust produced by the activity of former smelting plant in Veles.

The FENI smelting plant: The major source of anthropogenic environmental impact in the Tikvesh basin should be the FENI Industries’s smelting plant (Figure 4), where environmental concern intensified due to fact that it is located in the hearth of the well-known wine producing Tikveš region.

Plant has been operational since 1982 (produced ~ 5000 t of nickel metal annually), in 2005 it was acquired by Cunico Resources and steadily increased production to 16000 t per year.

Soil sampling programme around the FENI plant took place at two separate localities, one on the NW of the smelting plant and the other one on the S-SE of the smelting plant. In both cases samples were taken along two parallel profiles and one perpendicular to them (Figure 4).

Samples were analyzed to a standard array of heavy elements: Pb, Zn, Cu, Ni, Fe, Cr, Co and Mn (Table 2). Their concentrations were in the range as follows: 16±31 mg·kg\(^{-1}\) Pb, 117±286 mg·kg\(^{-1}\) Zn, 13±24 mg·kg\(^{-1}\) Co, 42±119 mg·kg\(^{-1}\) Cu, 158±292 mg·kg\(^{-1}\) Ni, 119±236 mg·kg\(^{-1}\) Cr and 2.24±3.79% Fe.

All of them were significantly above the reference values (Figure 5). Also, the calculated enrichment ratio (measured values over the reference value) speaks itself regarding the level of contamination.

![Figure 4 - Sampling locations around the FENI Industries smelting plant, small inset at the right upper corner gives the satellite position of the area.](image)

![Figure 5 - Measured concentrations of Ni vs. standard values around the Feni-industries’s smelting plant](image)
in mind the findings of [5, 6], probably cannot not be attributed solely to the anthropogenic input, since they were increased already due to geological composition.

It is probable that the FENI Industry plant, beside certain environmental impact, has not contributed extremely to measured values [5, 6, 7, 8].

Table 2. Concentrations of metals in soil samples from locations around the active smelting plant FENI in the vicinity of Kavadarci.

<table>
<thead>
<tr>
<th>Sample</th>
<th>n</th>
<th>Median</th>
<th>Min</th>
<th>max</th>
<th>Dutch list standard optim.</th>
<th>Dutch list standard action</th>
<th>above standard</th>
<th>below standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb (mg kg⁻¹)</td>
<td>24</td>
<td>22</td>
<td>16</td>
<td>31</td>
<td>85</td>
<td>530</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>Zn (mg kg⁻¹)</td>
<td>24</td>
<td>141</td>
<td>117</td>
<td>286</td>
<td>140</td>
<td>720</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>Cu (mg kg⁻¹)</td>
<td>24</td>
<td>63.5</td>
<td>42</td>
<td>119</td>
<td>36</td>
<td>190</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>Ni (mg kg⁻¹)</td>
<td>24</td>
<td>219.5</td>
<td>158</td>
<td>292</td>
<td>35</td>
<td>210</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>Fe %</td>
<td>24</td>
<td>3.46</td>
<td>2.24</td>
<td>3.79</td>
<td>1.8</td>
<td>-</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>Ba (mg kg⁻¹)</td>
<td>23</td>
<td>151.5</td>
<td>0</td>
<td>223</td>
<td>160</td>
<td>625</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>V (mg kg⁻¹)</td>
<td>24</td>
<td>47</td>
<td>24</td>
<td>75</td>
<td>42</td>
<td>250</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>Cr (mg kg⁻¹)</td>
<td>24</td>
<td>187</td>
<td>119</td>
<td>236</td>
<td>100</td>
<td>380</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>Co (mg kg⁻¹)</td>
<td>24</td>
<td>18</td>
<td>13</td>
<td>24</td>
<td>9</td>
<td>240</td>
<td>0</td>
<td>24</td>
</tr>
</tbody>
</table>

The Zletovo Pb-Zn Deposit: Study of environmental impact of the Zletovo mine we have started with airborne dust produced during the primary crushing of ore, when it is released significant amount of dust that poses serious threat to the environment [8, 9, 10]. Analyses displaying heavy metal concentrations in the dust averaged: 169 mg kg⁻¹ As, 86 mg kg⁻¹ Cd, 354 mg kg⁻¹ Cu, 10 mg kg⁻¹ Ni, 14800 mg kg⁻¹ Pb and 16400 mg kg⁻¹ Zn. All the measured values multiplexed above standard values, except nickel. Enrichment factors ranged from mediate ones such were those for copper of 20.8, cadmium of 28.7, arsenic of 32.5 up to high ones for zinc with 341.7 and lead 925. High concentration levels of heavy metals introduced by deposition from airborne dust and dispersion by wind, pose serious threat to an adjacent environment.

Soil sampling around the Zletovo mine was performed by other researchers but without any systematics and due to it was very hard to prepare complete review, which would reflect real situation regarding soil pollution [11]. We have decided to strengthen that knowledge and performed additional sampling (24 samples) in the vicinity of the Zletovo Pb-Zn mine.

Namely, it was determined that representative elements are lead, zinc, iron and manganese and they are given in more details within this paper (Table 6), while elements such Cr, V, Ni, Co have not displayed elevated concentrations (Table 3, Figure 6). An average amount of Pb in the world’s soils is 35 mg kg⁻¹ [1], in the European topsoil is 33 mg kg⁻¹ [2], in Macedonia (studied part) is 26 mg kg⁻¹ [12]. As it is obvious from Table 3, lead values ranged from the 42.30÷529.66 mg kg⁻¹ Pb, while the lowest values were determined near the Zletovo village the highest ones were determined in samples from localities Koritnica, Kiselica and Strmos.

In the main polluted area the average concentration of Pb is 8.6-times higher than the European Pb average and Macedonian average for 10.9-times. Although the average content of lead in the topsoil for the entire study area was found to be about 284.36 mg kg⁻¹, there are areas with increased concentration up to 529.66 mg kg⁻¹, although even such values were not above action values by the Dutch list (Table 3; Figure 6).

The average amount of Zn in the world’s soils is 90 mg kg⁻¹ [1], in the European topsoil is 68 mg kg⁻¹ [2], in Macedonia (studied part) is 55 mg kg⁻¹ [12]. The highest concentrations of zinc were determined near the Koritnica, Kiselica and Ziganci while the whole range was quite wide starting from 138 mg kg⁻¹ Zn and ending up to 3240 mg kg⁻¹ Zn. For the main polluted area, the average concentration of Zn is 19.2-times higher than the European Zn average and Macedonian average for 23.7-times. Similarly to the findings for lead, although the average content of zinc in the topsoil...
for the entire study area was found to be about 1303.5 mg kg\(^{-1}\), there are areas with very high level of contamination (Table 3; Figure 6).

Table 3. Concentrations of particular heavy metals in soil samples from the vicinity of the Zletovo Mine, Macedonia

<table>
<thead>
<tr>
<th>Sample</th>
<th>n</th>
<th>min</th>
<th>max</th>
<th>average</th>
<th>Dutch list (Optimum)</th>
<th>Dutch list (Action)</th>
<th>Above optimum</th>
<th>Above action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb (mg kg(^{-1}))</td>
<td>24</td>
<td>42.3</td>
<td>529.6</td>
<td>266,5442</td>
<td>85</td>
<td>530</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>Zn (mg kg(^{-1}))</td>
<td>24</td>
<td>138</td>
<td>3240</td>
<td>1180,333</td>
<td>140</td>
<td>720</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>Fe (g kg(^{-1}))</td>
<td>24</td>
<td>19.3</td>
<td>76.9</td>
<td>38.70</td>
<td>18</td>
<td>72</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>Mn (mg kg(^{-1}))</td>
<td>24</td>
<td>643</td>
<td>28000</td>
<td>6707.583</td>
<td>33</td>
<td>330</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

The average amount of Fe in the world’s soils is 35 g kg\(^{-1}\) [1], in the European topsoil is 21.7 g kg\(^{-1}\) [2], in Macedonia in the considered area is 33 g kg\(^{-1}\) [12].

As it is obvious from the table above (Table 3), we would like to stress out that iron values ranged from the 19.3÷76.9 g·kg\(^{-1}\) Fe.

Figure 6 - Measured concentrations of some heavy metals (Pb and Zn) vs. Dutch standard in soils around the Zletovo Mine, Macedonia. (Note: all plots have logarithmic vertical scale)

Either the iron haven’t shown significantly increased values, the highest ones were recorded for the locations such as Kiselica, Koritnica and Strmos. In the main polluted area the average concentration of Fe is 1.9-times higher than the European Fe average and Macedonian average for 1.2-times. Although the average content of iron in the topsoil for the entire study area was found to be about 40.67 g kg\(^{-1}\), there are areas with increased concentration up to 76.9 g kg\(^{-1}\), although only one value was above action value by the Dutch list.

On the World scale, the range of Mn average contents was calculated at 488 mg kg\(^{-1}\), while for the US soils it is 495 mg/kg [13], in European topsoil is 382 mg kg\(^{-1}\) [2], and in Macedonia in the considered area is averages 650 mg kg\(^{-1}\) [12]. Manganese analyses around the Zletovo mine area have shown the highest concentrations among analyzed elements, ranging from 643 up to 28000 mg kg\(^{-1}\) Mn. In the main polluted area the average concentration of Mn is 14.9-times higher than the European Pb average and Macedonian average for 11.9-times. Although the average content of Mn in the the entire study area was found to be about 7791.75 mg kg\(^{-1}\), there are areas with increased concentration up to 28000 mg kg\(^{-1}\), however all the measured values were above action value by the Dutch list (Table 3).

Here we are dealing with anthropogenic input in soils around the Zletovo mine, which clearly indicates their connection with the processing of lead-zinc ore from the mine.

The Buchim Cu Deposit: The only one active copper mine within the Macedonia was enclosed in ours environmental study. Considering airborne dust pollution we would like to stress out that the studies on this subject already exists [14, 15, 16], so we used them as representative ones, while interesting Cu and other elements anomalies in soils were given by [8, 17]. Our results, performed on 25 samples from 25 locations including minimal, maximal, average and referent values according to the New Dutchlist (www.contaminatedland.co.uk/std-guid/dutch-l.htm) are shown at Table 4. Distribution of some pollutants is shown at Figure 7a, b. These results are in agreement with those obtained by [18] from the study of soil pollution in the wider region of Radoviš and its environ where As, Cu, Pb, V and Zn were determined as anthropogenetic ele-
ments due to the mining and ore processing at the Buchim plant. That is especially accentuated in the eastern and southwestern parts of the main polluted area around flotation. High contents of Cu and Pb are not only due to mining works, but also the town works, traffic, industry and developed technological processes which emitted higher amounts of these heavy metals in air [14, 15, 16, 18, 19, 20, 21]. An average amount of arsenic in the World’s soils of 5 mg kg\(^{-1}\) [1], and European of 12 mg kg\(^{-1}\) [2] has been overcome within entire study area, ranging 13.1–225 mg kg\(^{-1}\) (average 63.904 mg kg\(^{-1}\); Table 4 and Figure 7a). In several anomalous areas it could be seen that the highest values are in the area closest to the outflow of flotation dam (from 51 to 225 mg kg\(^{-1}\) and so-called Buchim Lake and dry riverbed draining open pit mine and in the south-western part of the area (67.4–82.8 mg kg\(^{-1}\)).

Table 4. Statistical data from the soil samples around the Buchim copper mine

<table>
<thead>
<tr>
<th>Element</th>
<th>n</th>
<th>min</th>
<th>max</th>
<th>Average</th>
<th>Optimum (Dutch list)</th>
<th>Action (Dutch list)</th>
<th>Above optimum</th>
<th>Above action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al (%)</td>
<td>25</td>
<td>0.72</td>
<td>5.90</td>
<td>2.89</td>
<td>4.7</td>
<td>-</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Fe (%)</td>
<td>25</td>
<td>0.73</td>
<td>5.02</td>
<td>3.15</td>
<td>1.8</td>
<td>21</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>As (mg kg(^{-1}))</td>
<td>25</td>
<td>13.1</td>
<td>225</td>
<td>63.9</td>
<td>29</td>
<td>55</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>Cd (mg kg(^{-1}))</td>
<td>25</td>
<td>0.67</td>
<td>17.9</td>
<td>2.19</td>
<td>0.8</td>
<td>12</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td>Co (mg kg(^{-1}))</td>
<td>25</td>
<td>3.62</td>
<td>22.3</td>
<td>12.4</td>
<td>9</td>
<td>240</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>Cr (mg kg(^{-1}))</td>
<td>25</td>
<td>30.1</td>
<td>171</td>
<td>80.7</td>
<td>100</td>
<td>380</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Cu (mg kg(^{-1}))</td>
<td>25</td>
<td>17.8</td>
<td>1734</td>
<td>129</td>
<td>36</td>
<td>190</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>Mn (mg kg(^{-1}))</td>
<td>25</td>
<td>165</td>
<td>998</td>
<td>552</td>
<td>33</td>
<td>-</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Ni (mg kg(^{-1}))</td>
<td>25</td>
<td>9.8</td>
<td>69.4</td>
<td>29.5</td>
<td>35</td>
<td>210</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Pb (mg kg(^{-1}))</td>
<td>25</td>
<td>46</td>
<td>3465</td>
<td>288</td>
<td>85</td>
<td>530</td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td>Sr (mg kg(^{-1}))</td>
<td>25</td>
<td>17.6</td>
<td>132</td>
<td>75.8</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>V (mg kg(^{-1}))</td>
<td>25</td>
<td>14</td>
<td>144</td>
<td>83.6</td>
<td>42</td>
<td>250</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>Zn (mg kg(^{-1}))</td>
<td>25</td>
<td>88</td>
<td>3438</td>
<td>320</td>
<td>140</td>
<td>720</td>
<td>12</td>
<td>1</td>
</tr>
</tbody>
</table>

According to this, it is evident that the source of high arsenic in this region is directly related to processing of copper ores in the Buchim Mine.

During the processing of ore, probably one part of that arsenic have been released and distributed into the adjacent environment.

![Diagram of arsenic distribution in the soil compared with optimal and action values](image1)

**Figure 7 - a) Diagram of arsenic distribution in the soil compared with optimal and action values; b) Diagram of copper distribution in the soil compared with optimal and action values**

The cadmium range of 0.67–17.9 mg kg\(^{-1}\) (averaging 2.19 mg kg\(^{-1}\)) in the topsoil for the entire study area significantly overcome Cd in soils in the World of 0.35 mg kg\(^{-1}\) [1] and in European topsoil of 0.12 mg kg\(^{-1}\) [2]. The average concentration of Cd is more than 18-times higher than the European cadmium average and up to 7.5-13 times more than Macedonian average of 0.16 mg kg\(^{-1}\) (study in 2002, see [22]) and 0.29 mg kg\(^{-1}\) (study in 2005, see [23]). Cadmium concentrations were very high in the topsoils from the copper mine facilities and flotation dam vicinity. These higher contents are the result of anthropogenic origin where cadmium was introduced by mine industrial complexes as it was confirmed elsewhere [24].

Soil contamination by Cu compounds displayed the highest increased levels around Cu mines and smelters [25]. As Cu is only slightly mobile under most soil conditions elevated contents may persist for a long time. The average amount of Cu in the world’s soils is 30 mg kg\(^{-1}\) [1], in the European topsoil is 17 mg kg\(^{-1}\) [2] and in Macedonia is 31.8 mg kg\(^{-1}\) [19]. The average amount of Cu in the topsoil for the entire study area is 129.064 mg kg\(^{-1}\), with a range of 17.8–1734 mg kg\(^{-1}\) (Table 4; Figure 7b). In the main polluted area, the
The average concentration of Cu exceeds the European Cu average by a factor of 15.3 and Macedonian average for 8.2-times. The highest content of copper is present in topsoils from areas of the copper mine drainage dry riverbed close to the mine.

The average amount of Pb in the world's soils of 35 mg kg⁻¹ [1], in European topsoil is 33 mg kg⁻¹ [2] and in Macedonian is 44.3 mg kg⁻¹ [19] was overcome for the entire study area with an average of 288 mg/kg (range of 46–3465 mg kg⁻¹, Table 4). The average amount of Zn in the world's soils is 90 mg kg⁻¹ [1, 13], in the European topsoil is 68 mg kg⁻¹ [2] and in Macedonia is 31.8 mg kg⁻¹ [19]. The average Zn amount in the topsoil for the entire study area is 319.8 mg kg⁻¹, with a range of 88–3438 mg kg⁻¹ (Table 4). Similarly to the findings for lead, there are areas with very high level of contamination (Table 4), although all high Cu and Pb contents can not be attributed to mining works, but also can be due to traffic, industry and other processes which allow emission of higher amounts of these heavy metals [6, 14, 15, 16, 20, 21].

5. CONCLUSION

The results of this study have shown that at all the localities are characterized by increased values of pollutant heavy metals in soil, which can be attributed to the anthropogenic influx around the aforementioned mines and related processing facilities. Pollution halo diameter around them sometimes reaches over 20 km. Along common pollutants (Pb, Zn, Cd) around Zletovo mine at lead-zinc and Veles smelting were determined increased concentrations of As, Ag, W, Ni, Co etc., while around the FENI smelting along to Fe and Ni were determined increased values of Cr, V, Co, Mn etc. Increased concentrations, as expected, of Cu, As, Pb, Zn and Cd were determined around the Buchar mine.

REMARK

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REFERENCES

REZIME

KONTAMINACIJA ZEMLJIŠTA U OKOLINI NEKIH AKTIVNIH I ZATVORENIH RUDNIČKIH POSTROJEVA U REPUBLICI MAKEDONIJI

Nekoliko industrijskih izvora kontaminacije na teritoriji Republike Makedonije, su proučeni, jedan rudnik olova i cinka sa flotacijom, jedan rudnik bakra sa flotacijom i postrojenjem za luženje bakra, kao i jedno normalno postrojenje za proizvodnju dolomena iz olova i cinka sa flotacijom, jedan rudnik bakra sa flotacijom i postrojenjem za luženje bakra, kao i jedno normalno postrojenje za proizvodnju dolomena iz olova i cinka sa flotacijom.

Ključne reči: teški metali, kontaminacija, rudnici, antropogen, R. Makedonija

The Effect of Zinc on the Microstructure and Phase Transformations of Casting Al-Cu Alloys

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Copper is one of the main alloying elements for aluminium casting alloys. As an alloying element, copper significantly increases the tensile strength and toughness of alloys based on aluminium. The copper content in the industrial casting aluminium alloys ranges from 3.5 to 11 wt.%. However, despite the positive effect on the mechanical properties, copper has a negative influence on the corrosion resistance of aluminium and its alloys. In order to further improve the properties of Al-Cu alloys they are additionally alloyed with elements such as zinc, magnesium and others.

In this work experimental and analytical examination of the impact of zinc on the microstructure and phase transformations of Al-Cu alloys was carried out. In order to determine the effect of the addition of zinc to the structure and phase transformations of Al-Cu alloys two alloys of Al-Cu-Zn system with selected compositions were prepared and then examined using scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDX). The experimental results were compared with the results of thermodynamic calculations of phase equilibria.

Key words: Aluminium alloys, microstructure, phase transformations, SEM-EDX

1. INTRODUCTION

Alloys of aluminium are widely used in various industrial fields [1-3]. Dozens of different aluminium alloys are commercially used in the automotive and aerospace industry while several thousand aluminium alloys have been patented till now [1].

Although aluminium casting alloys are widely used, most of these alloys contain a small number of alloying elements. All alloying elements that are used for aluminium alloy design can be classified into three major categories: basic alloying elements, ancillary additions (or dopants), and impurities.

Magnesium, zinc, copper and semiconductor silicon have by far the biggest use as alloying elements [1].

These elements represent the main alloying elements in aluminium alloys because they are added in relatively large amounts and have a considerable impact on their microstructure and properties. For example, Mg content in Al-Si casting alloys with 7% of Si is only about 0.3% but it has predominant effect on alloy’s strength.

All main alloying elements have considerable solubility in aluminium. It is known [1] that only seven elements (magnesium, copper, silicon, lithium, manganese, germanium, and silver) have maximum solubility in aluminium larger than 1%. However, neither
one can form continuous solid solution with aluminium. Of these seven elements silver and germanium use as basic alloying elements is low, mainly due to economical reasons. Silver is a precious and expensive metal, while germanium is also an expensive element extensively used in the semiconductor industry. Lithium is mainly used in wrought aluminium alloys, but not in castings due to technological difficulties.

The aim of this work is experimental and analytical investigation of the effect of zinc addition on the microstructure and phase transitions of Al-Cu casting alloys. The copper content in the industrial casting aluminium alloys ranges from 3.5 to 11 wt.% [1].

Two ternary Al-Cu-Zn alloys with selected compositions were prepared and investigated using scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDX). The samples were investigated in as-cast state and after annealing. The experimental results were compared with the results of thermodynamic calculations of phase equilibria. Also, calculation of phase equilibria for the investigated alloys was done using CALPHAD method. Experimentally obtained results were compared with the results of thermodynamic calculation.

2. EXPERIMENTAL

Two alloys with nominal compositions Al-Cu7%Zn3% and Al-Cu3%Zn7% (in wt.%) were prepared in order to investigate the effect of zinc addition on microstructure and phase transition of Al-Cu casting alloys. Samples weighting about 3 g were prepared by induction melting of mixtures of high purity metals (99.99%) in protective atmosphere of nitrogen gas.

As-cast samples were investigated using SEM-EDX analysis and their overall compositions and compositions of co-existing phases were determined.

TESCAN VEGA3 scanning electron microscope with energy dispersive spectroscopy (Oxford Instruments X-act) was used for microstructural investigation of prepared alloys.

Microstructural analysis was carried out on the polished samples prepared by the classic metallographic procedure without etching. Overall compositions and compositions of coexisting phases were determined using EDX area and point analysis.

3. THEORETICAL BASIS

Calculation of phase equilibria was done using CALPHAD (calculation of phase diagrams) method [4-5]. CALPHAD method is based on determination of Gibbs energies for all phases which may occur in a given system. System’s phase equilibria can be calculated by using minimization of total Gibbs energy method.

Two basic requirements that must be met are:

- Gibbs energies of all phases appearing in the investigated system must be defined using appropriate thermodynamic models and their model equations should be stored in the thermodynamic database;
- Calculation of phase equilibria should be performed by minimization of system’s total Gibbs energy using appropriate thermodynamic software.

Gibbs energy of the phase can be expressed as:

\[ G_m = \sum_i x_i G_i^0 + G_m^{\text{ideal}} + G_m^E \]  

(1)

In equation (1) term \( \sum_i x_i G_i^0 \) represents contribution of pure elements to the Gibbs energy of the phase (Gibbs energy of mechanical mixture of pure elements). Term \( G_m^{\text{ideal}} \) is Gibbs energy of ideal mixing of elements and \( G_m^E \) is the excess Gibbs energy for the given phase.

Gibbs energy functions for pure elements (lattice stabilities) compiled by Scientific Group ThermoData Europe (SGTE) [6] were used in this work.

Equations for \( G_m^{\text{ideal}} \) and \( G_m^E \) terms depend on thermodynamic model used for description of Gibbs energy of the phase. An appropriate model has to be assigned to all individual phases. For example, in the case of substitutional model the Gibbs energy of the phase can be expressed as (2):

\[ G_m = \sum_i x_i G_i^0 + RT \sum_i x_i \ln(x_i) + \sum_j \sum_{ij} \sum_k x_i x_j L_{ij} \chi_{ij}(x_i - x_j) \]  

(2)

where \( \sum_k \chi_{ij}(x_i - x_j) \) represents Redlich-Kister polynomial \( L_{ij} \).

For \( V=0 \) equation (2) becomes equation of regular solution model.

For \( V=1 \) equation (2) becomes equation of sub-regular solution model.

Coefficients \( L_{ij} \) represent binary interaction parameters between elements \( i \) and \( j \) (i.e. Redlich-Kister parameters).

Redlich-Kister parameter’s dependence on temperature can be expressed by following equation:

\( L_{ij} = L_{ij}^{(b)} A_{ij} + L_{ij}^{(b)} B_{ij} T + \ldots \)
In the case of significant ternary interactions their influence on Gibbs energy of the phase can be taken into account by addition of \( G_{ijk} = x_i x_j x_k L_{ijk} \) term to the equation (2) where \( L_{ijk} \) represents ternary interaction parameter.

It turned out that determination of binary and ternary interaction parameters is sufficient to accurately define Gibbs energy of the phase in the multicomponent systems.

Optimized thermodynamic parameters from Liang and Schmid-Fetzer [7] were used for the calculation of phase equilibria in this work. Calculations were performed using PANDAT software [8].

Calculated phase diagrams of the constitutive binary systems and liquidus projection of the ternary Al-Cu/Zn system are presented in Figs 1 and 2.

Figure 1a represents phase diagram of the Al-Cu binary system. During cooling eutectic reaction \( R \rightarrow (\text{Al})+\text{Al}_2\text{Cu} \) occurs at 548 °C in the aluminium rich part of the phase diagram.

Maximum solubility of copper in aluminium at the temperature of eutectic reaction is 5.7 wt.%. Eutectic reaction in the Al-Zn binary system, shown in Fig. 1b, occurs at 381 °C. Zinc has the largest solubility in aluminium. At the temperature of the eutectic reaction it is about 82 wt.%.

Zinc also has significant solubility in copper. At 400 °C it reaches 39 wt.% (Fig. 1c).

Figure 2 shows calculated liquidus projection of the Al-Cu-Zn system with marked fields of primary crystallization and liquidus isotherm lines.

4. RESULTS AND DISCUSSION

Two samples from ternary Al-Cu-Zn system were prepared by melting the weighted masses of pure metals. Nominal overall compositions of investigated samples were: sample 1: Al-Cu7%Zn3% and sample 2: Al-Cu3%Zn7% (in wt.%). As-cast samples were investigated using SEM-EDX technique.

Fig. 3 shows SEM micrograph of the sample 1 under small magnification (50x). Overall composition...
of the sample 1 determined by EDX area analysis was Al-Cu8.2%Zn3.5% (wt.%).

Fig. 4 represents SEM micrograph of the sample 2 under small magnification (50x). Again, using EDX area analysis overall composition of the sample 2 was determined to be Al-Cu 4.7% Zn5.8% (wt.%).

Figure 3 – SEM micrograph of the sample 1 (Al-Cu8.2%Zn3.5%)

Figure 4 - SEM micrograph of the sample 2 (Al-Cu4.7%Zn5.8%)

Nominal and experimentally determined overall compositions of the samples investigated in this work are shown in table 1.

Table 1. Compositions of the samples investigated in this work

<table>
<thead>
<tr>
<th>Sample</th>
<th>Nominal overall composition (wt.%)</th>
<th>Experimentally determined overall composition using EDX analysis (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al-Cu7%Zn3%</td>
<td>Al-Cu8.2%Zn3.5%</td>
</tr>
<tr>
<td>2</td>
<td>Al-Cu3%Zn7%</td>
<td>Al-Cu4.7%Zn5.8%</td>
</tr>
</tbody>
</table>

After determination of samples’ overall composition the chemical compositions of individual phases were determined using EDX analysis.

Figure 5 shows SEM micrograph of the sample 1 under large magnification. Chemical compositions of individual grains were determined using combination of EDX point and area analysis (Figure 5).

Figure 5 - SEM micrograph of sample 1 under magnification 1000x. Large dark grains represent aluminium based solid solution (Al) while bright areas represent Al2Cu compound with small amount of dissolved zinc

The results of EDX analysis revealed that large dark grains in the microstructure of sample 1 represent solid solution based on aluminium, i.e. (Al) phase. Average chemical composition of dark phase was 94.4% Al, 2.7% Cu and 2.9% Zn. Microstructure of the sample 1 includes one additional phase appearing as the bright regions along the grain boundaries of the (Al) grains.

Phase fraction of the bright phase is much smaller compared to the dark phase. Average chemical composition of the bright phase obtained by EDX analysis was 51.7% Al, 46.5% Cu and 1.8% Zn.

Determined chemical composition of the bright phase is closest to the chemical composition of the binary intermetallic compound Al2Cu (Fig. 1a) containing 46-48%Al and 52-54%Cu. Obtained results suggest that under the condition of samples rapid cooling a certain amount of zinc dissolves in the Al2Cu phase i.e. it comes to the replacement of a certain amount of copper atoms with zinc atoms in the crystal structure of the Al2Cu phase.

Microstructure of the sample 2 is presented in Fig. 6. It can be seen that microstructure of sample 2 is very similar to the microstructure of sample 1 and it includes dark grains of the (Al) phase in the base and bright crystals of the Al2Cu phase along boundaries of the (Al) grains.

Average chemical compositions of the identified phases were: (Al) phase: 93.6% Al, 1.3% Cu and 5.1%
Zn; Al₂Cu phase: 48.1% Al, 49.4% Cu and 2.5% Zn. As with the sample 1, zinc does not form new phase with aluminium and copper, rather it stays dissolved in (Al) and Al₂Cu phases.

According to the calculated equilibrium solidification diagram presented in Figure 7a it can be seen that solidification of alloy 1 starts at 632 °C (liquidus temperature) with crystallization of (Al) solid solution (FCC phase) from the liquid phase (L phase). The change of phase fractions from sample 1 with temperature is presented in Figure 7b. With further cooling, fraction of the liquid phase decreases while fraction of the (Al) phase increases. At 534 °C Al₂Cu phase starts to crystallize from the melt and at 530 °C solidification of residual melt finishes (solidus temperature).

With further cooling below solidus temperature phase fraction of the (Al) phase decreases while phase fraction of the Al₂Cu increases.

At temperature of about 330 °C solid state phase transformation occurs and Al₂Cu phase decomposes into Al₅Cu₄Zn ternary compound and (Al) phase.

Calculated diagrams of equilibrium solidification and equilibrium phase fractions for the investigated samples 1 and 2 are presented in the Figures 7 and 8. Equilibrium phase fraction diagram shows changes of phase fractions with temperature in equilibrium state.

For the sample 2 calculated liquidus and solidus temperatures are 638 and 522 °C, respectively (Fig. 8a).

As in the case of sample 1 in the solid state phase fraction of the Al₂Cu phase initially increases with decrease of temperature while further cooling leads to the formation of the Al₅Cu₄Zn ternary compound (Fig. 8b).
Comparison between the results of SEM-EDX analysis and the results of thermodynamic calculation pointed out that experimentally determined microstructures of sample 1 and 2 in the as-cast state qualitatively correspond to the equilibrium phase compositions at temperatures above 300 °C.

The existence of the ternary Al₃Cu₂Zn compound, which according to the thermodynamic calculation occurs below approximately 330 °C, was not experimentally confirmed.

This could be explained by the fact that investigated alloys were in the as-cast state and that, because of relatively fast cooling solidification rates, equilibrium state corresponding to low temperature was not reached.

According to the thermodynamic calculation, Al₃Cu₂Zn ternary compound forms from the Al₃Cu phase by the solid-state phase transformation at low temperatures. This suggests that it is a very slow diffusion-controlled phase transition.

From the above discussion it can be concluded that under conditions of fast cooling microstructures of sample 1 and 2 consist of aluminium solid solution i.e. (Al) phase and Al₃Cu phase. Zinc is partially dissolved in the (Al) phase and partially dissolved in Al₃Cu phase. Thermodynamic calculation suggests that at temperatures below 330 °C under equilibrium condition Al₃Cu₂Zn phase becomes more stable than Al₃Cu phase.

In order to examine stability of the Al₃Cu₂Zn compound samples 1 and 2 were annealed at 300 °C for 5 h and slowly cooled inside the furnace. The goal was to achieve a microstructure that is closer to the equilibrium state than the microstructure of the as-cast samples.

After annealing samples were analyzed by SEM-EDX analysis. However, the existence of the Al₃Cu₂Zn compound was not confirmed. The microstructure of the annealed samples again included only (Al) and Al₃Cu phases (Figure 9).

5. CONCLUSION

The effects of the zinc addition on microstructure and phase transformations of the casting Al-Cu alloys were investigated in this work. Two Al-rich samples with variable contents of copper and zinc were prepared. Experimentally determined overall compositions of the investigated samples were: Al-Cu8.2%Zn3.5% (sample 1) and Al-Cu4.7%Zn5.8% (sample 2).

Samples in the as-cast state were investigated using SEM-EDX analysis. It was determined that microstructures of both investigated samples include two phases: aluminum based solid solution-(Al) phase and Al₃Cu phase along the grain boundaries of the (Al) phase. Zinc is partially dissolved in the (Al) phase and partially dissolved in the Al₃Cu phase. Experimentally obtained results were compared with the results of phase equilibria calculations according to CALPHAD method and based on the optimized thermodynamic parameters taken from literature.

The results of phase equilibria calculation predict that at temperatures lower than 330 °C Al₃Cu₂Zn ternary phase becomes more stable than Al₃Cu phase. In order to verify the results of thermodynamic calculation samples were annealed at 300 °C for 5 h. After annealing samples were again investigated using SEM-EDX analysis but the formation of the Al₃Cu₂Zn compound was not identified.

It can be concluded that phase transformation of Al₃Cu phase to Al₃Cu₂Zn phase represents very slow transition which is not occur under the conditions of fast solidification. Microstructures of the casting aluminium alloys with small contents of copper and zinc include (Al) and Al₃Cu phase. Zinc is partially dissolved in those two phases but it does not form a new phase.

6. ACKNOWLEDGEMENT

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REMARK

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THE EFFECT OF ZINC ON THE MICROSTRUCTURE AND PHASE...


REZIME

UTICAJ CINKA NA MIKROSTRUKTURU I FAZNE TRANSFORMACIJE LIVENIH AL-CU LEGURA

Bakar predstavlja jedan od osnovnih legirajućih elemenata za izradu aluminijumskih legura za livenje. Kao legirajući element bakar znatno povećava zateznu čvrstoću i žilavost legura na bazi aluminijuma. Sadržaj bakra u dvojnim industrijskim Al-Cu legurama za livenje se kreće od 3,5 do 11 mas.%. Međutim, pored pozitivnog uticaja na mehaničke osobine, bakar ima negativan uticaj na korozionu otpornost aluminijuma i njegovih legura. U cilju daljeg unapređenja svojstava Al-Cu legura vrši se njihovo dodatno legiranje elementima kao što su cink, magnezijum i dr.

U ovom radu je izvršeno eksperimentalno i analitičko ispitivanje uticaja cinka na mikrostrukturu i fazne transformacije Al-Cu legura. U cilju utvrđivanja uticaja dodatka cinka na strukturu i fazne transformacije Al-Cu legura pripremljene su dve legure Al-Cu-Zn sistema izabranih sastava koje su zatim ispitivane primenom skenirajuće elektronske mikroskopije sa energo-disperzivnom spektroskopijom (SEM-EDX). Dobijeni eksperimentalni rezultati su upoređeni sa rezultatima termodinamičkog proračuna faznih ravnoteža.

Ključne reči: aluminijumske legure, mikrostruktura, fazne transformacije, SEM-EDX

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TEHNIKA

INVITATION TO COOPERATION AND SUBSCRIPTION

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Calculation Methods’ Comparative Analysis of Monorail Hoist Crane Local Bending Effects

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The results of numerical and experimental researches of local bending problems, carried on classic and medium-wide I profiles, were a basis for the adoption of the current standards (EN 15011: 2014) which regulates the action of the local stress caused by the effect of cart wheels. Regarding the fact that IPB (HE-B) wide flange profiles are largely used for the main carriers of monorail transport systems, this paper presents the results of the action of the local stress caused by the effect of cart wheels on the HE-A flange profile, using the methods and procedures of relevant researchers, the procedures prescribed by the standard EN 15011 as well as the results of calculations using finite element method. It has been revealed, based on comparative analysis of the results, that in the transition zone low flange / rib longitudinal local stress on the lower contour flange, determined using the above mentioned standards have tightening characteristic, while all other methods, including finite element method, give the pressing nature of the considered voltage. In addition, all of these procedures, except for the finite element method, adopt the assumption that absolute value of voltage, caused by local bending on upper and lower contour of the loaded flange, are the same, and there is no physical justification. Bearing in mind the fact that stress identification, caused by the flange local bending, is an extremely important phase proving the strength of monorail beams, we may conclude that the application of standard EN 15011 does not provide reliable results when it comes to wide flange profiles.

Key words: monorail hoist crane, local bending, EN 15011, finite element method

1. INTRODUCTION

Different systems of internal transport widely use the concept of rolled carts with drooping profile, which is the basic support structure for transporting cargo. Cart wheels move along the lower contour flange and, in addition to overall bending of beams, they cause local stress.

In the historical preview, the so-called ordinary rolled I profiles were first used as the main carriers in all of those structural solutions, with inclined flange. The lack of lateral stability, due to the relatively narrow carrier flange derived from ordinary rolled I profile, requires their structural reinforcement. This is most often achieved by adding a valid U profile on the pressed flange, or adding a box-girder trapezoidal or rectangular cross section.

Ordinary rolled I profile with inclined flange were expelled by the broad medium-rolled IPE profiles with parallel flange contour. However, due to constraints related to the capacity of IPE profiles (maximum size IPE 600, i.e. the maximum height of 600 mm), wide flange profiles IPB (HE-A, HE-B) were predominantly used in the last 20 years for the purpose of creating the main single-girder cranes and crane paths.

Their capacity is much higher, since they are produced to the maximum height profile h = 1000 mm. It is of particular importance that wide flange profiles IPB, from the size 300 (HE-A 300, HE-B 300) to the size 1000 (HE-A 1000 HE-B 1000) is constant at b = 300 mm.

The influence of the cart wheels causes local bending of the low flange carrier and the emergence of biaxial stress state, Figure 1 (a).

The longitudinal stress due to the local bending (σx,l) changes in the thickness of the flange, figure 1 (b), and is algebraic added to the stress of general (global) bending (σx,g):

\[ \sigma_{x,\text{tot}} = \sigma_{x,f} + \sigma_{x,l}. \] (1)
The stress due to cross-bending carrier flange (\(\sigma_y\)) is also changed along the thickness of the carrier flange, figure 1 (b).

Stresses induced by local effect of wheel (stress \(F\)) at a distance \(i\), from the free contour of low flange (thickness \(t\)), figure 2, are determined on the basis of the general expression

\[
\sigma_{xy} = c_x(i) \frac{F}{t^2},
\]

(2)

\[
\sigma_{yx} = c_y(i) \frac{F}{t^2},
\]

(3)

where \(c_x(i)\) and \(c_y(i)\) are stress coefficients in longitudinal and transversal direction, figure 2. Instead of distance \(i\), dimensionless parameters of points’ position are often used, taking into account the ratio of the wheel distance from the free flange contour and flange width, for example: \(c = a/(a-i)/a\), figures 2 and 9; \(\lambda = 2i/(b-s)\), figures 7 and 10.

Figure 1 – (a) Local effect of wheels on lower flange of main carrier [1]; (b) stress distribution caused by global and local bending [2]

The stress caused by local bending depends on the thickness of the flange, besides the load intensity. Conventional (classical) I profiles have a greater flange thickness than the IPE profile, whose flanges are thinner for the same cross section height. At wide flange profiles IPB (HE-A, HE-B) flange thickness are significantly greater, which is the reason why they are predominantly used today for manufacturing the main girders.

The first solutions of the problem [3] of determining the stress, induced by the local bending of carriers’ flanges, were obtained by using the theory of plate bending. After that, experimental researches were conducted in order to determine the local stress state more accuratately. Researches of Hannover and Reichwald [4, 5] carried out for the needs of FEM (Fédération Européenne de la Manutention), include the results of all previous benchmark studies [6, 7, 8, 9], and constitute the basis for the adoption of the annex E of the standard EN 15011 [10], which was adopted by our country (SRPS EN 15011: 2014). Based on analysis of the works which are used as the basis of Hannover and Reichwald research, we may conclude that all experimental researches were carried on classic I profiles, i.e. on profiles with the inclined flange contour, as well as the medium-wide IPE profiles with parallel flange contours. In the existing literature, the problem of identifying a local stress state of wide flange IPB profile (HE-A, HE-B) is not considered. Therefore, the accuracy of the expression application formed on the basis of studies of classical profiles as well as medium-wide IPE profile, is questionable in terms of the problem of identifying a local stress state of wide flange IPB profile, regarding the fact that their geometrical characteristics significantly differ from the geometric characteristics of mentioned class profiles.

2. REVIEW OF PROCEDURES AND EXPRESSIONS FOR CALCULATION OF LOCAL STRESS STATE

A cross section view of girder loaded by local effect of wheel cart, figure 2, reminded the majority of researchers to solve the problem of local bending by using the model of equivalent console, whose width corresponds to the width of the zone of the local wheel effect. Accordingly, the highest load is expected in the transition zone low flange/rib, i.e. in the nip of equivalent console, cross-section 0, figure 2, longitudinal local stress on the lower contour flange of the bottom flange / rib, or the equivalent nip the console, while stress states, directly below the wheel (cross-section 1) and on the free edge of the lower flange (cross-section 2), are not analyzed in detail, except in standard EN 15011.

Figure 2 - The girder open cross section (HE-A 360) loaded with cart wheels
2.1 Gokhberg

Through the synthesis of theoretical solutions of Papkovich [3] and the results of experimental research on the valid I profile given by Rozenshteyn [11], Gokhberg [12] defined, based on the results of his own research, the curves for identification of the local stress state of the lower flange, exposed to the cart wheel effect which carries the winch with load, figure 3.

Figure 3 [12] - The position of the load caused by the influence of wheel and the diagrams of stress coefficients

2.2 Klöppel and Lie

The procedure of calculation according to Klöppel and Lie [13], based on plate theory, figure 4, does not allow to determine the local stress to a wider range of point position, but only for a constant parameter value of point position \( c/a = 0.85 \). In the case of wide flange profile HE-A 360, it corresponds to the distance between wheel and free flange edge \( i = 21.8 \text{ mm} \), which belongs to a domain that is predominantly met in engineering practice. According to Klöppel and Lie, the value of stress coefficients amounts: \( c_x = \pm 0.84 \); \( c_y = \pm 2.8 \); \( c_{x2} = \mp 1.6 \pm 1.8 \); \( c_{y2} = 0 \) (the upper sign applies to the upper flange contour and the lower sign applies to the lower flange contour).

Figure 4 [13] - Calculation method according to Klöppel and Lie

2.3 Sahmel

According to Sahmel [9], the calculation of local stress state in the transition zone low flange / rib, is performed on the model of the console equivalent, whose width \( l \) depends on the position of wheel, figure 5.

Figure 5 [9] - Calculation method according to Sahmel

Moment in the nip equivalent console (cross section 0) and the moment of inertia of cross section are determined on the basis of the expression

\[
M_y = F c, \tag{4}
\]

\[
W_y = \frac{h^2}{6}. \tag{5}
\]

In the cross section 0, normal stress in the transversal direction, caused by local bending of flange, is determined on the basis of the expression

\[
\sigma_{y0} = \pm \frac{M_y}{W_y}, \tag{6}
\]

while the value of the local normal stress in the longitudinal direction is determined on the basis of the expression

\[
\sigma_{x0} = \pm \nu \sigma_{y0}. \tag{7}
\]

2.4 Swiss recommendations B1

The calculation procedure prescribed by the Swiss recommendations of the 1979, „Berechnungsgrundlagen für Kranbahnen“ [14], is based on the Sahmel’s idea, i.e. on equivalent console model, figure 6.

It is adopted that the width of the equivalent console on the spot of flange - rib nip is

\[
l = 2.2c, \tag{8}
\]

wherein

\[
c = a - r - i, \tag{9}
\]
\[ a = 0.5(b - s), \quad (10) \]

Figure 6.

\( \text{Figure 6} \ [14] - \text{Calculation method according to Swiss recommendations BI: (a) the central cross-section of girder; (b) width of cross-section of equivalent console} \)

Momentum in the nip of equivalent console (cross-section 0), the moment of inertia of its cross section, as well as the value of the local transversal stress, are determined in the same way as in Sahmel’s procedure, analog to the expressions (4), (5) and (6),

\[ M_0 = Fc, \quad (11) \]

\[ W_0 = \frac{h_f^2}{6} = \frac{2.2cf^2}{6}, \quad (12) \]

\[ \sigma_{y0} = \frac{M_0}{W_0} = \pm \frac{Fc}{2.2ct_f^2} = \pm 2.73 \frac{F}{t_f^2}, \quad (13) \]

According to the cited recommendations, it is adopted that the value of the longitudinal normal stress, caused by local effect of wheel, is equal to the value of transversal stress, that is,

\[ \sigma_{x0} = \sigma_{y0}, \quad (14) \]

2.5 Becker

The relatively large difference between the results obtained from the classical plates theory and experimental research, have led to Becker [6] on intensive research, the dominant experimental character. He includes in his research classical I profile and, in that times, the new IPE profiles with parallel flange contours, as well (IPE 200, IPE 300 i IPE 360). Tets girders, range \( l=4920 \) mm, were screwed to the supports, figure 7, while the load was imposed by simulator via cart (set in the middle of the beam span) with the load hanging. Simulators wheels were discs \( d=100 \) mm and \( d=160 \) mm, 14 mm thick, 15 mm the radius of the contact surface.

\( \text{Figure 7} \ [6] - \text{Tets girder and cart simulator} \)

Based on the maximum value of the stress that occurs when the wheel is located directly above the measuring point, Becker has set formula for determining the value of a stress coefficient in a point of lower flange, just below the wheel

\[ c_{z1} = \frac{b - s}{2i} = \frac{1}{2} \sqrt{\lambda} \quad (15) \]

Based on the expression (15) we may conclude that it provides an extremely high value when the wheel is very close to the free edge of the flange, figure 8, that is,

\[ \lim_{\lambda \to 0} c_{z1} = \infty, \quad (16) \]

which is, in a physical sense, impossible.

Becker thought that the longitudinal stress of the local bending stress, calculated by using stress coefficient in the defined term (15), corresponds to the cross section of the flange away for \( b / 4 \) from its free edge. According to Becker, superimposing the stress from the general folding carrier and the local
longitudinal stress in the mentioned section, the value of the stress is gained as the reliable proof of strength.

Figure 8 – The curve of stress coefficient $c_{z1}$ according to Becker

2.6 Mendel

As a part of the doctoral thesis, Mendel [7,8] has published significant research results, which are, in some parts, in accordance with the results of Becker research. The dominant contribution of Mendel’s research was related to the calculation of the local stress state of the classic profile with inclined flange. He solved the problem using the classical theory of plates, and the impact of changes in the thickness of the flange (plate) was introduced by the variable stiffness plate. He solved the partial differential equation of the second order using the finite difference method. He adopted a cross-section of the transition zone low flange / rib (cross section 0) and a cross section corresponding to the line of loads impact (cross section 1) as reliable cross section for identification of local impact flange loads. It is important to note that Mendel did not consider the state of stress at the free end of the flange (2-section). Besides classic I profile, Mendel gave expressions for identifying local stress at medium wide IPE profile with parallel flange contour. Application of the classical theory of plate prevents the analysis to include the impact of the transition radius low flange / rib. In the depictions of cross-sectional profile mentioned radius is plotted, but the point reliable for stress analysis is located in a fictional point of intersection of the upper flange contour and the contours of the ribs. The values of stress coefficients in the longitudinal ($x$) and transversal ($y$) direction is determined depending on the value of the wheel position parameter ($c / a$), based on the diagram shown in figure 9.

According to Mendel, the absolute values of local stresses in the characteristic cross-sectional profile sections are the same at the top and bottom loaded flange contour. This indicates that Mendel did not take into account the contact stress, which is a serious flaw.

The significance of Mendel’s research stems from the fact that he has performed the first successful mutual validation of the results obtained by the classical theory of plates and the results obtained experimentally.

Figure 9 – Mendel’s curve of stress coefficient for I profile with parallel flange contour [8]

2.7 Hannover and Reichwald – standard EN 15011

Based on a critical analysis of the research results of Becker [6] and Mandela [7,8], and based on the results of their own research, Hannover and Reichwald [4, 5]:

- Adopted points 0, 1 and 2, figure 10, as reliable for identifying the local stress and as a strength proof of the carrier exposed to loads caused by wheels’ pressure moving on the lower flange of the carrier;
- suggested the following expressions for calculating the value of stress coefficients in the longitudinal ($x$) and transversal ($y$) direction for profiles with parallel flange contours,

\[
\begin{align*}
  c_{x0} & = 0,050 - 0,580\lambda + 0,148e^{0,015a}, \quad (16) \\
  c_{x1} & = 2,230 - 1,490\lambda + 1,390e^{-18,33a}, \quad (17) \\
  c_{x2} & = 0,730 - 1,580\lambda + 2,910e^{-6,00a}, \quad (18) \\
  c_{y0} & = -2,110 + 1,977\lambda + 0,0076e^{6,53a}, \quad (19) \\
  c_{y1} & = 10,108 - 7,408\lambda - 10,108e^{-1,364a}, \quad (20) \\
  c_{y2} & = 0, \quad (21)
\end{align*}
\]

whereby the parameter value of wheel position is determined by the expression

\[
\lambda = \frac{2i}{b - s}. \quad (22)
\]
Figure 10 [4] - Cross-section, load and position of reliable points of I profiles with parallel flange contour

Stress coefficients in the correspondent points of the upper flange contour have opposite sign [4], which means that the absolute value of the stresses at the top and bottom contour are equal.

In addition to experimental research, in the framework of a working group formed by the CETIM FEM (section IX, No. 9341, 1978) Finite element research of local stress state was also carried out. Hannover and Reichwald used software SAP IV-B, determining the calculation domain by finite element plate type. In this way it was impossible to model the transition zone with the corresponding radius, which presents a serious problem when it comes to the mid-wide profiles (IPE).

Therefore, Hannover and Reichwald state that there is a significant deviation in the point 0 in Finite element analysis of results compared to the results obtained from the experiment.

3. NUMERICAL EXAMPLE AND DISCUSSION

In order to carry out a comparative analysis of results obtained by applying the methods and expressions given by reference authors and reference standards / norms, calculation of carrier local stress was made which was derived from the profile HE-360 A, figure 2, whose geometrical characteristics, material properties and loads are given in table 1. In addition to the procedures presented in Section 2, the local stress state analysis was performed by using the finite element method (FEM), figure 11.

Stress elimination, caused by global bending in reference points of lower flange (0,1,2), was made by subtracting the value of the corresponding stress in the correspondent points of the upper flange (0’,1’,2’), with the changed sign. The calculation results are presented in Table 2.

<table>
<thead>
<tr>
<th>Table 1. Values necessary to identify local stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>Height of profile</td>
</tr>
<tr>
<td>Width of profile</td>
</tr>
<tr>
<td>Thickness of profile</td>
</tr>
<tr>
<td>Thickness of rib</td>
</tr>
<tr>
<td>The radius of the transition rib / belt</td>
</tr>
<tr>
<td>Distance from wheel to the free edge of the flange</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>Wheel load</td>
</tr>
</tbody>
</table>

Figure 11 - Finite element identification of stress states due to the effects of cart wheels: (a) the total normal stresses in the x axis direction; (B) the total normal stresses in the direction of the axis y
Table 2. Stresses caused by local bending

| Author                        | Local stresses (kN/cm²) | \(|\sigma_x|\) | \(|\sigma_y|\) |
|-------------------------------|-------------------------|-------------|-------------|
|                               | cross section           | 0 | 1 | 2 | 0 | 1 |
| Gokhberg                      | ±1.96                   | – | ±7.51 | ±7.35 | – |
| Klöppel and Lie               | ±0.84                   | – | ±5.55 | ±9.14 | – |
| Sahmel                        | ±2.48                   | – | ±8.28 | – |
| Swiss rec. B1                 | ±8.91                   | – | ±8.91 | – |
| Becker                        | –                       | ±4.56 | – |
| Mendel                        | ±2.61                   | ±8.16 | ±8.82 | ±3.92 |
| Hannover and Reichwald, EN 15011 | ±0.63          | ±6.61 | ±5.82 | ±5.94 | ±2.32 |
| FEM                           | +1.80                   | *          | +7.13 | *          |
|                               | –1.41                   | +8.32 | ±7.12 | –6.35 | +3.63 |

*contact stress

Based on comparative analysis of the results presented in Table 2 we may conclude the following:

- there is a significant deviation in calculation of local stresses values;
- with reference to all authors and sources, local longitudinal stresses on the bottom contour, in the cross-section 0, are of pressing character, except for Hannover and Reichwald, i.e., standard EN 15011;
- all the authors, sources and standard EN 15011 state that the absolute values of the stress in the correspondent points are equal.

The statement that the absolute values of stress in the correspondent points of the upper and lower contours are equal, is completely unfounded. At the cross-section 0, due to the radius impact, or local rigidity change, stresses on the upper and lower contours are not equal, which is convincingly proved by Mendel’s experimental results.

Very high Hertzian stresses appear at the contact surface of wheel and the upper surface of the lower flange (cross section 1), which, due to the limitations of the theory of thin plates, could not be included in the stress analysis presented in sections 2.1 ÷ 2.7. If it is assumed that the load of carrier is inserted by spherical wheel, 125 mm diameter, then the application of Hertz forms provides a surface pressure of -186.7 kN / cm², which is almost two magnitude levels higher of the absolute value than the values given in Table 2.

4. CONCLUSION

In the transition zone low flange / rib, the nature of longitudinal stress, induced by the local impact of wheel on the wide flange HE-A profile, and determined by the application of specific standard EN 15011 differs from the character of the considered stresses, specified by FEM and by procedures of recognized researchers, with the exception of Hannover and Reichwald, on the basis of their research the aforementioned standard is brought.

In addition, the absolute values of the local stress in the observed zone (both longitudinal and transversal), determined by the application of standard EN 15011, have the lowest values, excluding the value of longitudinal stress directly below the wheel, determined by the application of Becker form.

Above facts point to the conclusion that the application of the above standards does not give reliable results when it comes to wide flange profiles and indicates the need for further research into the problems of identifying local stress conditions caused by wheel cants while moving along the flange of the main girder monorail transport system.

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REMARK

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REZIME

UPOREDNA ANALIZA METODA PRORAČUNA UTICAJA LOKALNOG SAVIJANJA
POJASA JEDNOŠINSKIH NOSAČA DIZALICA

Rezultati numeričko-eksperimentalnih istraživanja problema lokalnog savijanja, obavljenih na
klasičnim i srednje širokim I profilima, predstavljali su osnovu za donošenje aktualnog standarda (EN
15011:2014) koji propisuje postupak proračuna lokalnih napona izazvanih dejstvom točkova kolica. S
obzirom na činjenicu da se za izradu glavnih nosača jednošinskih transportnih sistema danas
dominantno koriste širokopojasni IPB (HE-A, HE-B) profili, u radu su prezentirani rezultati proračuna
lokalnih napona izazvanih dejstvom točkova kolica na pojaz profila HE-A, primenom metoda i
postupaka relevantnih istraživača, postupka koji propisuje standard EN 15011, kao i rezultati proračuna
primenom metode konačnih elemenata. Na osnovu uporedne analize rezultata uočeno je da u zoni
tranzicije donji pojas/rebro podužni lokalni naponi na donjoj konturi pojasa, određeni primenom
navedenog standarda imaju zatežući karakter, dok sve ostale metode, uključujući i metodu konačnih
elemenata, daju pritiskujući karakter razmatranih napona. Osim toga, svi navedeni postupci, izuzev
metode konačnih elemenata, usvajaju pretpostavku da su na gornjoj i donjoj konturi opterećenog pojasa
apsolutne vrednosti napona izazvanih lokalnim savijanjem jednake, što nema fizičkog opravdanja.
Imajući u vidu činjenicu da identifikacija napona izazvanih lokalnim savijanjem pojasa predstavlja
izuzetno važnu etapu dokazivanja čvrstoće jednošinskih nosača, zaključuje se da primena standarda EN
15011 ne daje pouzdane rezultate kada je reč o širokopojasnim profilima.

Ključne reči: jednošinski nosači dizalica, lokalno savijanje, EN 15011, metoda konačnih elemenata
Modelling and Analysis of 2-axis Reconfigurable Parallel Mechanism MOMA with Translatory Actuated Joints

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Modelling and analysis of a 2-axis reconfigurable parallel mechanism is shown in this paper. Generalized model for solving the inverse and direct kinematic problem is presented. Generalized equations showing the solution of kinematic problems of parallel mechanism applied for any configuration of reconfigurable 2-axis parallel mechanism are realized. Secluded characteristical mechanism configurations are shown as the realization examples. Workspace is determined for chosen configurations and possible singular mechanism positions are analysed.

Key words: 2-axis reconfigurable workparallel mechanism, inverse and direct kinematic problem, workspace, singularities

1. INTRODUCTION

Reconfigurable 2-axis parallel mechanism – MOMA belongs to a generation of reconfigurable technological module [1] which can exist individually or in a combination with other mechanisms in order to build new machine tools. Acronym MOMA presents Modular machine tool (MOdular MAchine Tool) with open architecture for control on basis of reconfigurable 2-axis parallel mechanism with actuated translatory joints and legs with constant length.

MOMA is established as a modular system on whose bases reconfiguring both hardware and software part of the system can be performed. Only the part referring to managing generalized model for solving inverse and direct kinematic problem, the analysis of workspace and singularities for chosen characteristic configurations of reconfigurable parallel mechanism, shown by Figure 1.

Parallel mechanism, which is considered in this paper, is produced by generalizing parallel mechanism 2D TeMoPaM (Technological module with parallel mechanism) [3]-[5], on a model of parallel mechanisms with similar configuration such as Trijoint [6], two parallelogram mechanism [7], Specht [8] and redundant driven plane parallel mechanism [9].

The studies also give specific attention to reconfigurable machine tools and manufacturing system whose configuration can easily and quickly be changed [10]. Characteristic of reconfigurable systems is customization or adjustment to the current production needs in economically accepted way [11]. Developed reconfigurable 2-axis parallel mechanism allows two reconfigurable approaches: (i) changing module on a machine and (ii) using integrated functions of reconfigurability on a machine [12].

Figure 1 – CAD models of the five basic types M1-M5

The expected main result of configuring is one configuration of MOMA machine, chosen by some criterion. In order to achieve the main result it is necessary to cover the configuration path from geometrical and kinematic models, through Jacobian inverse kinematics and singularity analysis, workspace analysis, optimization of some machine elements (for example, length of legs) [13], obtaining the virtual
prototype, virtual prototype simulations, to the configuration of machine hardware on basis of available module fund and operation testing for the final verification of configurated new machine tool [14].

2. DESCRIPTION OF RECONFIGURABLE 2-AXIS PARALLEL MECHANISM

CAD model of basic conception of reconfigurable 2-axis parallel mechanism, type M1, is shown in Figure 2. Parallel mechanism consists of two identical driving translatory axis DA1 and DA2 which provide translational motion of sliders S1 and S2 along the guide. The maximum stroke of driving axis is h=200 mm. Legs L1 and L2 are tied to the sliders with the help of rotating joints. Rotating joints are not actuated. Legs are also mutually tied by rotating joint and this bond between legs is at the same time a moving platform of parallel mechanism P. Legs of parallel mechanism have constant length.

![Figure 2 – CAD model of basic conception of 2-axis reconfigurable parallel mechanism, type M1](image)

Parallel mechanism consists of series of modules and reconfigurable of mechanism from Figure 2 is in a fact that mutual position of some modules can be changed (for example, driving axis) and some modules are part of family of elements with different dimensions (for example, legs of mechanism). Configuration of parallel mechanism can easily and quickly be changed by the construction program [2,14]. Every possible parallel mechanism configuration is defined by the construction program and some of possible parallel mechanism configurations for further analysis are shown in this paper in Figure 3.

During the change of parallel mechanism configuration, driving axis DA1 and DA2 rotate around reference points R1 and R2.

![Figure 3 – Configurations of reconfigurable 2-axis parallel mechanism for analysis with basic parameters display](image)

In Figure 3a and 3b angles $\alpha_i$ are defined by the statement $\alpha_i=3\pi/2+\gamma_i$. For Figure 3a configuration angles $\gamma_i$ have values $\gamma_1=-5^\circ$ and $\gamma_2=+5^\circ$, for Figure 3b configuration $\gamma_1=+5^\circ$ and $\gamma_2=-5^\circ$. For parallel mechanism configurations in Figure 3c and Figure 3d the basis of mechanism changes in a way that orientation angles of operating axis for parallel mechanism configuration in Figure 3c have value $\alpha_1=\pi$ and $\alpha_2=3\pi/2$ whilst in Figure 3d configuration have value $\alpha_1=0^\circ$ and $\alpha_2=\pi/2$. In Figure 3 are also shown internal coordinates of parallel mechanism $p_i$ and reference points $R_i$ which are essential for further analysis of reconfigurable parallel mechanism.

3. GEOMETRIC MODEL OF PARALLEL MECHANISM AND SOLVING IKP AND DKP

Generalized geometric model of reconfigurable parallel mechanism with two degrees of freedom which will be used for solving inverse kinematics problem (IKP) and direct kinematics problem (DKP) is shown in Figure 4.

Two coordinate systems are adopted for this geometric model and those are stationary coordinate system $\{B\}$ connected to a base and motional coordinate system connected to the platform of parallel mechanism. Vectors defined by the geometry of parallel mechanism shown in Figure 4 are:
• $\mathbf{b}_{\text{Ri}} = [x_{\text{Ri}}, y_{\text{Ri}}]^{T}$ - Position vector of reference points R in relation to stationary coordinate system $\{B\}$;

• $\mathbf{b}_{\text{OP}} = [x_{P}, y_{P}]^{T}$ - Position vector of platform of parallel mechanism P in relation to stationary coordinate system $\{B\}$;

• $\mathbf{a}_{i} = [a_{xi}, a_{yi}]^{T}$ - Unit vectors defined by the orientation of parallel mechanism guides. At this moment the general form of unit vectors $\mathbf{a}_{i}$ is present, but in next chapter it will be precisely defined according to the parallel mechanism configuration;

• $\mathbf{p}_{i}^{\mathbf{a}_{i}}$ - Vectors of the internal coordinates, whilst $p_{i}$ is a scalar controlled by the actuators;

• $\mathbf{l}_{i}^{\mathbf{z}_{i}}$ - Vectors defined by the position, orientation and the length of legs. Vectors $\mathbf{z}_{i}$ are unit vectors defined by orientation of legs. Values of $\mathbf{l}_{i}$ presents length of legs.

Figure 4 – Generalized geometric model of parallel mechanism M O M A

According to the geometric model in Figure 4 the following vector equations can be written:

\begin{equation}
\mathbf{k}_{i}^{\mathbf{w}_{i}} = \mathbf{b}_{\text{OP}} - \mathbf{b}_{\text{Ri}} \tag{1}
\end{equation}

\begin{equation}
\mathbf{l}_{i}^{\mathbf{z}_{i}} = \mathbf{k}_{i}^{\mathbf{w}_{i}} - p_{i} \mathbf{a}_{i} \tag{2}
\end{equation}

By squaring the equation (2) quadrating equation of this form is obtained

\begin{equation}
l_{i}^{2} = p_{i}^{2} - 2p_{i}(\mathbf{a}_{i}^{T} \mathbf{k}_{i}^{\mathbf{w}_{i}}) + (\mathbf{k}_{i}^{T} \mathbf{w}_{i})^{2} \tag{3}
\end{equation}

On the basis of equation (3) the solution of inverse kinematic problem in general form is obtained

\begin{equation}
p_{i} = \left(\mathbf{a}_{i}^{T} \mathbf{k}_{i}^{\mathbf{w}_{i}}\right) \pm \sqrt{\left(\mathbf{a}_{i}^{T} \mathbf{k}_{i}^{\mathbf{w}_{i}}\right)^{2} - \left(\mathbf{k}_{i}^{T} \mathbf{w}_{i}\right)^{2} + l_{i}^{2}} \tag{4}
\end{equation}

By the exchange of parameters and known values of parallel mechanism in equation (3), implicit equations (5) and (6) used for further analysis of parallel mechanism are obtained

\begin{equation}
p_{i}^{2} - 2p_{i} \left[ a_{x}(x_{P} - x_{R}) + a_{y}(y_{P} - y_{R}) \right] + (x_{P} - x_{R})^{2} + (y_{P} - y_{R})^{2} - l_{i}^{2} = 0 \tag{5}
\end{equation}

\begin{equation}
p_{i}^{2} - 2p_{i} \left[ a_{x}(x_{P} - x_{R}) + a_{y}(y_{P} - y_{R}) \right] + (x_{P} - x_{R})^{2} + (y_{P} - y_{R})^{2} - l_{i}^{2} = 0 \tag{6}
\end{equation}

For further analysis of parallel mechanism equation (5) is going to be observed as implicit function $f_{1}$ whilst equation (6) is going to be observed as implicit function $f_{2}$.

I) The solution of inverse kinematic problem

If vector $\mathbf{b}_{\text{OP}}$ is known regarding platform coordinates of parallel mechanism in stationary coordinate system $\{B\}$, solving the equations (5) and (6) by internal coordinates $p_{i}$, equations which present the solution of inverse kinematic problem are obtained

\begin{equation}
p_{i} = B_{i} - \sqrt{B_{i}^{2} - C_{i}} \tag{7}
\end{equation}

\begin{equation}
p_{i} = B_{i} - \sqrt{B_{i}^{2} - C_{i}} \tag{8}
\end{equation}

where

\begin{equation}
B_{i} = a_{x}(x_{P} - x_{R}) + a_{y}(y_{P} - y_{R}) \tag{9}
\end{equation}

\begin{equation}
C_{i} = (x_{P} - x_{R})^{2} + (y_{P} - y_{R})^{2} - l_{i}^{2} \tag{9}
\end{equation}

II) The solution of direct kinematic problem

By solving equation system (5) and (6) by the external coordinates of the parallel mechanism $x_{P}$ and $y_{P}$, the solution of direct kinematic problem is obtained. The equation (10.a) is valid for Figure 2a, 2b and 2d configurations, and equation (10b) is valid for Figure 2c configuration. The equation (11) is valid for all configurations.

\begin{equation}
y_{P} = \frac{-v_{10} - \sqrt{v_{10}^{2} - 4v_{9}v_{11}}}{2v_{9}} \tag{10.a}
\end{equation}

\begin{equation}
y_{P} = \frac{-v_{10} + \sqrt{v_{10}^{2} - 4v_{9}v_{11}}}{2v_{9}} \tag{10.b}
\end{equation}

\begin{equation}
x_{P} = v_{7} + y_{P}v_{8} \tag{11}
\end{equation}

The introduced changes in solving direct kinematic problem are given in equations (12).
\begin{align*}
  v_1 &= 2(p a_1 + x_{R1}) \\
  v_2 &= 2(p a_1 + y_{R1}) \\
  v_3 &= p_1^2 + 2 p_1 (a_{x1} x_{R1} + a_{y1} y_{R1}) - l_1^2 + x_{R1}^2 + y_{R1}^2 \\
  v_4 &= 2(p a_2 + x_{R2}) \\
  v_5 &= 2(p a_2 + y_{R2}) \\
  v_6 &= p_2^2 + 2 p_2 (a_{x2} x_{R2} + a_{y2} y_{R2}) - l_2^2 + x_{R2}^2 + y_{R2}^2 \\
  v_7 &= (v_6 - v_3)/(v_4 - v_1) \\
  v_8 &= (v_5 - v_3)/(v_4 - v_1) \\
  v_9 &= 1 + v_7 \\
  v_{10} &= 2 v_9 y_8 - v_1 y_8 - v_2 \\
  v_{11} &= v_9^2 - v_1 y_8 + v_3
\end{align*}

(12)

4. THE ANALYSIS OF WORKSPACE

Before the workspace analysis itself, it is necessary to complete derived equations by defining unit vector \( \mathbf{a}_i \). According to Fig. 4 listed unit vectors are in form \( \mathbf{a}_i = [a_{x_i}, a_{y_i}]^T \), but they can be also written the other way

\[
  \mathbf{a}_i = T^{-1} \begin{bmatrix} \cos \alpha_i & \sin \alpha_i \end{bmatrix}^T
\]

(13)

Matrix \( T \) is the transformation matrix and it is introduced to generalize derived equations and to make them valid for all parallel mechanism configurations. For parallel mechanism configurations in Figure 3a and 3b transformation matrix is

\[
  T = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\]

(14)

Transformation matrix (14) is unit matrix and it doesn’t change unit vectors \( \mathbf{a}_i \), so their form is \( \mathbf{a}_i = [\cos \alpha_i, \sin \alpha_i]^T \).

For mechanism configurations in Fig. 3c and 3d angles \( \alpha_1 = 225^\circ \) and \( \alpha_2 = 315^\circ \) are adopted. The angle \( \beta \) is the angle which all the unit vectors are rotated in relation to the axis of stationary coordinate system \( \{B\} \). Introducing transformation matrix (15) for parallel mechanism configuration in Figure 3c and transformation matrix (16) for mechanism configuration in Figure 3d, unit vectors \( \mathbf{a}_i \) are taken into direction of axis coordinate system \( \{B\} \) by transformation.

Described transformations are shown in Figure 5.

\[
  T = \begin{bmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{bmatrix}
\]

(15)

\[
  T = \begin{bmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{bmatrix}
\]

(16)

For the analysis of operating space of parallel mechanism configuration shown in Figure 3, the following parameters are adopted:

- The legs of the same lengths were used for all configurations \( l_1 = l_2 = 195 \text{ mm} \);
- For parallel mechanism configuration in Figure 3a and 3b the coordinates of reference points in coordinate system \( \{B\} \) are \( x_{R1} = 100 \text{ mm}, x_{R2} = 100 \text{ mm}, y_{R1} = y_{R2} = 0 \text{ mm} \);
- For parallel mechanism configuration in Figure 3c the coordinates of reference points in coordinate system \( \{B\} \) are \( x_{R1} = 250 \text{ mm}, y_{R1} = x_{R2} = 0 \text{ mm}, y_{R2} = 250 \text{ mm} \);
- For parallel mechanism configuration in Figure 3d the coordinates of reference points in coordinate system \( \{B\} \) are \( x_{R1} = 117 \text{ mm}, y_{R1} = x_{R2} = 0 \text{ mm}, y_{R2} = 117 \text{ mm} \);
- For parallel mechanism configuration in Figure 3a the angles that define the orientation of the guide are \( \alpha_1 = 3\pi/2 - 5^\circ \) and \( \alpha_2 = 3\pi/2 + 5^\circ \);
- For parallel mechanism configuration in Figure 3b the angles that define the orientation of the guide are \( \alpha_1 = 3\pi/2 + 5^\circ \) and \( \alpha_2 = 3\pi/2 - 5^\circ \).

Using the derived equations and adopted parameters of parallel mechanism for every mechanism configuration in Figure 3, workspaces shown in Figure 6 are obtained.

The obtained workspaces are attainable workspaces but because of the final dimensions of the elements of parallel mechanism, the legs of mechanism can be found only on the one side of the guides so the parallel mechanism platform can’t be found in every point of the workspace. This part of the workspace in Figure 6b and 6d is textured by curve.
MODELLING AND ANALYSIS OF 2-AXIS RECONFIGURABLE...

5. JACOBIAN MATRIX AND SINGULARITY ANALYSIS

For the further analysis of reconfigurable parallel mechanism in Figure 3 Jacobian matrix of inverse kinematics is derived – the equations (17) and (18) and Jacobian matrix of direct kinematics given in equations (19) and (20).

\[
J_f = \begin{bmatrix} \frac{\partial f_1}{\partial \theta_1} \\
\frac{\partial f_1}{\partial \theta_2} \\
\frac{\partial f_1}{\partial \theta_3} \\
\frac{\partial f_1}{\partial \theta_4} \end{bmatrix}
\]

(17)

\[
\frac{\partial f_1}{\partial \theta_1} = 2p_r - 2\left[a_u (x_p - x_w) + a_v (y_p - y_w)\right]
\]

\[
\frac{\partial f_1}{\partial \theta_3} = \frac{\partial f_2}{\partial \theta_3} = 0
\]

(18)

\[
J_d = \begin{bmatrix} \frac{\partial f_1}{\partial x_p} & \frac{\partial f_1}{\partial y_p} \\
\frac{\partial f_2}{\partial x_p} & \frac{\partial f_2}{\partial y_p} \end{bmatrix}
\]

(19)

\[
\frac{\partial f_1}{\partial x_p} = 2(x_p - x_w) - 2p_u a_u
\]

\[
\frac{\partial f_2}{\partial y_p} = 2(y_p - y_w) - 2p_v a_u
\]

(20)

On the basis of Jacobian matrix of inverse and direct kinematics, Jacobian matrix of parallel mechanism is derived and its general form is given in the equation (21).

\[
J = J_f^p \cdot J_d
\]

(21)

In the equations (18) and (20) the components of the unit vectors are present, and for the analysis of specific parallel mechanism configurations derived transformation matrix (14), (15) and (16) are used. According to the equation (21) with the parallel mechanism parameters from the previous chapter, for every configuration in Figure 3 the valuations of determinant of the Jacobian matrix were calculated for every point of attainable workspace of the mechanism and the results are shown in the form of a diagram in Figure 7.

Figure 6 – The workspaces of different parallel mechanism configurations

Figure 7 – The distribution detJ for different parallel mechanism configurations

Analysing the distribution det (J) and the diagram in Figure 7, singular positions of parallel mechanism configurations in Figure 3 are given. The singular parallel mechanism configurations in Figure 3a and 3b are shown in Figure 8a and 8b. Parallel mechanism configurations in Figure 3a and 3b don’t have singularities of direct kinematics.

Figure 8 – Singular configurations: a) for mechanisms from Figure 3a; b) for mechanism from Figure 3b

Singular parallel mechanism configurations in Figure 3c are shown in Figure 9 and these are singularity of inverse kinematics and singularity of direct kinematics. Singularities of inverse kinematics appear when even one of the platform coordinates is equal to...
the legs lengths (Figure 9a). For the adopted parameters of parallel mechanism it is $x_0 = 195\,[\text{mm}]$ and/or $y_0 = 195\,[\text{mm}]$. Singularity of direct kinematics appear when the cranks between legs and sliders are found in the origin point, or when their coordinates have values $x_{Z1} = x_{Z2} = y_{Z1} = y_{Z2} = 0$.

As in the previous case, mechanism in Figure 3d has the singularities of inverse kinematics (Figure 10a) and the singularities of direct kinematics (Figure 10b).

The singularity of inverse kinematics appears when the platform coordinates are $x_P = y_P = 0$, whereas the singularity of direct kinematics appears when the crank coordinates between couplers and sliders have values $x_{Z1} = x_{Z2} = y_{Z1} = y_{Z2} = 0$.

The positions of parallel mechanism platform in singular mechanism positions are shown in Figure 8-10.

But because of the geometry of component elements of the mechanism and also the whole assembly of mechanism the parallel mechanism platform can’t be found in every point of the workspace given on the basis of derived equations of kinematic problems.

In Figure 8-10 the workspace obtained by calculation is rounded by discontinuous lines where as the workspace for real physical model is textured and rounded by full line. According to that, parallel mechanism configuration in Figure 3b cannot take singular position shown in Figure 8b. Also the configurations in Figure 3c and 3d cannot take the positions where singularities of direct kinematics appear as shown in Figure 9b and 10b, respectively.

6. CONCLUSION

The main purpose of this paper is managing of generalized kinematic model for solving inverse and direct kinematic problem of reconfigurable 2-axis parallel mechanism. Derived general equations, with the change of certain parameters, are further appliable for management forming for any configuration of reconfigurable parallel mechanism, which the characteristic of integrated reconfigurability of managing this kind of machine is enabled by.

Before the physical realization of any parallel mechanism configuration, derived equations were used for analysis of wanted configuration. First, the workspace was analysed, and then the singularities of parallel mechanism. As it is shown in this paper, these kind of analyses can be done for any configuration and optimal configuration for user’s needs can be obtained.

By conducting the analysis for four shown configurations it can be concluded that by the change of certain mechanism parameters, except the shape and size of the operating space, singularities can be influenced, or if the singular mechanism positions are known, they can be physically prevented and avoided.
Further plans for described parallel mechanism is the research of new configurations of reconfigurable mechanism and also the implementation of mechanism in hybrid reconfigurable mechanisms with three and more degrees of loose.

REMARK

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REFERENCES


REZIME

MODELIRANJE I ANALIZA REKONFIGURABILNOG DVOOSNOG PARALELNOG MEHANIZMA MOMA SA OSNAŽENIM TRANSLATORnim ZGLOBOVIMA

U ovom radu je prikazano modeliranje i analiza jednog rekonfigurabilnog dvoosnog paralelnog mehanizma. Predstavljen je generalizovani model za rešavanje inverznog i direktnog kinematičkog problema. Izvedene su uopštena jednačine koje predstavljaju rešenje kinematičkih problema paralelnog mehanizma koje važe za bilo koju konfiguraciju rekonfigurabilnog dvoosnog paralelnog mehanizma. Kao primjer realizacije pokazane su izdvojene karakteristične konfiguracije mehanizma. Za izdvojene konfiguracije određen je radni prostor i analizirani su mogući singularni položaji mehanizma.

Ključne reči: rekonfigurabilni dvoosni paralelni mehanizam, inverzni i direktni kinematički problem, radni prostor, singulariteti
LMI Approach for Sliding Mode Control and Analysis of DC-DC Converters

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Circuits’ and in particular DC/DC converters’ switching behavior is analyzed in this paper using the equivalent control modeling of the dynamic systems’ sliding mode regime. As a representative example and also being one of the most complex circuits among DC/DC converters, the Ćuk converter is chosen. It is shown how the converter’s behavior in the steady state regime can be studied and analyzed by the linear matrix inequalities based stability conditions for linear dynamic systems with nonlinear sector bounded perturbations. The maximization of the nonlinear sector bound provides a limit for applying the linear ripple approximation in the converter operation analysis. Furthermore, our approach is validated by providing simulation results for two different switching surfaces of practical interest.

Key words: DC/DC converter, Ćuk converter, sliding mode, linear matrix inequalities

1. INTRODUCTION

In this work, we study a sliding mode regime as a nonlinear (due to switching) system modeling behavior [1-2] of DC/DC converters using the concept of equivalent control as introduced and developed by Utkin (see, for example, [1, 3]). In particular, we consider the Ćuk converter as a representative, one of the most complex, and important example of DC/DC converters [12]. We propose an approach in which a nonlinear dynamic model resulting from applying so-called equivalent control [1], is linearized around its equilibrium and represented as the sum of its linearized portion and the remainder which is nonlinear. This representation is known to be well suited for a Lyapunov stability analysis based on Linear Matrix Inequalities (LMI) [4].

LMI represent a special class of convex optimization formulations [5] which thus inherit all the benefits of convex programming algorithms such as uniqueness of solutions, convergence to a solution if it exists, and a definite test for feasibility of problems where the answer depends on whether or not convex algorithms converge. In particular, the LMI formulation enables an application of convex programming in computing a quadratic Lyapunov function which proves stability of the overall nonlinear system as well as switched systems [6].

Figure 1 – Ćuk converter containing (a) unidirectional switch S and a diode D; (b) bidirectional switches S1 and S2.

One of the key ingredients in this formulation is the sector bounding of the additive nonlinearity which is thus treated as a perturbation [7]. Furthermore we obtain a relationship between the simulation results and the domain in which the nonlinearity is sector bounded with the sector being maximized using LMI
formulation. This relationship enables us to estimate a size of the hysteresis used to design a switching sequence for which the converter operates in a proper steady state regime.

Most of the research on control of the Ćuk converter has been focusing on controlling two state variables, as in [8] where it is related to the sliding mode control under an assumption that \( C_1 \gg C_2 \) (for the capacitors \( C_1 \) and \( C_2 \) denoted as in Fig. 1) which results in an overall system reduction.

This reduction was performed in some particular cases by exactly one reactive element elimination [9]. However, there are some other works concerning sliding mode control of the Ćuk converter which incorporated a full-order system model as reported in [10].

Publication [10] describes sliding mode controls of the Ćuk converter built with bidirectional switches, which do not produce any discontinuous regimes. LMI approach has been already used for a design of the sliding-mode controlled buck converter [11].

In this paper we show how the sliding mode control of the Ćuk converter in its all continuous and discontinuous regimes can be analyzed using an LMI based stability analysis for linear systems with an additive nonlinearity. Stability conditions in the case of each switching surface are formulated using LMI and the additive nonlinearity (treated as a perturbation) bound is computed. The sector bounded nonlinearity is shown to be in a direct connection with the linear ripple approximation [12].

The paper is organized as follows. In Section 2, the sliding mode analysis and how to compute equivalent control for a class of dynamic systems which model DC/DC circuits’ switching behavior are presented. Dynamic properties of the Ćuk converter and its modeling are described and developed in Section 3. In Section 4, a switching surface analysis for two different surfaces of interest as well as corresponding simulation results are provided. Finally, some concluding remarks are summarized in Section 5.

2. SLIDING MODE ANALYSIS, STABILITY AND CONTROL

For a switching system such as DC/DC converter [13], the concept of the sliding mode control is materialized through an ON-OFF operation of a controllable switch. Considering that for any converter there is only one switching signal, there are two subsystems in the continuous conduction mode which can be rewritten in a compact matrix form as

\[
\dot{x} = A x + B + (C x + D) u
\]

where \( x \) denotes the state vector consisting of \( n \) state variables and \( u \in \{0,1\} \) is the scalar indicator showing whether the controllable switch is conducting or not. Matrices \( A, B, C \) and \( D \) are of appropriate dimensions determined by dimensions of \( x \) and \( u \). Essentially the system \( (1) \) represents a set of \( n \) linear differential equations with a switching variable. For the control of DC/DC converters, the switching law is given by

\[
u = \begin{cases} 1, & \text{switch to 1 when } S(x) < -\Delta \\ 0, & \text{switch to 0 when } S(x) > \Delta, \end{cases}
\]

where we assume that the sliding surface is of a linear form \( S(x) = M(x - x^*) \) with the coefficients being entries of a row vector \( M = [m_1 \ldots m_n] \), \( \Delta \) is a positive number and a constant column vector \( x^* \) is an equilibrium point and steady-state vector.

Sliding mode control technique is applied in order to analyze the converter’s behavior on the switching surface using the concept of equivalent control [1].

The system’s motion in the sliding mode is restricted to the switching surface \( S(x) = 0 \) if the surface is attractive. In the steady-state is also \( \dot{S}(x) = 0 \), [1], and thus, the equivalent control can be obtained from the vector equation

\[
u_{eq} = -\left( \frac{\partial S}{\partial x}(C x + D) \right)^{-1} \frac{\partial S}{\partial x}(A x + B),
\]

if \( \frac{\partial S}{\partial x}(C x + D) \) is nonsingular, which will be satisfied in the cases of our interest. After substituting \( u_{eq} \) in Eq. (1) we obtain

\[
\dot{x} = A x + B + (C x + D) u_{eq}.
\]

An equilibrium and steady-state vector \( x^* \) can now be computed as a constant solution to Eq. (4). Furthermore, we represent the system as the sum of the linear part \( A_1 (x - x^*) \) (computed using Taylor’s expansion) and the exact nonlinear remainder computed as

\[
h(x) = \dot{x} - A_1 (x - x^*)
\]

where \( \dot{x} \) is given in the Eq. (4).

The sliding surface equation \( S(x) = 0 \) enables an elimination of one state variable, in general. By introducing the change of variables \( y = x - x^* \), where \( x^* \) is an equilibrium, and denoting as \( z \) the vector of
variables $y_i$ which are not eliminated, the reduced system dynamics can be written as

$$\dot{z} = A^*_n \times (n-1) z + h^*_n (n-1) \times 1 (z),$$  \hspace{1cm} (6)

where matrix $A^*$ and nonlinearity $h^*$ are obtained after one state variable is eliminated using the sliding surface equation.

System stability on the desired sliding surface is determined by finding a Lyapunov function candidate of the quadratic type

$$V(z) = z^T P z,$$  \hspace{1cm} (3)

where $P$ is a constant positive definite matrix. The next step is to compute $V(z)$ as follows:

$$\dot{V}(z) = z^T (A^T P + PA^T) z + 2z^T \Phi^T(z)$$  \hspace{1cm} (4)

The stability analysis is performed using LMI [4] which is an efficient and almost the only way to compute Lyapunov functions for systems whose dynamics are represented by a linear and a sector bounded nonlinear part. The LMI problem is formulated using the S-procedure [14] which maximizes the bound on the nonlinear part. The approach due to being based on convex programming will always provide a solution if the problem is feasible and the convergence in the case when the solution exists is fast. Now, the LMI problem to examine systems stability can be formulated as follows [7]:

$$\min \gamma \frac{\alpha}{\sqrt{\gamma}}$$

subject to $Y > 0$

$$\begin{bmatrix}
A^* Y + Y A^{*T} & I & Y H^T \\
I & -I & 0 \\
HY & 0 & -\gamma I
\end{bmatrix} < 0.$$  \hspace{1cm} (5)

A solution would provide matrix $Y = \tau P^{-1}$, for some positive value $\tau$ (see [7] for more details), which maximizes the sector bound $\alpha = \frac{1}{\sqrt{\gamma}}$ so the system is Lyapunov stable. Lyapunov function derivative is then

$$\dot{V}(z) = -z^T Q z + 2z^T \Phi^T(z) < 0, \hspace{1cm} z \neq 0,$$  \hspace{1cm} (6)

where $Q = -(A^T P + PA^T) < 0$ and the nonlinear term/remainder satisfies the following sector bound

$$h^* T h^* \leq \alpha^2 z^T H T Hz.$$  \hspace{1cm} (7)

The nonlinear remainder’s sector bound shape is determined by a matrix $H$ and a positive parameter $\alpha > 0$. The following nonsingular transformation [7]

$$x = Tx,$$  \hspace{1cm} (8)

with matrix $T$ being formed from the eigenvectors of the matrix $A^*$ provides larger values for $\alpha$, that is, a better sector bound. Therefore, the LMI formulation in the transformed space

$$\tilde{H} = HT,$$  \hspace{1cm} (9)

for the preselected matrix $\tilde{H}$ results in sector bound value denoted as $\tilde{\alpha}$, which is related to $\alpha$ as

$$\alpha = \frac{\tilde{\alpha}}{\sqrt{\gamma}}.$$  \hspace{1cm} (10)

The maximization of the sector bound provides a limit for applying the linear ripple approximation, that is, a limit for considering state variables time constants to be negligible.

3. MODELING BEHAVIORS OF THE ĆUK CONVERTER

The Ćuk converter depicted in Fig. 1 is a complex fourth order DC/DC converter [12] which for those reasons is chosen to illustrate our approach. In particular, Figure 1a shows a Ćuk converter which applies switches realized by an unidirectional switch and a diode, while Figure 1b shows a synchronous Ćuk converter employing current and voltage bidirectional switches. For the synchronous converter bidirectional switches are controlled with state(S2)=¬state(S1), where ¬ denotes negation.

A. Sliding domain and operating modes

Depending on the Ćuk converter’s switches realization, a few operating modes can be determined and analyzed. Both realizations of the Ćuk converter depicted in Fig. 1 operate in two continuous modes, that is, the first one being when switch S is on and a diode isn’t (in Figure 1b switch S1 is on and S2 is off) and the second one being when switch S is off and diode D is conducting (switch S1 is off and S2 is on where again we refer to Figure 1b).

In the continuous conduction mode the state space equations are given by

$$\frac{dv_{L1}}{dt} = \frac{v_{in}}{L1} - \frac{v_{C1}}{L1} (1-u), \hspace{1cm} \frac{dv_{L2}}{dt} = \frac{v_{C1}}{L2} + \frac{v_{C2}}{L2}.$$

$$\frac{di_{L1}}{dt} = \frac{i_{L1}}{C1} (1-u) - \frac{i_{L2}}{C1}, \hspace{1cm} \frac{di_{L2}}{dt} = -\frac{i_{L2}}{C2} - \frac{v_{C2}}{RC2}.$$  \hspace{1cm} (15)

where $u = 1$ is when S is on and D is off and $u = 0$ when S is off and diode D is on. Additionally, switch S1 from Fig. 1b is controlled with signal $u$ and switch
S2 with \( u \). Eq. (15) can be rewritten in the compact matrix form suitable for applying sliding mode control as in Eq. (1), with matrices defined as follows:

\[
A = \begin{bmatrix}
0 & 0 & \frac{1}{L_1} & 0 \\
0 & 0 & 0 & \frac{1}{L_2} \\
\frac{1}{C_1} & 0 & 0 & 0 \\
0 & \frac{1}{C_2} & 0 & 0
\end{bmatrix}, \quad B = \begin{bmatrix}
\frac{v_{IN}}{L_1} \\
0 \\
0 \\
-\frac{1}{C_1}
\end{bmatrix}, \quad C = \begin{bmatrix}
0 & 0 & \frac{1}{L_1} & 0 \\
0 & 0 & 0 & \frac{1}{L_2} \\
-\frac{1}{C_1} & 0 & 0 & 0
\end{bmatrix}
\]

with matrix \( D \) being zero matrix and thus omitted in what follows. Vector of the state space variables \( x = [i_{L1} \ i_{L2} \ v_{C1} \ v_{C2}]^T \) is defined as \( x_1 = i_{L1}, \ x_2 = i_{L2}, \ x_3 = v_{C1} \) and \( x_4 = v_{C2} \), with the prescribed syntax steady-state values being \( i_{L1} = x_1^*, \ i_{L2} = x_2^*, \ v_{C1} = x_3^* \) and \( v_{C2} = x_4^* \).

A synchronous converter depicted in Figure 1b can operate only in the continuous modes. Additionally, the Ćuk converter shown in Figure 1a operates in two discontinuous modes, discontinuous inductor current mode (DICM) and discontinuous capacitor voltage mode (DCVM).

DICM occurs when the switch \( S \) is turned off and the sum of the inductor currents goes to zero, that is, \( i_{L1} + i_{L2} = 0 \), which turns off the diode. State space equations in DICM are as follows:

\[
\begin{align*}
\frac{di_{L1}}{dt} &= \frac{v_{IN} - v_{C1} - v_{C2}}{L_1 + L_2}, \\
\frac{di_{L2}}{dt} &= \frac{-v_{C1} - v_{C2}}{L_1 + L_2}, \\
\frac{dv_{C1}}{dt} &= -\frac{i_{L2}}{C_1}, \\
\frac{dv_{C2}}{dt} &= -\frac{i_{L2}}{C_2} - \frac{v_{C1}}{RC_2}.
\end{align*}
\]

DCVM occurs in the state when switch \( S \) is on and the diode is off and capacitor voltage \( v_{C1} \) reaches zero. That creates conditions for the diode to turn on and converter enters DCVM resulting in the following state space equations:

\[
\begin{align*}
\frac{di_{L1}}{dt} &= \frac{v_{IN}}{L_1}, \\
\frac{di_{L2}}{dt} &= \frac{v_{C2}}{L_2}, \\
\frac{dv_{C1}}{dt} &= 0, \\
\frac{dv_{C2}}{dt} &= -\frac{i_{L2}}{C_2} - \frac{v_{C1}}{RC_2}.
\end{align*}
\]

In order to apply the sliding mode control technique to the Ćuk converter, inverting hysteresis regulator with thresholds \( \pm \Delta \) is used.

Regulator produces controlling signal \( u \) as defined in Eq. (2) with the sliding surface determined using the following equation:

\[
S(x) = m_1 x_1 + m_2 x_2 + m_3 x_3 + m_4 x_4 - m_5
\]

where \( m_5 \) becomes a weighted sum of the reference values multiplied by the corresponding coefficients \( m_1, \ldots, m_4 \) given with expression

\[
m_5 = m_1 x_1^* + m_2 x_2^* + m_3 x_3^* + m_4 x_4^*.
\]

We primarily consider a Ćuk converter containing a switch and a diode which can operate in all continuous and discontinuous modes. For such a converter, state variable \( x_3 \) is positive and \( x_4 \) is negative, in the steady state, respectively. Thus, it is assumed that \( m_1 > 0, \ m_2 > 0, \ m_3 > 0, \ m_4 < 0 \) and \( m_5 > 0 \).

Now, an equivalent control is \( u_{eq} = -x_4^*/(v_{IN} - x_4^*) \) and the corresponding steady-state \( x_1^* = x_4^2/(Rv_{IN}) \), \( x_2^* = -x_4^*/R \), \( x_3^* = v_{IN} - x_4^* \), where \( x_4^* \) is determined by the switching surface.

**B. Ripple approximation**

The characteristic values of the DC/DC converters’ are adjusted so that the time constants of the capacitors and the inductors are much longer than the switching period. Thus, the capacitors’ voltages and inductors’ currents steady-state values are considered when the ripple is computed [12]. This means that, by using the linear ripple approximation, inductors’ currents of the Ćuk converter either linearly increase or decrease during a switching period. When the switch \( S \) is on, for \( u_{eq} T_S \) time interval, then the inductors’ currents increase as

\[
\Delta i_{L1} = \frac{v_{IN}}{L_1} u_{eq} T_S,
\]

\[
\Delta i_{L2} = \frac{x_4^*}{L_2} u_{eq} T_S = \frac{v_{IN}}{L_2} u_{eq} T_S,
\]

while when the diode is on during the rest of the period, \( (1 - u_{eq}) T_S \) long, the currents decrease by the same amount. Similarly, for the capacitors’ currents we apply linear ripple approximation [12] and obtain that capacitor \( C_1 \)'s voltage ripple is equal to

\[
\Delta v_{C1} = x_4^* u_{eq} T_S/C_1,
\]

while the voltage ripple on capacitor \( C_2 \) is very small comparing to absolute ripple change of the inductors’ currents \( \Delta i_{L1} \) and \( \Delta i_{L2} \) and capacitor voltage \( \Delta v_{C1} \). Capacitor \( C_2 \)'s current during the switching period equals \( i_{C2} = -i_{L2} - \frac{v_{C2}}{R} \), so the capacitor’s voltage variation is
\[
\Delta v_{C2} = \frac{\Delta i_{L2}}{8C_2} T_S. \tag{16}
\]

Using the steady state equations and the ripple of the state variables given in Eqs. (21), (22) and (23) one can determine the hysteresis value \( \Delta \).

4. SWITCHING SURFACE ANALYSIS

In this section we are going to provide analysis for the Ćuk converters' behavior on the switching surfaces \( S(\mathbf{x}) = x_1 - m_5 \) and \( S(\mathbf{x}) = m_1 x_1 + m_2 x_2 - m_3 \) as representative ones, yet the procedure is general and thus can be applied to any other switching surface in the same way. One of the surfaces of the importance is \( S(\mathbf{x}) = m_1 x_1 + m_4 x_4 - m_3 \) which can be used for controlling output voltage disturbance as well as the input current [15], but it won’t be analyzes in this paper. In order to achieve \( x_3 > v_{IN} \) as \( u_{eq} = \frac{x_3 - v_{IN}}{x_3} \), which results in the following steady-state:

\[
\begin{align*}
   x_1^* &= m_5, \\
   x_2^* &= \mp \sqrt{\frac{m_5 v_{IN}}{R}}, \\
   x_3^* &= v_{IN} \mp \sqrt{m_5 v_{IN} R}, \\
   x_4^* &= \pm \sqrt{m_5 v_{IN} R}.
\end{align*}
\tag{17}
\]

In order to achieve \( x_3 > 0 \) and \( x_4 < 0 \), the second solution is chosen. The first solution is negative and thus physically unacceptable.

The system’s stability on the sliding surface can be verified through the introduced approach of linearization and by finding matrix \( \mathbf{P} \) as in Eq. (9) to establish Lyapunov stability.

On the sliding surface \( S(\mathbf{x}) = x_1 - m_5 \), variable \( x_1 \) is constant and thus the equation for \( x_1 \) can be eliminated. The stability analysis is then performed in terms of variables \( \mathbf{z} = [y_2 \ y_3 \ y_4]^T \) and the remainder nonlinearity

\[
\mathbf{b}^*(\mathbf{z}) = \begin{bmatrix} 0 \\
   -v_{IN} y_2 y_3 + y_3 y_3^2 \\
   (y_3 + x_3^*) x_3^* C_1
\end{bmatrix}^T
\]

During the switching subinterval when the switch \( S \) is on and the diode is off, the inductor current \( i_{L1} \), presenting controlling variable, linearly changes, according to the linear ripple approximation:

\[
\Delta i_{L1} = 2 \Delta = \frac{v_{IN}}{L_4} u_{eq} T_S. \tag{18}
\]

Using Eq. (25), the switching period \( T_S \) can be computed and then used in the ripple calculation for other state variables as given in Eqs. (21), (22) and (23).

In Figure 2, steady state waveforms for different values of the regulator hysteresis bound \( \Delta \in \{10 \text{ m}, 100 \text{ m} \} \) when \( m_5 = 0.5 \), are shown. Steady-state values are then \( \mathbf{x}^* = [0.5 \text{ A} \ 1 \text{ A} \ 15 \text{ V} \ -5 \text{ V}]^T \).

\[\text{(a) Calculated and measured values are } T_S = 6 \mu\text{s} \]

\[\Delta i_{L1} = \Delta i_{L2} = 20 \text{ mA} \quad \Delta v_{C1} = 2 \text{ V} \quad \Delta v_{C2} = 750 \mu\text{V} \]

\[\text{(b) Calculated values are } T_S = 60 \mu\text{s} \]

\[\Delta i_{L1} = \Delta i_{L2} = 200 \text{ mA} \quad \Delta v_{C1} = 20 \text{ V} \quad \Delta v_{C2} = 75 \text{ mV} \]

\[\text{Measured is } T_S = 57.55 \mu\text{s} \]

Figure 2 – Steady-state waveforms for regular hysteresis bound (a) \( \Delta = 10 \text{ m} \), (b) \( \Delta = 100 \text{ m} \).

Furthermore, the diagrams in Fig. 2a show a high level of linear behavior and fit well the linear ripple approximation analysis. In Fig. 2b, the nonlinearity in
the ripple becomes evident especially in the waveform for $i_{L1}$. It shows that the time constants caused by real parts of eigenvalues are comparable to the switching period.

The system stability is verified using the LMI approach and computing the nonlinearity bound $\alpha$. The nonlinear remainder $h^*(z)$ has nonzero expression only at the location $h_3^*(y_3) = h^*(y_3)$. By choosing matrix $H$ to be a 3 by 3 matrix with all entries equal to zero except the one at position (2,2) being equal to 1, and using the LMI convex program as in Eq. (9) we obtain the maximized sector size. In particular, one can show that the nonlinear term satisfies

$$|h_3^*| \leq \left(\frac{\tilde{\alpha}}{\|T_2\|}\right)|y_3|,$$

where $T_2$ is the second column of the inverse of a transformation matrix $T$ as in Eq. (14). The nonlinearity perturbation bound is computed as

$$\alpha = 9.4995 \times 10^{-3}.$$

Figure 3 – The nonlinear term $h_3^*$ is plotted in red and the sector bound $\alpha|y_3|$ is plotted in blue for different values of $\Delta$ in subfigures (a)-(d).

In Figure 3, diagrams $h_3^*(y_3)$ for different values for $\Delta$ are shown. It can be seen that the error $h_3^*$ lies inside the perturbation limit when $\Delta \leq 11$, and exceeds the sector bound when $\Delta > 100$. A dominant time constant that causes nonlinearity influencing waveforms is due to eigenvalues $\lambda_{1,2} = -\frac{\sqrt{L_2} \pm \sqrt{L_2 - 4C_2 R}}{2C_2 R L_2}$ of the system model when the switch $S$ is off and the diode $D$ is on. The case when $\Delta = 100$ shows a large nonlinear behavior especially in the waveform for $i_{L1}$ when $u = 0$, as depicted in Figure 2b. It can be also observed that the left side of the diagram in Figure 3c shows steeper increasing of the error while decreasing $y_3$. In this case the error forces the system to approach the other infeasible equilibrium (the first solution in Eq. (24)).

Considering obtained sector bound $\alpha$ in Eq. (11), the limit for applying linear ripple approximation can be determined as crossing point of nonlinearity $h_3^*$ and the sector bound $\alpha |y_3|$. It can be seen that $\Delta y_3 = \Delta v_{C1} \approx 3.4$ is a limit for considering linear ripple approximation in this example and from Eq. (21), the following can be derived:

$$\Delta = \frac{1}{2} \left( \frac{C_1}{L_4} \right) \frac{y_3}{x_2},$$

which provides $\Delta = 17$ as a limit. In Figure 3d this is depicted as a limit ripple confirming the LMI procedure computation. Clearly the calculated error for all simulated cases shows when and if the linear ripple approximation can be used.

B. Switching surface $S(x) = m_1 x_1 + m_2 x_2 - m_5$

The sliding surface $S(x) = m_1 x_1 + m_2 x_2 - m_5$ allows hysteresis window current mode control [12] in which the average of a weighted sum of inductors’ currents is kept at a desired constant value. The equivalent control produces equilibria

$$x_1 = \frac{2m_1 m_4 + m_2 v_{IN} \pm \sqrt{v_{IN}^2 - 4m_1}}{2m_1}, \quad x_2 = \frac{m_3 - m_1 x_1}{m_2},$$

$$x_3 = \frac{v_{IN} + m_2 v_{IN} \pm \sqrt{v_{IN}^2}}{2m_1}, \quad x_4 = \frac{m_2 v_{IN} \pm \sqrt{v_{IN}}}{2m_1},$$

for $E = \frac{\sqrt{m_2 v_{IN} + m_3 m_5 R}}{2m_1 - m_2 + E^2}$. Of our interest is the second solution because it provides a positive value for $x_3$ and a negative value for $x_4$. This choice results in $u_{eq} = \frac{E - m_2 \sqrt{v_{IN}}}{\sqrt{v_{IN}} \sqrt{2m_1 - m_2 + E^2}}$.

For the case of the switching surface $S(x) = m_1 x_1 + m_2 x_2 - m_5$ we can eliminate state variable $y_2$ and get reduced state vector $z = [y_1 \ y_3 \ y_4]^T$. The nonlinear remainder $h^*(z) = \begin{bmatrix} 0 & h_3^* & 0 \end{bmatrix}^T$ is given by

$$h_3^* = -\frac{m_2 x_4 y_3 - R v_{IN} (m_1 - m_2) y_1}{m_2 C_1 R v_{IN} x_2 y_3 (m_1 L_2 + m_2 L_4) x_3} \times \left( y_3 \left( m_2 L_4 x_4 + m_1 L_2 v_{IN} \right) - y_4 m_2 L_4 x_3 \right).$$

We can compute $T_S$, which is then used to compute inductors currents’ and capacitors voltages’ ripple as described by Eqs. (21), (22) and (23) based on
2\Delta = m_1 \Delta L_1 + m_2 \Delta L_2 = \left( \frac{m_1}{L_1} + \frac{m_2}{L_2} \right) v_{IN} u_{eq} T S. \tag{22}

In order to demonstrate a bound for the linear ripple approximation particular, the values for switching surface \( S(x) = m_1 x_1 + m_2 x_2 - m_5 \) are chosen as \( m_1 = m_2 = 1, m_5 = 2 \), which produce the following steady-state values.

\[
x^* = \left[ (3-\sqrt{5})A \ 6-2\sqrt{5} \ A \ s(\sqrt{5}+1) \ V \ \frac{-30+10\sqrt{5}}{\sqrt{5}-1} \ V \right]^T
\]

Using the LMI convex program we obtain the sector size parameter value as \( \alpha = \tilde{\alpha} \left| \begin{bmatrix} 5 \end{bmatrix} \right| = 7.5308 \cdot 10^3 \).

5. CONCLUSION

In this paper we applied an equivalent control model of a sliding (or switching) surface to characterize the steady-state analysis of DC/DC converters. This is done by linearizing nonlinear sliding mode dynamics and representing it by a linear part and a sector bounded nonlinear remainder. Furthermore, using the linear matrix inequalities stability approach we estimated the size and the shape of the sector which the nonlinear remainder satisfies. The nonlinear sector bound is then used to determine the limit for applying linear ripple approximation in the converter operation analysis. This approach is demonstrated of the Ćuk converter’s example for two switching surfaces of the practical importance.

Figure 5 – Phase diagram \( x_2(x_1) \) in the case when \( S(x)=m_1x_1+m_2x_2-m_5 \)

In order to see the difference between the case of unidirectional switch \( S \) and a diode and bidirectional switches, in Figure 6 time diagrams when \( S(x) = x_1 + x_2 - 4 \) are provided. One may also observe that DCVM reduces significantly the inductor currents’ ripple and the capacitor \( C_i \)’s voltage. In addition, the phase diagrams shown in Fig. 7 confirm the previous analysis and agree with the phase plot from Figure 5.

Figure 6 – State variables versus time in the case when \( S(x)=x_1+x_2-4 \) when the switches are realized as (a) an unidirectional switch and a diode; (b) bidirectional

Figure 4 – The nonlinear term \( h^3 \) is plotted in red and the sector bound \( \alpha \left| y_3 \right| \) is plotted in blue for different values of \( \Delta \) in subfigures (a)-(d).

The nonlinear remainder term is computed based on simulations when \( \Delta \in \{ 1 \mathrm{m}, 10 \mathrm{m}, 100 \mathrm{m} \} \) and shown in Figure 4. One may notice an effect of nonlinearity when \( \Delta = 100 \mathrm{m} \), as depicted in Figure 4c. We can also observe maximal \( \Delta \) for which the influence of the system eigenvalues is negligible comparing to the switching period and estimate \( \Delta \nu_{C_1} \max = 11.1 \mathrm{V} \). By using the following expression:

\[
\Delta = \frac{\Delta \nu_{C_1} \nu_{IN} C_1}{2 x_2^2} \left( \frac{m_1}{L_1} + \frac{m_2}{L_2} \right)
\]

we compute \( \Delta = 90 \mathrm{m} \). We can confirm that this is indeed the boundary value as depicted in Figure 5d. The resulting phase diagram for this sliding surface is given in Figure 5. At a start up the system’s trajectory follows \( x_2 = 0 \) and \( u = 1 \), before it gets to the switching surface \( m_1 x_1 + m_2 x_2 - m_5 = 0 \). Then there is a small overshoot when \( u = 0 \) until a steady state is reached. After that the system’s motion stays on \( m_1 x_1 + m_2 x_2 - m_5 = 0 \). When \( m_5 \) is large enough so that DCVM occurs, after reaching the sliding surface, then voltage \( \nu_{C_1} \) drops to zero, so the system’s motion in DCVM returns to the switching surface via yellow trajectories as depicted in Figure 6 (with \( u = 1 \)). In the case of the bidirectional realization there is no discontinuous regime, so when \( m_5 \) is very large the return to the switching surface occurs as depicted by green trajectories in Figure 5, that is, \( u = 1 \).
6. ACKNOWLEDGEMENT

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REMARK

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REFERENCES


REZIME

LMI PRSTUP U PROJEKTOVANJU SLIDING-MODE KONTROLE I ANALIZI DC-DC KONVERTORA

Prekidačko ponašanje kola, specijalno DC-DC konvertora je analizirano u ovom radu korišćenjem ekvivalentne kontrole za modelovanje sliding-mode režima dinamičkih sistema. Kao reprezentativni primer i jedan od najkompleksnijih DC-DC konvertora, izabran je Cuk konvertor. Pokazuje se da se ponašanje konvertora u ustaljenom stanju može posmatrati i analizirati korišćenjem uslova stabilnosti baziranih na linearnim matričnim nejednačinama sa nelinearnom perturbacijom ograničenom u sektor. Maksimizacija nelinearnog ograničenja u sektoru daje granicu za primenu linear ripple aproksimacije u analizi rada konvertora. Staviše, naš pristup je potvrđen simulacijama za dve različite prekidačke površine od interesa.

Ključne reči: DC/DC konvertor, Cuk konvertor, sliding-mode, linearne matrične nejednačine
TECHNICS

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Measuring Global Logistics Efficiency Using PCA-DEA Approach

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Original scientific paper
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In situation of increasing global trade, concentration of production and economic crisis cause the increasing importance of freight transport and logistics. In that manner, economic performances of a country are very affected by logistics performances. Measuring efficiency of logistics activities on global level is important for all participants in international trade. This paper proposes the new methodology for measuring global logistics efficiency that integrates international and domestic indicators into single measure. The Principal Component Analysis – Data Envelopment Analysis (PCA-DEA) approach is used in this paper. Proposed approach is tested on a numerical example which consists of eight countries. According obtained efficiency scores observed countries are ranked. The paper also identifies the most important factors affecting the global efficiency. Several hypotheses are tested in this paper. The results show that the proposed approach can be used for evaluation of logistics activities at the global level.

Key words: Efficiency, Logistics Performance Index, PCA–DEA approach

1. INTRODUCTION

High logistics performances can improve accessibility to international flows and increase trade volume. In recent years, logistics has increasing importance in the organization of international flows. Logistics performances of all sectors influence on the economic growth and prosperity of a country [10].

Some authors stated that the role of logistics is not only to move products and materials but also to create competitive advantage by providing services which meet customer demand [8]. Logistics influences market demand effectively by creating customer satisfaction, sales and market share [22].

Efficiency is a very important indicator of operations analysis, and it is one of the basic and the most frequently used performances. Measuring, monitoring and improving efficiency are the main tasks for companies in the 21st century.

The importance of efficiency measuring in logistics has been recognized in literature [18]. In the process of winning new markets, the company gives special importance to logistics activities of the countries. The efficient logistics activities decrease logistics costs in goods or services purchased by end customers and also improve a country’s access to international markets and increase the trade volume.

Quality and efficient activities can further help country to gain a competitive advantage over other countries on regional and international markets. In the international supply chains effectiveness and efficiency of country logistics systems are key factors of country success.

This paper investigates possibilities of measuring efficiency logistics activities in countries on the global level. Measuring and monitoring efficiency of the country logistics activities is important for domestic and for international logistics operators, as well for other entities. Efficiency measurement process follows a number of problems.

There is lack of papers in literature that analysis mentioned problems. A new approach for measuring efficiency on the global level based on PCA-DEA approach is proposed in this paper. Proposed model is tested on numerical example. Numerical example is based on the study of the World Bank [5]. According obtained efficiency scores the observed countries are ranked. The ranking scores are compared with the existing LPI approach. There is difference in the
ranking of proposed approach and World Bank approach.

Next section gives a review of indicators used for measuring efficiency in logistics from different perspectives. Methodology for measuring Global Logistics Efficiency Index (GLEI) is given in the third section. In the section four proposed methodology is tested on numerical example. Hypotheses are also tested in section four. At the end of the paper, the concluding remarks and directions of future research are presented.

2. LITERATURE REVIEW AND HYPOTHESIS DEFINITION

In literature there are not enough papers that deal with logistics efficiency on global level. The importance of logistics activities in globalization era is recognized in literature [17], [20]. The importance of logistics in international trade flows is emphasized in [9]. O’Connor (2010) investigates the importance of regions on city logistics activities using Global Logistics Index (GLI). The author also shows the impact of infrastructure on global city functions. An overview of the emerging transport geography of logistics and freight distribution is given in [12]. They also provide an analysis the relationship between logistics and the core dimensions transport geography (flows, nodes/locations and networks). Some authors linking improvements in transport and logistics with improvements in import/export performances. Hummels (1999) estimates that exporters with 1% lower shipping costs have a 5-8% higher market share. Lima and Venables (2001) find that differences in infrastructure quality account for 40% of the variation in transport costs for the coastal countries and up to 60% for the landlocked countries.

One of the most frequently used indicators of global logistics activities is Logistics Performance Index (LPI). This index was introduced in 2007 through the cooperation between the World Bank and academic partners. This is useful tool for estimation logistics friendliness of a particular country. The LPI measures trade logistics performance in the 155 countries. This index can help national leaders, key policymakers, and private sector traders understand the challenges in reducing logistical barriers to international commerce [5]. Trade logistics is an important element of country competitiveness. Freight transport and logistics industry represent one of the most dynamic and important sectors of the European economy, accounting for at least 10 percent of GDP. The international supply chains are strong only as its weakest link. The LPI survey is organized as questionnaire with two parts: international and domestic [5]. The international parts relate to six key areas of logistics performances and respondents foreign logistics professionals. In the domestic LPI respondents in more detail estimate the logistics environment in the countries where they work. The LPI is used in the literature as the basis of different approaches. Kim and Min (2011) measure the efficiency of the supply chain of a country from a green perspective by proposing the Green Logistics Performance Index (GLPI) combining the LPI and the Environmental Performance Index (EPI). Authors suggested GLPI as a good indicator of a country’s green logistics efficiency, showing what impact the country’s logistics competitiveness has on its environment. Lau (2011) defined composite index for measuring green logistics performances.

This approach is also based on the LPI. Global Logistics Efficiency Index is a new indicator that combines a number of partial indicators into a single measure. This indicator also integrates domestic and international LPI indicators in order to give better measure of logistics operations in particular country [3].

Logistics activity in particular country describes a large number of different indicators, and the problem is how to select relevant indicators which describe logistics activity in the best way. This is the basic problem in application the Data Envelopment Analysis (DEA) method, as one of the most frequently used methods for efficiency measuring [7]. In that manner, it is necessary to examine influence of various factors on the country logistics activity and to select the most important.

Depending on the perspective there are two groups of indicators: domestic (national) and international. Domestic indicators provide information describe logistics activities from the perspective of the local (domestic) entities.

On the other side international indicators come from foreign logistics and trade entities. To the best of our knowledge, there are no papers in the literature that integrate domestic and international indicators in single measure. In order to obtain the most relevant efficiency score it is necessary to include internal (domestic) and external (international) indicators.

As mentioned before one of the most frequently used methods for efficiency evaluation is DEA method. In situation of large number of different indicators and relatively small number of the Decision Making Units (DMUs) discriminatory power of the DEA models is low. In order to solve mentioned problems we proposed methodology based on the Principal Component Analysis – Data Envelopment Analysis (PCA-DEA) approach.

On the basis of the previously described three basic hypotheses are set in this paper:
H1: There is difference in ranking between proposed model and LPI scores
H2: Quality indicators have the greatest influence on the efficiency scores
H3: There is the difference in the efficiency scores between countries of EU and other countries
Efficiency scores of the proposed model are used for hypotheses confirmation.

3. MODEL DEVELOPMENT - GLOBAL LOGISTICS EFFICIENCY INDEX

The development of appropriate models for estimating DC efficiency is an iterative process. For each iteration it is necessary to analyze the obtained results. The model development methodology and its application for measuring the DC efficiency are shown in Figure 1.

![Figure 1 - Model development methodology](image-url)

The figure shows the basic steps for the model development and solving the aforementioned problems. After recognizing the necessity of measuring the efficiency on the global level the set of observed countries is defined. The next step relates to defining the list of relevant indicators. In that sense we define fifteen indicators. Six of them are international while nine are domestics. All indicators are separated in two groups. The first international indicator relates to transport infrastructure. Roads, ports and railroads are very important for efficient logistics activities. The costs of arranging international shipments also have influence on logistics activities in particular country. The next international indicator is the speed, simplicity and predictability of customs procedures. Three mentioned international indicators are used as inputs in proposed approach. Quality of logistics services provided by logistics providers, transport operators, freight forwarding agencies, etc. are crucial for international trade flows. Timeless relates to shipments that reach the consignees within the scheduled or expected time. As timeless, ability track and trace shipments are also used as outputs in the proposed approach.

The group of domestic indicators has nine indicators. Eight of them are input, while one is output indicator. The only output indicator is the percent of quality correct shipments. Numerous factors affect quality of shipments in the international transport (theft, damage in transport, deterioration due inappropriate transport conditions, etc.). Lead time and export costs may greatly affect the efficiency of logistics activities. Number of import and export agencies and number of import and export forms influence the ease and speed of international goods flows. The physical inspection and multiple inspections significantly slow the customs clearance.

For overcoming the problem of variable selection PCA approach is used. The PCA is data reduction technique of multivariate data. The PCA explains the variance structure of a matrix of data through linear combinations of variables, consequently reducing the data to a few principal components (PCs), which generally describe 80-90% of the variance in the data [21]. If most of the population variance can be attributed to the first few components (dummy variables), then they can replace the original variables with minimum loss of information. After defining input and output variables the PCA was separately applied to eleven inputs and four outputs. In the reduced data set the influence is on the most influential variables.

As mentioned, in the PCA the most of the population variance can be attributed to the first few components, so they can replace the original variables with minimum loss of information ([1], [2]). According to [11] a random vector $X=X_1, X_2, ..., X_p$ (the $p$ is the number of original inputs/outputs chosen to be aggregated) has the correlation matrix $C$ with eigenvalues $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_p \geq 0$ and normalized eigenvectors $l_1, l_2, \ldots, l_p$.

Consider the linear combinations, where the superscript $\text{T}$ represents the transpose operator:

\[ X_{PC} = l_1^T X_1 + l_2^T X_2 + \ldots + l_p^T X_p, i = 1, 2, \ldots, p \]  
\[ \text{Var}(X_{PC}) = l_i^T C l_i, i = 1, 2, \ldots, p \]
As mentioned before, the PCA ranks PCs in a descending order of importance. Alder and Golany (2002) set additional constraints that require the weight of PC\(_1\) to be at least that of PC\(_2\), the weight of PC\(_2\) to be at least that of PC\(_3\) and so on. The PCA–DEA model for a DMU used in this paper has the following form [4]:

\[
\begin{align*}
\max_{U_{pc} Y_{pc}} & U_{pc} Y_{pc} \\
\text{Subject to:} & \\
V_{pc} X_{pc} & = Y_{pc} \\
V_{pc} X_{pc} - U_{pc} Y_{pc} & \geq 0 \\
V_{pc} L_{x} & \geq 0
\end{align*}
\]

4. CASE STUDY RESULTS

Model proposed in previous section is tested on the set eight countries. Namely, in this paper we analyze the Global Logistics Efficiency Index of the eight countries: Bosnia and Herzegovina, Bulgaria, Croatia, Hungary, Macedonia, Romania, Russia and Serbia.

List of indicators that are used in observed example are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Indicators for efficiency evaluation [5]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Infrastructure</td>
</tr>
<tr>
<td>International shipments costs</td>
</tr>
<tr>
<td>Customs speed and simplicity</td>
</tr>
<tr>
<td>Lead time</td>
</tr>
<tr>
<td>Export costs</td>
</tr>
<tr>
<td>Import agencies</td>
</tr>
<tr>
<td>Export agencies</td>
</tr>
<tr>
<td>Import forms</td>
</tr>
<tr>
<td>Exports forms</td>
</tr>
<tr>
<td>Physical inspection (% of import shipments)</td>
</tr>
<tr>
<td>Multiple inspection (% of shipments physically inspected)</td>
</tr>
<tr>
<td>Quality of logistics services</td>
</tr>
<tr>
<td>Timeliness</td>
</tr>
<tr>
<td>Quality of shipments (%)</td>
</tr>
<tr>
<td>Tracking &amp; tracing</td>
</tr>
</tbody>
</table>

\(^a\)I-Input; O-Output; \(^b\) IN-International indicator; D-Domestic indicator

Input and output category is indicated in the second column. As mentioned before the proposed approach integrates the six international and the nine domestic indicators.

The values in Table 1 are result of interviews with domestic and international logistics providers who evaluate logistics performances of particular countries.

4.1. Principal component analysis scores

The first phase of efficiency measuring is the PCA application for all groups of inputs and outputs separately. From each group main components were selected. All extracted components explain minimum 80% of total variance of each group. The results of principal component analysis are presented in Table 2.
As indicated the second column of Table 2 there are 11 input and 4 output variables. The two PCs are extracted from the group of input indicators. They explain a vast of the majority of the variance in the original data matrices, since they explain 83.91%.

Table 2. PCA scores

<table>
<thead>
<tr>
<th>Inputs</th>
<th>PC 1</th>
<th>PC 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure</td>
<td>0.77</td>
<td>0.46</td>
</tr>
<tr>
<td>International shipments costs</td>
<td>0.79</td>
<td>-0.33</td>
</tr>
<tr>
<td>Customs speed and simplicity</td>
<td>0.77</td>
<td>-0.50</td>
</tr>
<tr>
<td>Lead time</td>
<td>0.42</td>
<td>0.87</td>
</tr>
<tr>
<td>Export costs</td>
<td>0.82</td>
<td>0.29</td>
</tr>
<tr>
<td>Import agencies</td>
<td>-0.31</td>
<td>0.75</td>
</tr>
<tr>
<td>Export agencies</td>
<td>-0.40</td>
<td>0.90</td>
</tr>
<tr>
<td>Import forms</td>
<td>0.96</td>
<td>0.15</td>
</tr>
<tr>
<td>Exports forms</td>
<td>0.95</td>
<td>0.28</td>
</tr>
<tr>
<td>Physical inspection (% of import shipments)</td>
<td>0.82</td>
<td>-0.09</td>
</tr>
<tr>
<td>Multiple inspection (% of shipments physically inspected)</td>
<td>0.97</td>
<td>-0.06</td>
</tr>
<tr>
<td>Variance explained</td>
<td>57.58</td>
<td>26.33</td>
</tr>
</tbody>
</table>

In the first PC which explains more than 57% of total variance number of import and export forms, physical inspection and multiple inspections have the greatest influence (Table 3). Slightly lower impact has the infrastructure, costs of international shipments and customs speed and simplicity. In that manner it can be concluded that in the first component greater importance have domestic than international indicators. In the second PCs domestic indicators (lead time and number of export agencies) are dominant.

On the output side two PCs are also extracted which explain 87.8% of total variance. Quality of logistics services and track and trace are dominant in the first PC which explain almost 59% while quality of shipments is dominant in the second PC. The first output PCs relates to international indicators, while the second relates to domestic indicators.

4.2. Efficiency scores

The second phase of efficiency measurement process is the PCA-DEA model for evaluating efficiency. The classical DEA models cannot be applied in this case. They do not have sufficient discriminatory power, considering the fact that almost all DMUs are efficient.

The LPI scores have some shortcomings. The LPI scores presented in the fourth column of Table 3 are based only on six international indicators. In order to obtain real measure of the GLEI of country it is necessary to include domestic and international measures.

Model described in this paper overcome shortcomings of the previous approaches (Table 3).

Table 3. Efficiency scores according different approaches

<table>
<thead>
<tr>
<th>DMU</th>
<th>Benchmarks according PCA–DEA model</th>
<th>DEA model</th>
<th>LPI score</th>
<th>PCA DEA model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bosnia and Herzegovina</td>
<td>Hungary-0.85204,Croatia-0.070745</td>
<td>1</td>
<td>3.21 (1.00)</td>
<td>0.792147</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>Hungary-0.67849,Croatia-0.30778</td>
<td>1</td>
<td>3.17 (0.99)</td>
<td>0.941696</td>
</tr>
<tr>
<td>Croatia</td>
<td>Croatia-1</td>
<td>1</td>
<td>3.16 (0.98)</td>
<td>1</td>
</tr>
<tr>
<td>Hungary</td>
<td>Hungary-1</td>
<td>1</td>
<td>3.00 (0.93)</td>
<td>1</td>
</tr>
<tr>
<td>Macedonia, FYR</td>
<td>Hungary-0.85897</td>
<td>1</td>
<td>2.99 (0.93)</td>
<td>0.667816</td>
</tr>
<tr>
<td>Romania</td>
<td>Hungary-0.94283</td>
<td>1</td>
<td>2.80 (0.87)</td>
<td>0.723258</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>Hungary-0.86065</td>
<td>0.98</td>
<td>2.58 (0.80)</td>
<td>0.474099</td>
</tr>
<tr>
<td>Serbia</td>
<td>Croatia-0.69616,Hungary-0.23028</td>
<td>1</td>
<td>2.56 (0.80)</td>
<td>0.734125</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>1.00</td>
<td>0.91</td>
<td>0.79</td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td>0.01</td>
<td>0.08</td>
<td>0.18</td>
</tr>
</tbody>
</table>

*(LPI normalized score)*

The PCA DEA model simultaneously improves discrimination power of the standard DEA model and integrates domestic and international indicators. In the observed set two countries are efficient, Croatia and
Hungary. It roughly means that these countries have the best combination of inputs and outputs. The GLEI of Bulgaria is 0.94 and it significant higher than other countries. The lowest efficiency score has the Russia. This consequence of high cost and large number of import and export forms. The Serbia is also inefficient with the efficiency under average score. A low efficiency score is the result of relatively low logistics quality and competence as well as relatively low % of the shipments that meeting quality (only 57%).

4.3. Hypotheses testing

In this section three hypotheses are tested. The fist hypothesis investigates the differences in LPI proposed approach rankings. In that sense the next hypothesis is defined:

H1: There is difference in ranking between proposed model and LPI scores

In order to test this hypotheses rank correlation is used. According p (0.125>0.05) value there is now significant correlation between compared approaches. This also means that the PCA–DEA ranking is different from the LPI rankings.

In recent years, quality indicators in logistics have become important. The Influence of quality indicators on efficiency scores is recognized in literature. In this paper we defined and tested next hypothesis:

H2: Quality indicators have the greatest influence on the efficiency scores

According Table 3 in both output PCs quality indicators are dominant. Namely quality of logistics services has the correlation coefficient 0.91 in the first PC, while quality of shipments 0.98 in the second output PC. This confirms hypothesis that quality indicators have the greatest influence on the efficiency scores. This is in accordance with the results presented in [4].

It is assumed that the EU countries are more efficient than other countries. Next hypothesis is formulated:

H3: There is the difference in the efficiency scores between countries of EU and other countries.

Table 4. Hypotheses tests statistics

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Test</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3</td>
<td>Mann-Whitney (α=0.05)</td>
<td>4.5</td>
</tr>
<tr>
<td>U</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Z</td>
<td></td>
<td>0.393</td>
</tr>
<tr>
<td>Asymp. Sig. (2-tailed) - p</td>
<td>Kolmogorov - Smirnov (α=0.05)</td>
<td>0.639</td>
</tr>
<tr>
<td>Z</td>
<td>0.809</td>
<td></td>
</tr>
</tbody>
</table>

In order to test previous hypotheses the non-parametrical Mann-Whitney and Kolmogorov-Smirnow tests are used (Table 4). In observed example tests indicate whether the efficiency scores differ between subgroups.

The results are relatively unexpected and can be explained with relatively small set of countries. The EU countries in this case are Bulgaria, Rumania and Hungary. These countries are the less developed the EU members with a relatively undeveloped infrastructure and logistics in general. It is important to note that results relate only to observed example and they are not general.

5. CONCLUSIONS

In order to improve trade flows and country economies it is necessary to measure, monitor and improve efficiency of logistics activities. The main problem is how to select, from a large number of indicators, those that best describe the logistics activity of a country. Model proposed in this paper combines domestic and international logistics performances in single measure of efficiency.

In order to investigate the importance of indicators the PCA method is used. It was observed that qualitative indicators, such as quality of the logistics services and quality of the shipments, are more important than other indicators. As mentioned, this paper is one of the first that develop the efficiency metric that assesses both environmental and logistics performances of the country from a global perspective. The central part of the proposed methodology is the efficiency measurement model. In observed example the standard DEA models that are commonly used in literature could not be applied.

The PCA–DEA approach is used in order to improve the discriminatory power of model. This model provides useful information about the benchmarks, as well as potential improvements of inefficient countries. Proposed model can be used for evaluation of logistics activities at the global level and improves existing approaches.

Three hypotheses are set in this paper. In the first hypotheses we confirm that there is significant statistical difference in ranking between proposed model and LPI scores developed in [4]. The discriminatory power of the proposed model is higher than the compared model. In second hypothesis we confirm that quality indicators are very important for the global efficiency measurement. The third hypotheses investigated difference in efficiency scores between countries of the EU and other countries. In the observed example there is no significant statistical difference between mentioned groups. It is important to note that the
results of three hypotheses are not general and relates only to observed example, but they are a good guideline for further research.

The proposed model represents good basis for the new models development. In future research is desirable to extend the observed set. It is also possible to use the proposed approach for analysis the efficiency change in time.

In future research it is also necessary to define appropriate corrective measures for efficiency improving.

5. ACKNOWLEDGMENT

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REMARK

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REFERENCES


MERENJE GLOBALNE LOGISTIČKE EFIKASNOSTI PRIMENOM PCA-DEA PRISTUPA


Ključne reči: efikasnost, LPI, PCA-DEA pristup
Railway Stations as Efficiency Decision-Making Units – Input and Output DEA Model

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Previous announcement
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It is known from the literature that efficiency is relative, since it applies to analysed data only, and that it is identical only in application of two opposite models. In this paper we have revived two essentially different ways, by means of which for different data is reached the same efficiency: the input and the output model received using the DEA method (Data Envelopment Analysis). The information about efficiency is so necessary, however, not sufficient, because a new issue of selection of the most favourable data values or dilemma input vs. output DEA model is open. The solution of this simple theory is complex in practice, therefore, it is necessary to consider realization (difficulty and possibility) of targeted inputs (the input model) and targeted outputs (the output model).

A very simple example of railway stations of the Passenger Transport Section Belgrade has shown that from an inefficient model to an efficient one lead: (I) reduction of the number of cashiers and the number of trains, in case of the input model, and (II) increase of the number of passengers and reduction of the number of trains, in case of the output model. In this way, the measures for improvement of efficiency fall within the domain of stations and operators, on one hand, and the market, on the other. Hence the recommendation for railway stations is that not only that they should be flexible themselves, in the context of the input model, but they should also keep up with the environment and fulfil the market conditions through a more effective service, which is the point of the output model.

Key words: efficiency, DEA, input/output model, railway stations

1. INTRODUCTION

Modern companies perform their services on an open and free market, and the success of the company is not only the issue of mere survival but is set as much higher – as facilitation to secure the survival. [1] In that sense, the indicator of performance success is efficiency expressed by the generally-known ratio between the output (result) and input (investment) – if we put it simply – or as a ratio between the weighted input and weighted output sum in a more complex case. [2]

Transportation companies accomplish their objectives not only through transportation of passengers and goods, but also through the entire transportation process which also comprises the activities that precede and follow the said process. These activities take place in the infrastructure facilities generally called stations. The specific feature of railway stations is the therefore important that they perform successfully, which in this paper means efficiently; that is why we treat them here as efficiency decision-making units. Efficiency measurement is an important task of the management aimed at better understanding of the previous performance of the unit and planning of its future development. [3]

Information on efficiency is relative if compared with the analysed data. This means that different data display different efficiency which is, however, valid only in application of one and the same model. On one side, the data obtained from practice (empirical data) are indeed changeable (daily, monthly, and annual unevenness in this respect are well-known) and they cannot be influenced (accidentally or by planning). On the other side, it is known from mathematics that two opposite models give the same result: smaller input and the same output (input model) or the same input and bigger output (output model). The fact that different models (by the values of the input and output variables) result in the same objective (all units are efficient) precisely leads us to the dilemma – input vs output DEA model?
The content of the paper consists of 5 chapters. After this first, introductory chapter, follows the second chapter where examples are given with the papers with application of the DEA method aimed at solving the problems in the area of transportation.

The third chapter provides the explanation of the DEA method by application of the input and output CCR model. In chapter 4 a Case Study is made with the example of the Passenger Transport Section Belgrade applied the DEA method for measurement of efficiency of railway stations.

In that example, the DEA model consists of: 8 decision-making units (stations), two input variables (number of cashiers and number of dispatched trains) and 1 output variable (number of dispatched passengers). Chapter 5 provides a conclusion regarding the method applied and the models for efficiency measurement.

2. EXAMPLES OF DEA METHOD APPLICATION FOR SOLVING THE PROBLEMS IN THE TRANSPORTATION AREA

Application of DEA method in various fields of natural and social sciences for problem solving in calculation and efficiency achievement (which is an economic problem) is use because efficiency is and economic concept.

In the spirit of this paper, where the subject matter of the research are railway stations and the research problem is efficiency achievement and the sub-problem is the choice between the input or the output DEA model, the referential bibliography comes from two types of works from the area of transportation: with the input and the output oriented DEA models.


Examples of application of the output-oriented DEA model are: Noroozzadeh and others in [6] estimated the efficacy of 25 European railways by application of the output-oriented DEA model, where undesirable outputs are minimised (number of traffic accidents and number of victims). Fernandes and others in [7] estimated the efficacy of 35 Brazilian domestic airports by using 6 inputs and 1 output, where the desirable output is maximised (number of passengers).

Mokhtar and others in [8] estimated the efficiency of 6 container terminals on the Malaysian peninsula by use of 7 inputs and 1 output while applying the output-oriented DEA models. Barnum and others in [9] evaluated the efficacy of 16 Park and Ride parking lots by use of 2 inputs and 2 outputs.

In the area of transportation, the decision-making units to be compared may be [10]: bus lines, railway lines, Park and Ride parking lots, railway stations, garages and paratransit operations.

3. DEA METHOD – INPUT AND OUTPUT CCR MODEL

Precursor of the DEA method is the idea of Farrell from 1957 [11] which Charnes, Cooper and Rhodes upgraded in 1978 [2] by the linear programming method (LP) thus creating a new method for calculation of efficiency titled Data Envelopment Analysis (DEA). The basis of accepting and improvement of this method by numerous authors is its wide applicability in various areas of research, its simplicity and comprehensibility, suitability in cases of various inputs/outputs and, in the end, swift realisation by user software.

Mathematically, DEA method can be described by models comprising the objective function and two types of limitations. Those are the following models, Table 1:

- Model 1: General mathematical DEA model is in a non-linear form and represent a formula for calculation of efficiency which in case of \( m \) various inputs and \( s \) various outputs, reads [10]:

\[
Efikasnost = \sum_{i=1}^{m} \sum_{j=1}^{s} x_{ij} + \sum_{j=1}^{s} \frac{1}{x_{ij}} \leq \sum_{i=1}^{m} \frac{1}{x_{ij}} \leq \sum_{i=1}^{m} \frac{1}{x_{ij}}
\]

- Model 2: Input-oriented primal CCR model [2], is obtained by conversion of non-linear into a linear task, which is them easily solved by the LP method. That way you can get an optimum solution where optimisation criterion is to minimise the objective function value (linear function of variables in this model is inefficiency), with the given limitations (system of linear inequalities). [12]

Hereby we minimise the inputs with the same outputs.

- Model 3: Output-oriented CCR model [2], where optimisation criterion is to maximise the objective function value (i.e. efficiency in this model). Hereby we maximise the outputs with the same inputs.

Although Models 2 and 3 have different optimisation criteria, the problem is unique as per theorem [12]:

\[
F(X) = \max_{X \in D} F(X) \quad \Leftrightarrow \quad F(X) = \min_{X \in D} F(X).
\]

(2) Where \( D \) is the area of permissible solution

Values in the table have the following meanings:

- \( h_k \) – relative efficiency of \( k \) DMU,
- \( q \) – relative
inefficiency, $n$ – number of DMU for comparison, $m$ – number of inputs, $s$ – number of outputs, $r$ – weighting coefficient for output $r$, $v_i$ – weighting coefficient for input $i$. Limitations I in Models 2 and 3 are obtained by conversion of non-linear into a linear model, where denominator is set to be equal to one and where all variables are put on one side of inequality. Limitations II are the conditions set in order to avoid a decision-making unit to be excluded from the analysis. Textually, mathematical task can be described as follows:

Determine the values of weights (of independent variables) of inputs and outputs so that the relevant decision-making unit (DMU) has the biggest relative efficiency (dependent variable) in the output orientation or inefficiency in the input orientation, where the weighting sum of the relevant DMU input is equal to one and other DMU exceeding of equaling zero. The problem is complicated by lack of knowledge of analytic function form by which we get the value of the dependable variable for the given values of the independent variables.

Table 1. Basic DEA models – general form

<table>
<thead>
<tr>
<th>Osnovni CCR DEA modeli</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula za efikasnost</td>
<td>NLP CCR LP Primal</td>
<td>Ulazni model CCR LP Primal</td>
<td></td>
</tr>
<tr>
<td>Ulazni model</td>
<td>CCR LP Primal</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Funkcija cilja

$Izlazni model$

$\text{max } h_k = \frac{\sum \mu_i y_{ik}}{\sum v_j x_{jk}}$

$k = 1, \ldots, n$

$s I$

$\sum \mu_i y_{ij} \leq 1$

$j = 1, \ldots, n$

$\sum v_j x_{jk} \geq \varepsilon$

$i = 1, \ldots, m$

$\mu_i \geq \varepsilon$, $r = 1, \ldots, s$

$v_j \geq \varepsilon$, $i = 1, \ldots, m$

$\sum v_j x_{jk} = 1$

$s I$

$\sum \mu_i y_{ij} = 1$

$j = 1, \ldots, n$

$0 \leq \mu_i, y_{ij} \leq 1$

$i = 1, \ldots, m$

$s I$

$\sum v_j x_{jk} \geq 0$

$j = 1, \ldots, n$

$\mu_i \geq \varepsilon$, $r = 1, \ldots, s$

$v_j \geq \varepsilon$, $i = 1, \ldots, m$

$\sum v_j x_{jk} \leq 0$

$j = 1, \ldots, n$

$s I$

The number of DMU is at least twice bigger than the sum of various inputs and outputs [15] as confirmed by numerous bibliography examples where efficiency measurements were performed: 6 warehouses by use of 2 (input) + 1 (output) variables [16], 8 scenarios of work of the Danube port in Pančev by use of 3+1 variable [17], 16 Australian and other international ports by use of 6+2 variable [18].

Flexible DMU regarding the decisions to be brought in the end (reduction/increase of a certain input and/or output), but it is not required that they are completely free relative to those decisions. [19].

Assumption for use of the said CCR models is a constant yield on the scope of production which is according to [20] "an expression that denotes production function where simultaneous production growth factor of the same percentage causes the output growth in the same proportion". Target inputs/outputs that turn inefficient units into efficient ones are obtained by later Sensitivity Analysis.

TECHNICS – TRAFFIC (2016) 89
The given input and output CCR DEA primal models are two opposite ways to get the same efficiency value. Similarly, there are primal and dual CCR DEA models or primal and dual LP models. It is more practical (easier) to solve primal LP model in some tasks, and dual LP in some others. Analogously in practice we decide in favour of reorganisation per system of the input or output DEA model. As each practice example is specific, and practical use is the end goal of every theoretical work, a universal recommendation cannot be given for any of the two offered models. Therefore, follows a concrete example from the later practice of Serbian railways.

4. CASE STUDY: PASSENGER TRANSPORT SECTION BELGRADE

In this example, the efficiency DMU are railway stations within the Passenger Transport Section Belgrade, of the company “Serbian Railways” AD. Stopping stations are excluded from the analysis as there are no cashiers in them). Data Envelopment Analysis, Sensitivity Analysis and Comparative Analysis are applied in the research.

The existing model of the Passenger Transport Section Belgrade has 8 DMU (railway stations), 2 input variables (the number of cashiers and the number of dispatched trains) and 1 output variable (the number of dispatched passengers). Table 2. (Passengers of BG train are not counted in (line Novi Beograd – Pančevo) and Vukov Spomenik station which dispatches only the BG train, because as of 01st Feb 2012 Bus Plus tickets are in use.)

Based on Table 2, the number of DMU is more than two times bigger than the sum of input and output. Further on, all the stations within the Passenger Transport Section Belgrade have similar performance conditions as they belong to the same Section (and the same company), and to the cities of Belgrade and Pančevo. Also, the quantity and quality of the input-output work is measured by the same input and output variables. Hereby the conditions for DEA method defined in chapter 3 are met, followed by multi-phase process of calculation and achievement of efficacy.

I phase – Data Envelopment Analysis (DEA) is performed first by analysing the data from Table 2 by the input CCR model, and then by the output CCR model, derived from the efficiency formula, Table 3. Solutions of these models represent the efficiency values obtained by use of the computer tool Excel Solver (ES), Table 2.

Table 2. The existing state of the Passenger Transport Section Belgrade

<table>
<thead>
<tr>
<th>Sekcija za prevoz putnika Beograd</th>
<th>POSTOJEĆE STANJE</th>
<th>Eff za iste podatke, suprotne modele</th>
<th>Efikasna/Neefikasna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jedinice odlučivanja (železničke stanic)</td>
<td>Ulazni podaci za DEA model</td>
<td>Uazni model</td>
<td>Izlazni model</td>
</tr>
<tr>
<td>DMU1 (Beograd)</td>
<td>Ulaz 1 (blagajnika)</td>
<td>44</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Ulaz 2 (vozova)</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Izlaz (putnika)</td>
<td>2,566</td>
<td></td>
</tr>
<tr>
<td>DMU2 (Mladenovac)</td>
<td>4</td>
<td>17</td>
<td>82</td>
</tr>
<tr>
<td>DMU3 Rakovica</td>
<td>3</td>
<td>71</td>
<td>112</td>
</tr>
<tr>
<td>DMU4 (Zemun)</td>
<td>2</td>
<td>51</td>
<td>60</td>
</tr>
<tr>
<td>DMU5 (Batajnica)</td>
<td>3</td>
<td>51</td>
<td>197</td>
</tr>
<tr>
<td>DMU6 (Novi Beograd)</td>
<td>4</td>
<td>70</td>
<td>132</td>
</tr>
<tr>
<td>DMU7 (Pančevočki Most)</td>
<td>3</td>
<td>30</td>
<td>543</td>
</tr>
<tr>
<td>DMU8 (Resnik)</td>
<td>2</td>
<td>31</td>
<td>34</td>
</tr>
</tbody>
</table>

N the output model, the task is set to find the maximum objective function (efficiency). Limitations I are obtained when: (1) the nominator of efficiency formula equals the unit, (2) all variables are out on one side of the inequality. Limitations II for weightings of variables are set in order to avoid some units to be excluded from the analysis. If we split up this task into 8 tasks of linear programming for each of the 8 DMUs, then in each task we look for the values of variables v1, v2, and so the objective function – value of the number of passengers for each station – reaches the

1Passenger Transport Section Belgrade is now already a former Section of "Railways of Serbia" company, reorganised in August 2015.

2Source: [21]

3Source: [22]

4Source: [23]
maximum\textsuperscript{5} under the defined limitations.

Mathematical models LP2–LP8 are obtained based on LP1 by changing of the objective function and the first limitation I (marked in the table).

II phase – Sensitivity Analysis consists of determination of referential units for inefficient units using the best practice principle.

The results of the analysis are projected (targeted) values of the input and output variables with which all units perform efficiently, Table 4.

Table 3. DEA models of the Passenger Transport Section Belgrade

<table>
<thead>
<tr>
<th>Osnovni DEA modeli</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula za efikasnost</td>
<td>( \text{max} h_1 = \sum_{i=1}^{m} \frac{\mu_i y_{ij}}{\sum_{r=1}^{s} y_{rj}} )</td>
<td>( \text{min} q_j = v_1 x_{1j} + v_2 x_{2j} )</td>
<td>( \text{max} h_1 = \frac{1}{y_{ij}} )</td>
</tr>
<tr>
<td>Ograničenja I</td>
<td>( \sum_{i=1}^{m} \mu_i y_{ij} \leq 1, j = 1, \ldots 8 )</td>
<td>( \mu_1 y_{11} = 1 )</td>
<td>( v_1 x_{11} + v_2 x_{21} = 1 )</td>
</tr>
<tr>
<td>Ograničenja II</td>
<td>( \sum_{j=1}^{n} y_{j} \leq 1 )</td>
<td>( v_1 y_{11} + v_2 y_{21} = 1 )</td>
<td>( 1 y_{ij} - v_1 x_{11} - v_2 x_{21} \leq 0 )</td>
</tr>
</tbody>
</table>

Table 4. Projected state of the Passenger Transport Section Belgrade

<table>
<thead>
<tr>
<th>DMU</th>
<th>Ulazni DEA model</th>
<th>Izlazni DEA model</th>
<th>Eff za različite podatke, suprotne modele</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UL1</td>
<td>UL2</td>
<td>IZL</td>
</tr>
<tr>
<td>DMU 1</td>
<td>44</td>
<td>50</td>
<td>2.566</td>
</tr>
<tr>
<td>DMU 2</td>
<td>1</td>
<td>4</td>
<td>82</td>
</tr>
<tr>
<td>DMU 3</td>
<td>1</td>
<td>7</td>
<td>112</td>
</tr>
<tr>
<td>DMU 4</td>
<td>1</td>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>DMU 5</td>
<td>2</td>
<td>11</td>
<td>197</td>
</tr>
<tr>
<td>DMU 6</td>
<td>1</td>
<td>8</td>
<td>132</td>
</tr>
<tr>
<td>DMU 7</td>
<td>3</td>
<td>30</td>
<td>543</td>
</tr>
<tr>
<td>DMU 8</td>
<td>1</td>
<td>2</td>
<td>34</td>
</tr>
</tbody>
</table>

As can be seen in Table 5, both projected models with target inputs and outputs become efficient. Add ins and differences up to the targeted inputs and outputs are the values of changes required for efficient performance of stations which is graphically displayed on Figure 1. The changes are in the domain of stations (number if cashiers), operators (number of trains), as in other domains (number of passengers). In such a dilemma, when the changes are already quantified, it is further on necessary to measure the weighting and possibility for implementation of improvement of efficiency measures, and make a decision accordingly.

Company reorganisation in the sense of reduction of cashiers’ number and the number of trains is a change that is easier to implement, and the new organisation includes the advanced system of ticket sale and quality station and driving staff.

\textsuperscript{5}Output variable – no. of passengers – is a desirable output to be maximised. There are also the undesirable outputs such as [6]: polluters, industrial water expenditure, traffic accidents and others.

TECHNICS – TRAFFIC (2016) 91
On the other hand, the increase in the number of passengers presumes the improvement of the transportation service i.e. a more efficient service rendered and that is the measure that is more difficult to implement. Efficacy is the measure of satisfaction of users with the offered service, and is therefore in the interest of passengers. [24] Generally, the increase in the number of passengers is realised by attracting them through the improvement of the transportation service – safety improvement, lower ticket prices, more comfortable, faster and more regular and frequent trains.

Table 5. Comparative analysis of the existing and projected state

<table>
<thead>
<tr>
<th>Jedinice</th>
<th>Postojeći neefikasni model</th>
<th>POTREBNE MERE</th>
<th>Projekovani efikasni ulazni DEA model</th>
<th>Efikasnost</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMU 1</td>
<td>UL1 44 UL2 50 IZL 2.566</td>
<td>UL1 -3 UL2 -13 IZL 0</td>
<td>UL1 40 UL2 50 IZL 2.566 Eff 1</td>
<td></td>
</tr>
<tr>
<td>DMU 2</td>
<td>4 17 82</td>
<td>-3 -13 0</td>
<td>1 4 82 Eff 1</td>
<td></td>
</tr>
<tr>
<td>DMU 3</td>
<td>3 71 112</td>
<td>-2 -64 0</td>
<td>1 7 112 Eff 1</td>
<td></td>
</tr>
<tr>
<td>DMU 4</td>
<td>2 51 60</td>
<td>-1 -47 0</td>
<td>1 4 60 Eff 1</td>
<td></td>
</tr>
<tr>
<td>DMU 5</td>
<td>3 51 197</td>
<td>-1 -40 0</td>
<td>2 11 197 Eff 1</td>
<td></td>
</tr>
<tr>
<td>DMU 6</td>
<td>4 70 132</td>
<td>-3 -62 0</td>
<td>1 8 132 Eff 1</td>
<td></td>
</tr>
<tr>
<td>DMU 7</td>
<td>3 30 543</td>
<td>0 0 0</td>
<td>3 30 543 Eff 1</td>
<td></td>
</tr>
<tr>
<td>DMU 8</td>
<td>2 31 34</td>
<td>-1 -20 0</td>
<td>1 2 34 Eff 1</td>
<td></td>
</tr>
</tbody>
</table>

Postojeći neefikasni model | POTREBNE MERE | izlazni DEA model
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DMU 1</td>
<td>UL1 44 UL2 50 IZL 2.566</td>
<td>UL1 40 UL2 50 IZL 2.566 Eff 1</td>
</tr>
<tr>
<td>DMU 2</td>
<td>4 17 82</td>
<td>1 4 82 Eff 1</td>
</tr>
<tr>
<td>DMU 3</td>
<td>3 71 112</td>
<td>1 7 112 Eff 1</td>
</tr>
<tr>
<td>DMU 4</td>
<td>2 51 60</td>
<td>1 4 60 Eff 1</td>
</tr>
<tr>
<td>DMU 5</td>
<td>3 51 197</td>
<td>2 11 197 Eff 1</td>
</tr>
<tr>
<td>DMU 6</td>
<td>4 70 132</td>
<td>1 8 132 Eff 1</td>
</tr>
<tr>
<td>DMU 7</td>
<td>3 30 543</td>
<td>3 30 543 Eff 1</td>
</tr>
<tr>
<td>DMU 8</td>
<td>2 31 34</td>
<td>1 2 34 Eff 1</td>
</tr>
</tbody>
</table>

Figure 1 – Necessary changes: input (left) vs. output (right) DEA model

The condition from the beginning of the paper – that the decision-making units should be flexible in the sense of the input model – can be supplemented with a recommendation to follow both – the environment which is dynamic, and the transportation market which is also changeable and subject to influences which is in fact the sense of the output model.

5. CONCLUSION

In the process of reaching the objective it is very important not only to define a concrete goal, but also to highlight and then select the way of its realisation. If efficiency is the objective, then the ways are the input and output DEA models with extremely different values of variables. With this knowledge, suitability of either model depends on the concrete example (type of input and output, closer determination of the decision-making unit).

The paper is significant for: (1) theory, in the sense that railway stations represent one more in the series of facilities where the DEA method has been successfully applied and confirmed; (2) practice, as the suggested new models of efficient performance of real railway stations of the Passenger Transport Section Belgrade:
input (less cashiers and trains) and output (more passengers and somewhat less trains).

Extension of the example would include: (I) besides the input and output data, also the data on the internal structure of stations, where the Network Data Enveloping Analysis is applied; (II) all stations for transportation of passengers in the railway network of the Republic of Serbia, when due to a large number of decision-making units’ dual model is applied; (III) stations for transportation of goods, where the YMK model is applied [25] for measurement of efficiency of two independent sub-systems (sub-system of stations for transportation of passengers and sub-system of stations for transportation of goods).

The input model is easier for application, because it is within the domain of a flexible railway (station and operator). Contrary to this, the output model is more powerful and has higher efficiency, but is more difficult to implement because it is in the domain of the railway (service quality), as well as within the domain of market (transportation demand). It is therefore conclusive that the railway stations are units on whose efficiency it is to be decided in accordance with the abilities and possibilities they have capacity to adjust themselves to the transportation market, self-modifications or changes in the market as such.

REMARK

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REFERENCES


REZIME

ŽELEZNIČKE STANICE KAO JEDINICE ODLUČIVANJA O EFIKASNOSTI – ULAZNI I IZLAZNI DEA MODEL

Iz literature je poznato da je efikasnost relativna jer važi samo za analizirane podatke, a da je identična samo kod primene dva suprotna modela. U radu smo osvetili dva suštinski različita načina kojima se za različite podatke dobija ista efikasnost: ulazni i izlazni model dobijeni metodom DEA (Data Envelopment Analysis). Informacija o efikasnosti je tako potrebna, ali ne i dovoljna, jer se otvara novi problem izbora najpovoljnijih vrednosti podataka ili dilema ulazni vs. izlazni DEA model. Rešenje ove jednostavne teorije u praksi je složeno, te je potrebno sagledati realizaciju (težinu i mogućnost) ciljnih ulaza (ulazni model) i ciljnih izlaza (izlazni model).

Na veoma jednostavnom primeru železničkih stanica Sekcije za prevoz putnika Beograd pokazano je da od neefikasnog do efikasnog modela vodi: (I) smanjenje broja blagajnika i broja vozova, kod ulaznog modela i (II) povećanje broja putnika i smanjenje broja vozova, kod izlaznog modela. Tako su mere za poboljšanje efikasnosti u domenu stanica i operatora, s jedne strane i tržiša, s druge strane. Otuda je za železničke stanice preporuka, ne samo da su one same fleksibilne, u smislu ulaznog modela, već i da prate okruženje, te ispunjavaju uslove tržišta kroz efektivniju uslugu, što je smisao izlaznog modela.

Ključne reči: efikasnost, DEA, ulazni/izlazni model, železničke stanice
Application the MABAC Method in Support of Decision-Making on the Use of Force in a Defensive Operation

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This paper presents the application of a new method of multicriteria comparison of border approximate area - MABAC. The basis of the method is reflected in defining a distance of criterion function of each observed alternative from the border approximate area. The border approximate area is defined by a separate procedure for each criteria and depends on the value of all alternatives according to the observed criteria. The method is shown through six simple steps made in order to support decision-making on the use of force in a defensive operation. Previous studies were used for the definition of criteria and their weight coefficients. Key words: MABAC (Multi-Attributive Border Approximation area Comparison), decision-making, course of action, defensive operation

1. INTRODUCTION

The Serbian Armed Forces (SAF) and its sections are used in different types of combat and other operations [1]. In order to use the SAF in a defense and other operations, one of the most important issues is making the decision about how to use forces in reaching set target.

The military decision-making process is paid special attention to, because in the center of every decision is a human being, and not all people are expected to respond equally in situations in which they may find themselves [21]. Nevertheless, many decisions are not made based on a precisely elaborated system (criteria, weights of criteria and methods to be used are not specified, etc.), but these rely on the knowledge and experience of commanders and their staff (decision-makers in the army) and procedures that in certain situations do not reflect real operational environment.

In this paper is presented a key segment of a defense operation preparation of Land Forces (LF), based on which is improved the decision-making process concerning the use of forces - units. The criteria and weight coefficients of criteria are taken from previous research, while for the selection of the best course of action will be applied the method of multicriteria comparison of border approximate areas (MABAC - Multi-Attributive Border Approximation area Comparison). This method is selected because, in comparison to other methods of multi-criteria decision-making (SAW, COPRAS, MOORA, TOPSIS and VIKOR), it provides stable (consistent) solutions and it is considered a reliable tool for rational decision-making, as provided in detail in [20].

2. PROBLEM DESCRIPTION

The term "operation" is interpreted in different ways. Currently, in the SAF mostly applied definition, which shapes practical behavior, is provided in the Doctrine of the Serbian Armed Forces. Under the operation is understood "a collection of combat and/or non-combat activities, movements and other actions taken by a single concept, individually or in cooperation with other defense forces, in order to achieve the overall objective of different significance" [6]. "Defensive operations are the type of combat operations applied in cases in which the enemy has the initiative and seeks to occupy specific territory or strives..."
to break into defended area" [6]. Regardless of how the operation is defined, constant changes of the operating environment and physiognomy of modern warfare require continuous development of techniques, processes and procedures in order to improve the planning, organization and realization of operations [1].

In the Instructions for Operational Planning and Commands in the Serbian Armed Forces (Instructions) [29] is elaborated the process of planning military operations. In fact, in the mentioned Instructions, but also in those who were in force before it, the planning process is realized in three phases: 1) prediction, 2) decision-making and 3) plan development [25]. One segment of the planning process is the development, analysis and comparison of courses of action. In the broadest sense, a course of action presents the way in which the mission can be executed [28]. With the development of courses of action it is defined the beginning and the end of activities, which performs the operation, where it is performed, why it is performed, how it is to be performed, etc. [28].

The essence of the problem is in the selection of a single course of action, which will be selected by the decision-maker (DM), based on the comparison of all elaborated courses (alternatives). The main problem occurring in official documents is that the evaluation of courses of action differs from mission to mission, as well as from persons participating in the decision-making process [29]. This creates room for error, especially if the decision is made by less experienced persons. Taking into account that the reality of war has its differentia specifica, which is difficult to perceive through education, training, exercises and the like [2], the application of multiple criteria decision-making methods in the planning of operations is imposed as a necessity.

A general approach to the selection of course of action is presented in [7], where through the process of war games are perceived advantages and disadvantages of the courses of action, i.e. well-developed courses of action are improved. The process itself is explained through general steps, and the DM should define criteria and their weight coefficients and the like. In addition to the approach provided in [7], papers can be found in which is shown a selection of courses of action (in different types of operations) by using various multiple criteria methods [1, 8, 10, 11, 14].

3. THE MABAC METHOD

The MABAC method is developed by Pamucar and Cirovic [20]. In the paper [20] it is used a hybrid model, DEMATEL-MABAC, in which the DEMATEL method is used to determine weight coefficients of criteria and the MABAC method is used for ranking alternatives. In this paper, weight coefficients of criteria are taken from [14] and used for further implementation of the MABAC method.

The basic assumption of the MABAC method is reflected in the definition of the distance of criteria function of each observed alternative from the border approximate area. In the following part is presented the procedure of implementing the MABAC method, i.e., its mathematical formulation, which consists of 6 steps:

Step 1. Forming initial decision matrix (X). In the first step it is performed the evaluation of m alternatives by n criteria. The alternatives are presented with the vectors \( A_i = \{x_{i1}, x_{i2}, \ldots, x_{in}\} \), where \( x_{ij} \) is the value of the \( i \) alternative by \( j \) criterion (\( i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \)).

\[
X = \begin{bmatrix}
    C_1 & C_2 & \ldots & C_n \\
    A_1 & x_{11} & x_{12} & \ldots & x_{1n} \\
    A_2 & x_{21} & x_{22} & \ldots & x_{2n} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    A_m & x_{m1} & x_{m2} & \ldots & x_{mn}
\end{bmatrix}
\] (1)

where \( m \) is the alternative number, \( n \) is total number of criteria.

Step 2. Normalization of initial matrix (X) elements.

\[
N = \begin{bmatrix}
    C_1 & C_2 & \ldots & C_n \\
    A_1 & t_{11} & t_{12} & \ldots & t_{1n} \\
    A_2 & t_{21} & t_{22} & \ldots & t_{2n} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    A_m & t_{m1} & t_{m2} & \ldots & t_{mn}
\end{bmatrix}
\] (2)

Elements of normalized matrix (N) are obtained by applying the expression:

a) For benefit-type criteria

\[
t_{ij} = \frac{x_{ij} - x_{j}^{-}}{x_{j}^{+} - x_{j}^{-}}
\] (3)

b) For cost-type criteria

\[
t_{ij} = \frac{x_{ij} - x_{j}^{+}}{x_{j}^{+} - x_{j}^{-}}
\] (4)

where \( x_{ij}^{-}, x_{ij}^{+} \) and \( x_{j}^{+} \) present the elements of initial decision matrix (X), wherein \( x_{ij}^{+} \) and \( x_{j}^{+} \) are defined as follows:
\( x^+ = \max \{x_1, x_2, \ldots, x_n\} \) represents maximum values of the observed criterion by alternatives.
\( x^- = \min \{x_1, x_2, \ldots, x_n\} \) represents minimal values of the observed criterion by alternatives.

Calculation of weighted matrix \((V)\) elements.

\[
V = \begin{bmatrix}
v_{11} & v_{12} & \cdots & v_{1n} \\
v_{21} & v_{22} & \cdots & v_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
v_{m1} & v_{m2} & \cdots & v_{mn}
\end{bmatrix}
\]

(5)

Weighted matrix \((V)\) elements are calculated based on the expression (6):

\[
v_{ij} = w_i^j t_{ij} + w_i^j
\]

(6)

where \(t_{ij}\) presents the elements of normalized matrix \((N)\), \(w_i^j\) presents weight coefficients of criteria. By applying the expression (6) it is obtained the weighted matrix \((V)\), which can also be written as follows:

\[
V = \begin{bmatrix}
w_1 t_{11} + w_1 & w_1 t_{12} + w_1 & \cdots & w_1 t_{1n} + w_1 \\
w_2 t_{21} + w_2 & w_2 t_{22} + w_2 & \cdots & w_2 t_{2n} + w_2 \\
\vdots & \vdots & \ddots & \vdots \\
w_m t_{m1} + w_m & w_m t_{m2} + w_m & \cdots & w_m t_{mn} + w_m
\end{bmatrix}
\]

(7)

where \(n\) presents total number of criteria, \(m\) presents total alternatives number.

**Step 4.** Determination of border approximate area matrix \((G)\). The border approximate area for every criterion is defined according to the expression (8)

\[
g_i = \left(\prod_{j=1}^{m} v_{ij}\right)^{1/m}
\]

(8)

where \(v_{ij}\) presents weighted matrix elements \((V)\), \(m\) presents total alternatives number.

After calculating the values \(g_i\) by criteria, it is formed the matrix of border approximate area \((G)\) (9) in the form \(n \times 1\) (\(n\) presents total number of criteria by which is performed the selection of the alternatives offered).

\[
G = \begin{bmatrix}
g_1 & g_2 & \cdots & g_n
\end{bmatrix}
\]

(9)

**Step 5.** Calculation of matrix elements of alternative distance from the border approximate area \((Q)\)

\[
Q = \begin{bmatrix}
q_{11} & q_{12} & \cdots & q_{1n} \\
q_{21} & q_{22} & \cdots & q_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
q_{m1} & q_{m2} & \cdots & q_{mn}
\end{bmatrix}
\]

(10)

The alternative distance from the approximate border area \((q_{ij})\) is determined as the difference of weighted matrix elements \((V)\) and the values of border approximate area \((G)\)

\[
Q = V - G
\]

(11)

which can be written in another way:

\[
Q = \begin{bmatrix}
v_{11} - g_{11} & v_{12} - g_{12} & \cdots & v_{1n} - g_{1n} \\
v_{21} - g_{21} & v_{22} - g_{22} & \cdots & v_{2n} - g_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
v_{m1} - g_{m1} & v_{m2} - g_{m2} & \cdots & v_{mn} - g_{mn}
\end{bmatrix}
\]

(12)

where \(g_{ij}\) presents the border approximate area for the \(C_i\) criterion, \(v_{ij}\) presents weighted matrix elements \((V)\), \(n\) presents the number of criteria, \(m\) presents the alternatives number.

The alternative \(A_i\) can belong to the border approximate area \((G)\), upper approximate area \((G^+)\) or lower approximate area \((G^-)\), i.e., \(A_i \in \{G \lor G^+ \lor G^-\}\).

The upper approximate area \((G^+)\) presents the area where the ideal alternative is located \((A^+)\), while the lower approximate area \((G^-)\) presents the area where the anti-ideal alternative is located \((A^-)\) (Figure 1).
Belonging of the alternative \( A_i \) to the approximate area \( (G^+, G^- \) or \( G^-) \) is determined based on the expression (13)

\[
A_i \in \begin{cases} 
    G^+ & \text{if } q_{ij} > 0 \\
    G & \text{if } q_{ij} = 0 \\
    G^- & \text{if } q_{ij} < 0
\end{cases}
\]  

(13)

In order to be selected as the best one from the set, the alternative \( A_i \) should belong to the upper approximate area \( (G^+) \) by as many criteria as possible. For instance, if the alternative \( A_i \) belongs to upper approximate area by 5 criteria (out of total of 6 criteria), and by one criterion it belongs to lower approximate area \( (G^-) \), this means that according to 5 criteria it is close or equal to the ideal alternative, but by one criterion it is close or equal to the anti-ideal alternative. A higher value \( g_i \in G^+ \) shows that the alternative \( A_i \) is closer to the ideal alternative, while a smaller value \( g_i \in G^- \) shows that the alternative \( A_i \) is closer to the anti-ideal alternative.

Step 6. Ranking alternatives. The calculation of the values of criteria functions by alternatives (14) is obtained as the sum of the alternatives distances from the border approximate area \( (q_{ij}) \). Summing the matrix elements \( Q \) by lines are obtained final values of criteria function of alternatives

\[ S_j = \sum_{i=1}^{n} q_{ij}, \quad j = 1, 2, ..., n, \quad i = 1, 2, ..., m \]  

(14)

where \( n \) presents the number of criteria, \( m \) presents the number of alternatives.

4. PROBLEM SOLVING

Solving problem of decision support in forces use in a defensive operation, or selection of course of action, is performed through some steps that make that process. These include: defining criteria and weight coefficients; ranking alternatives and sensitivity analysis of output results.

4.1. Defining criteria and weight coefficients

Defining of the criteria by which the alternatives are evaluated is one of the most important segments of decision-making. For this purpose, a large number of methods is developed. Recently, methods of group decision-making are increasingly being used, in which a single attitude is based on the attitudes and opinions of DM/experts.

One of the most commonly used methods for “harmonization of different opinions of experts about a phenomenon that will happen in the future” is the Delphi method [18]. The method is based on an examination of highly qualified experts in one or more areas, with the help of questionnaires, in order to collect information that will be processed specifically into the data useful for analysis or prognosis [22]. The examination is performed in several rounds, until obtaining valid data. Based on this method a study is conducted, results of which were published in [14]. In the paper mentioned are defined applicable criteria that influence the final decision, as well as the weight coefficients of the criteria. The weight coefficients of criteria are obtained using the method of the analytic hierarchy process (AHP) developed by Thomas L. Saaty [23].

The AHP method is a widely applied method, more about which can be seen in considerable number of papers, such as [3, 5, 9, 12, 14, 16, 19, 23, 26] and others. This method provides good conditions for application, both in individual and group decision-making [27, 31].

Applying the foregoing method are obtained the following criteria that influence the selection of course of action of units in a defensive operation, which are taken from [14]:

- Maneuver (C1) - "skillful use of movements and fire to bring one’s own forces in a more favorable position in relation to the enemy on strategic, operational and tactical level" [6]. When talking about maneuver, Jovanovic [13] points out the fire maneuver, forces maneuver and resources maneuver, which is integrated in this criterion;
- Fire (C2) – activity that directly leads to achieving the defined goal [14];
- Command (C3) – "activity of system guidance towards a single goal by linking and coordinating all activities" [7];
- Intelligence activities (security) (C4) – total knowledge of the enemy, which represents the basis for one’s own ideas and actions [15];
- Mobility (C5) – the ability of the armed forces, as a whole or individual arms, branches and units, to master the space (land, sea, air space) in different soil, climatic and combat conditions, on the battlefield or outside of it [30];
- Logistics (C6) – organization of material support and treatment of the armed forces in peace and war [30];
- Simplicity (C7) – qualitative ability of leaders to realize successfully the assignments received from a superior officer, in optimal time [4];
• Anti-aircraft warfare (C₈) – content of combat operations causing losses to the enemy air forces on land, in air and their infrastructure [6].

All listed criteria are developed in detail and presented in [14]. These criteria are the same for both the defense and the attack operation, which is specifically covered in [1]. The main difference appears in the weight coefficients of criteria. The weight coefficients of criteria in a defensive operation are taken from [14], Table 1.

Table 1. Weight coefficients of criteria

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Weight coefficient of criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maneuver (C₁)</td>
<td>0.178</td>
</tr>
<tr>
<td>Fire (C₂)</td>
<td>0.284</td>
</tr>
<tr>
<td>Command (C₃)</td>
<td>0.207</td>
</tr>
<tr>
<td>Intelligence activities (security) (C₄)</td>
<td>0.100</td>
</tr>
<tr>
<td>Mobility (C₅)</td>
<td>0.057</td>
</tr>
<tr>
<td>Logistics (C₆)</td>
<td>0.064</td>
</tr>
<tr>
<td>Simplicity (C₇)</td>
<td>0.044</td>
</tr>
<tr>
<td>Anti-aircraft warfare (C₈)</td>
<td>0.066</td>
</tr>
</tbody>
</table>

Since all criteria have descriptive (linguistic) character, the values of criteria are defined through fuzzy linguistic descriptors, figure 2.

Figure 2 - Graphic display of fuzzy linguistic descriptors

Every criterion can be described with 5 values: VB – very bad, B – bad, M – medium, G – good and E – excellent. The membership functions of fuzzy linguistic descriptors are defined through the expressions:

\[
\mu_{VB} = \begin{cases} 
1, & 1 \leq x \\
2 - x, & 2 \leq x \leq 2 
\end{cases} 
\]

\[
\mu_{B} = \begin{cases} 
1, & 1 \leq x \leq 2 \\
3 - x, & 2 \leq x \leq 3 
\end{cases} 
\]

\[
\mu_{M} = \begin{cases} 
1, & 1 \leq x \leq 2 \\
3 - x, & 2 \leq x \leq 3 
\end{cases} 
\]

\[
\mu_{G} = \begin{cases} 
1, & 1 \leq x \leq 2 \\
3 - x, & 2 \leq x \leq 3 
\end{cases} 
\]

\[
\mu_{E} = \begin{cases} 
1, & 1 \leq x \leq 2 \\
3 - x, & 2 \leq x \leq 3 
\end{cases} 
\]

Defuzzification of fuzzy linguistic descriptors is performed with one of the famous expressions [24]:

\[
A = ((t₂ - t₁) + (t₃ - t₁)) / 3 + t₁
\]

\[
A = \left[ \lambda t₃ + t₂ + (1 - \lambda) t₁ \right] / 2
\]

where \( \lambda \) presents the degree of certainty of the DM (in the interval [0,1], depending on the certainty of the DM in a given statement, where \( \lambda = 1 \) corresponds to the maximal value and \( \lambda = 0 \) corresponds to the minimal value). \( t₁ \) is the left distribution of the fuzzy number, \( t₂ \) is where the membership function of the fuzzy number is equal to 1 and \( t₃ \) is the right distribution of the fuzzy number.

4.2. Ranking alternatives

The MABAC method shall be shown on the example of ranking five illustrated alternatives, through the criteria defined earlier (real presentation would require setting up a complete tactical situation, which is graded as military secret). The first step in the implementation of the MABAC method is defining the initial decision matrix (X). The initial decision matrix is obtained with the defuzzification of fuzzy linguistic descriptors by each criterion using the expression (21).

\[
\begin{align*}
& C₁ \quad C₂ \quad C₃ \quad C₄ \quad C₅ \quad C₆ \quad C₇ \quad C₈ \\
& A₁ \quad [1.10 \quad 3.12 \quad 3.89 \quad 4.2 \quad 2.21 \quad 1.03 \quad 3.00 \quad 5.00] \\
& A₂ \quad [3.05 \quad 3.98 \quad 2.96 \quad 3.02 \quad 4.10 \quad 2.99 \quad 1.10 \quad 4.03] \\
& X = A₁ \quad [1.90 \quad 4.95 \quad 3.01 \quad 2.90 \quad 4.96 \quad 4.06 \quad 5.00 \quad 1.10] \\
& A₁ \quad [2.85 \quad 3.87 \quad 3.12 \quad 1.05 \quad 2.98 \quad 4.89 \quad 3.30 \quad 4.90] \\
& A₂ \quad [4.77 \quad 3.00 \quad 4.87 \quad 3.01 \quad 1.97 \quad 3.99 \quad 2.04 \quad 4.00] 
\end{align*}
\]

The second step is the normalization of the initial matrix elements. Since all the criteria for making normalized matrix (N) are benefit-type, it is used the expression (3).

\[
\begin{align*}
& C₁ \quad C₂ \quad C₃ \quad C₄ \quad C₅ \quad C₆ \quad C₇ \quad C₈ \\
& A₁ \quad [0.00 \quad 0.06 \quad 0.49 \quad 1.00 \quad 0.08 \quad 0.00 \quad 0.49 \quad 1.00] \\
& A₂ \quad [0.53 \quad 0.50 \quad 0.00 \quad 0.63 \quad 0.71 \quad 0.51 \quad 0.00 \quad 0.75] \\
& N = A₁ \quad [0.22 \quad 1.00 \quad 0.03 \quad 0.59 \quad 1.00 \quad 0.78 \quad 1.00 \quad 0.00] \\
& A₁ \quad [0.48 \quad 0.45 \quad 0.08 \quad 0.00 \quad 0.34 \quad 1.00 \quad 0.56 \quad 0.97] \\
& A₂ \quad [1.00 \quad 0.00 \quad 1.00 \quad 0.62 \quad 0.00 \quad 0.77 \quad 0.24 \quad 0.74] 
\end{align*}
\]

The third step is the calculation of weighted matrix V. The calculation is performed by using the expression (6).
The fourth step is to determine the matrix of the border approximate area \((G)\). The calculation is performed by using the expression (8).
\[
G = \begin{bmatrix}
0.25 & 0.39 & 0.26 & 0.15 & 0.08 & 0.10 & 0.06 & 0.11 \\
\end{bmatrix}
\]

The fifth step is the calculation of distance matrix elements of alternatives from the border approximate area \((Q)\). The calculation is performed by using the expression (11).
\[
Q = \begin{bmatrix}
A_1 & -0.07 & -0.08 & +0.04 & +0.05 & -0.02 & -0.04 & 0.000 & +0.02 \\
A_2 & +0.02 & +0.04 & -0.06 & +0.01 & +0.02 & 0.000 & -0.02 & +0.01 \\
A_3 & -0.03 & +0.18 & -0.05 & +0.01 & +0.04 & +0.01 & -0.03 & -0.04 \\
A_4 & +0.01 & +0.03 & -0.04 & -0.05 & 0.000 & +0.03 & -0.01 & +0.02 \\
A_5 & +0.11 & -0.10 & +0.15 & +0.01 & -0.02 & +0.01 & -0.01 & +0.01 \\
\end{bmatrix}
\]

The last step is the ranking of alternatives by using the expression (14). The final results and the ranks of alternatives are presented in the Table 2.

In the Table 3 are provided situations of changes in weight coefficients (nine situations), based on which is performed the ranking of already shown alternatives.

The rank of alternatives after the application of the situations is provided in the Table 4.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>S_5</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_1</td>
<td>-0.092</td>
<td>5.</td>
</tr>
<tr>
<td>A_2</td>
<td>0.021</td>
<td>3.</td>
</tr>
<tr>
<td>A_3</td>
<td>0.136</td>
<td>2.</td>
</tr>
<tr>
<td>A_4</td>
<td>-0.001</td>
<td>4.</td>
</tr>
<tr>
<td>A_5</td>
<td>0.154</td>
<td>1.</td>
</tr>
</tbody>
</table>

The results from the Table 2 indicate that the alternative A_5 is ranked as the first one, and the alternative A_1 as the last one and the least favorable.

4.3. Sensitivity analysis of output results

A sensitivity analysis of output results is usually recommended as a means for checking the stability of the results [17]. The sensitivity analysis is performed by changing the initial weight coefficients of criteria.

In the Table 3 are provided situations of changes in weight coefficients (nine situations), based on which is performed the ranking of already shown alternatives.

The rank of alternatives after the application of the situations is provided in the Table 4.

In the Table 4 are shaded the ranks of alternatives that match with the ranks obtained by the application of real weights of criteria. Analyzing the obtained results, it can be concluded that there is a significant stability of output results in most situations.

This is supported with the fact that the alternatives A_3 and A_5 are mostly ranked as the first and the second, as expected for a stable system, bearing in mind that when using real criteria weights the difference obtained in the final values of criteria functions is very small (0.018). In addition, A_1 in larger number of situations is ranked as the fifth, respectively, the third or fourth, and in no case is presented as a proposal for solving the problem.

5. CONCLUSION

The output results obtained by applying the MABAC method show that the method can be used as a support in making a decision on using forces in a defensive operation of Land Forces and formulation of a decision strategy. Furthermore, this study appears as a continuation of research from which are used the criteria and their weight coefficients.

In addition to the practical contribution of the paper, from theoretical side it is shown the setting of a new method - MABAC, and its successful implementation in practice. The steps of the method are simple and explained in detail and provide the possibility of its application and further research in terms of its improvement, and also its verification through the comparison with other methods for multicriteria decision-making. With the new method it is enriched the theoretic background of the decision-making theory.

REMARK

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REFERENCES


REZIME

PRIMENE METODE MABAC U PODRŠCI ODLUČIVANJU UPOTREBE SNAGA U ODBRAMBENOJ OPERACIJ

U radu je prikazana primena nove metode višekriterijumske komparacije graničnih aproksimativnih oblasti - MABAC. Osnovna postavka metode ogleda se u definisanju udaljenosti kriterijumske funkcije svake posmatrane alternative od granične aproksimativne oblasti. Granična aproksimativna oblast definiše se posebnim postupkom za svaki kriterijum i zavisi od vrednosti svih alternativa po posmatranom kriterijumu. Metoda je prikazana kroz šest jednostavnih koraka u podršci odlučivanja upotrebe snaga u odbrambenoj operaciji. Za definisanje kriterijuma i njihovih težinskih koeficijenata iskorišćena su ranija istraživanja.

Ključne reči: MABAC (Multi-Attributive Border Approximation area Comparison), odlučivanje, varijanta upotrebe, odbrambena operacija
GLOBAL TRENDS AND THEIR IMPACT ON CITY LOGISTICS...

Global Trends and Their Impact on City Logistics Management

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Original scientific paper

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Changes to economic and social environment are increasingly gathering pace and survival on the market requires a broad range of logistical services and their efficient implementation. Competitiveness of the region and the city, as a champion of economic development, depends on efficiency of logistical solutions which must be adaptable to new conditions and market requirements. This paper presents some of the most important global trends from the viewpoint of impact on an urban environment logistics. For the purpose of defining sustainable solutions, an analysis of described social, economic, technological, environmental and other trends should be an integral part of city logistics planning and management.

Key words: global trends, impact, city logistics, planning, management

1. INTRODUCTION

Logistics industry is under influence of many global trends [1] which have entailed many significant changes in planning, management and realisation of the flows of goods at longer distances into urban environments. Cities represent places of great concentrations of people and generate large amounts of goods.

City functions depend on efficiency of the flows of goods, but logistical processes and activities enabling their implementation are often ignored and neglected. Logistical requirements are under influence of global trends, and their organisation and realisation in a city depend on specific factors describing an urban environment, such as [2]: economic structure, spatial plans and land purpose, traffic infrastructure, logistical systems infrastructure, policies and regulations pertaining to logistics, freight transport and delivery vehicles, etc.

Trends and factors are variable categories, but their analysis may help identify problems and determine directions for the city logistics development (figure 1). However, such analyses are most often shunned which in turn often renders the city planners’ decisions inadequate. In order to make implementation of the flows of goods more efficient and environmentally acceptable, the cities must establish an adequate planning and management system. To this end, the rest of the paper features some global trends from the standpoint of impact on logistics and freight transport in urban environments (figure 2). The aim is to show dependencies and interaction of city logistics with other elements of a large and complex social and economic system of a city and environment.

Figure 1 - Dependencies and interaction between city logistics and environment

Figure 2 - Global trends with strongest impact on city logistics
2. IMPACT OF SOCIAL TRENDS

Social trends with the strongest and most direct impact on CL planning and management are as follows: global population growth, urbanisation, demographic structure changes and consumer society development.

In the 1960-2010 period, the world population doubled and totals today around seven billion people, and continues to grow. Latest population projections suggest that the pace of world population growth will slow down in the upcoming decades and hit by the middle of this century 9.3-billion mark. In addition, the projected population growth in urban environments is from 3.6 billion in 2011 to 6.3 billion in 2050. [3]

Given a slump in the rural population size by around 0.3 million, the population growth rate will become mostly an urban phenomenon.

Historically, the process of urbanisation used to be prompted by a concentration of investments and jobs in urban environments. Manufacturing activities, services, culture, health care, education, and better employment opportunities, along with a higher living standard, have attracted many people from villages to cities. According to available estimates, about 80% of world GDP and about 85% of European Union’s GDP are generated in urban environments. [4] Data corroborate the fact that well-functioning cities constitute the foundation for society’s economic growth. Bearing this in mind, developed regions have reached much higher levels of urbanisation relative to undeveloped regions. Thus, in 2011, there was 78% of total population in urban areas in developed regions (in Europe – 73%) and only 47% in less developed regions. In the middle of the 20th century, urban population made up around 50% of total population of OECD member countries; at the turn of this century – 77%; and by 2020 – this figure should reach as much as 85%. [5]

The urbanisation trend is here to stay, therefore, by 2050 urban population will most likely comprise 86% of total population in developed regions, i.e. 64% in less developed regions. Overall, the expectation is that the world population will have been 67% urban by the middle of the 21st century. [3] Population growth has a direct impact on the volume of the flows of goods in a city (over 15t per resident [6]), hence, solutions and plans should be adjusted to future requirements. Apart from the growth of urban population, we are also witnessing the growth of population in central city zones [7], as well as a phenomenon of population moving out of some parts of the city and into peripheral, suburban zones, and much more rarely into entirely non-urban areas. This is indicative of existing dispersion of places of residence, work and other activities, respectively. [8] Rapid urbanisation has caused great problems. Densely populated urban communities demand deliveries of a greater amount of goods, which in turn generates more movement of a larger number of vehicles and more jams in metropolitan traffic arteries, and this is adversely reflected in the living conditions, mobility and living environment.

A population age structure analyses point to a trend of an increasingly ageing population. The share of the elderly (65 and above) in EU25 will rise from 16.4% in 2004 to 29.9% by the middle of this century. [9,10] Such a demographic change may boost purchases at smaller local shops as well s demand for home deliveries. From the CL viewpoint, this would additionally aggravate the problems of organisation and realisation of the flows of goods. The number of deliveries and the numbers of delivery vehicles and vehicle-kilometres are on the rise meaning a more negative environmental impact and a drop in the quality of live in the city. [11]

Growing demand for logistical services in the city is also a consequence of the hyperconsumer society development. This is the society of mass consumption, high living standards and high purchasing power where it is possible to buy not only what you need but also anything you might want. With the development of new IC technologies, consumption liberates itself of temporal and spatial boundaries and constraints, hence one may do his/her shopping in/from spaces which are not explicitly consumer-oriented (such as shops) at any given time. Consumption growth spurs on further growth of production whereby profits are generated, and vice versa, such a growth spurs on further growth in consumption. Except for growth, consumer demands are becoming less predictable, whilst consumption is more individualised, intimate and hedonistic. [11]

Such trends significantly increase complexity of urban environment logistics and must be subjected to an analysis when planning future CL solutions.

3. IMPACT OF ECONOMIC TRENDS

Globalisation and creation of the single market, as well as the growing strength of the services sector overshadowing its industrial, manufacturing counterpart, have left a mark and set the course for further development of Europe and the rest of the world. These circumstances play into the hands of regions and cities with a good strategic position and a strong, versatile services sector. Accessibility, capability to connect local and regional logistic and transport systems and networks, will render them considerably more competitive. [1] Free trade and globalisation, i.e. separation and drifting apart of the place of production from the place of consumption, have resulted in a significant growth of demand for logistical services. The volume of the flows of goods is increasing, individual requests
are becoming more fragmented, and survival on the market depends on customer satisfaction, i.e. the quality of logistical services. On the other hand, growth and new forms of trade, new business strategies, strengthening of the hospitality industry, expansion and construction of new urban structures all set complex requirements for logistical services providers. Meeting these requirements entails various modalities for logistical chains structures, a large number of participants, various logistical strategies, systems and processes, and intensive transport flows for various categories of vehicles.

Broader assortment and shorter lifetime of a product, on one hand, and current trends in production and distribution based on a very low level of inventory and just-in-time (JIT) deliveries as well as efficient consumer response (ECR), on the other hand, have been instrumental in the growth of the frequency of smaller deliveries. With a rise in the frequency of deliveries, the number of vehicle movements also increase, whilst the loading space utilisation factor drops, i.e. there are more freight vehicle-kilometres in the city. Thus, traffic jams and bottlenecks multiply which has a direct adverse impact on the reduction in efficiency and costs of goods delivery, thereby effectively deteriorating the living conditions in the city. [11]

From the viewpoint of CL planning and management, a broader product assortment influences the growth of logistics flows volume in the city, but also spatial characteristics of, above all, shopping facilities. Namely, the need for additional space for displaying goods is rising, but this in turn leads to a reduction in storage space in retail facilities [12], i.e. there is more demand for storing retail facilities’ goods in the city [2].

Development of new forms of trade (e-commerce or home-based commerce) and a rise in demand for home deliveries pose new challenges for future planners and decision-makers in the city. Implementation of these flows in line with the existing schemes is increasingly less cost-effective and environmentally acceptable. Most home deliveries are made by the post office and express courier delivery services, whilst many logistics providers are not interested in this market segment due to many problems likely to occur in implementation. [13] Home delivery service prices are relatively high and considered to be the biggest obstacle to its future growth. [14] In addition, failed deliveries which may occur if the buyer in question is not at home (at his address) at the time of delivery create additional transport-related and environmental problems. [15, 16, 17] To resolve the growing problems which e-commerce is facing, CL specialisation as well as planning and implementation of a network of collection delivery points (CDPs) is required. The problem of failed deliveries to home address is to be resolved through application of these systems. On top of that, surveys also show significant effects on passenger shopping rides. [18,19]

Technological developments are conducive to changes in the overall social and economic system. New technologies are altering our lifestyles, production, consumption, logistical and other processes. Digitalisation and modern technologies (high-tech) provide incentives for personalised consumption patterns and production of individualised products tailored to the wishes and needs of a given individual. [1] Development of new software and broader application of home 3D printers will enable designing, creating and manufacturing less complex products for our own needs. Personalisation and home production may change considerably the structures of logistical chains both globally and locally. From the CL standpoint, demand for home delivery and reverse flow logistics shall grow in particular. Logistics providers will be delivering new cartridges for 3D printers and collecting products for recycling. Except for the above, the impact of technological developments on CL planning is reflected in a higher degree of automation of storage, transport and other logistical systems, a wider and more complex application of telematics and identification systems, development of more energy efficient modes of propulsion (electric and hybrid vehicles, vehicles powered by natural gas, hydrogen fuel cells, etc.).

4. IMPACT OF TRENDS IN SPATIAL PLANNING

Regions with better access to raw materials and markets have an opportunity to be more competitive [20], hence traffic and logistical infrastructure development is one of the critical factors of regional development. [21, 22] On the other hand, accessibility of logistical services is determined by the selection of an economic system’s location, which in turn leads to changes in the system of purpose and use of land. [23] Urban planning significantly influences the flow of goods and transport in a city. Spatial organisation of industrial, commercial and logistical systems has a direct impact on the vehicle-kilometre figure for delivery vehicles and other CL parameters.

Along with the growth and development of cities, the purpose of urban land is partially or entirely changing. Central city zones are becoming increasingly more attractive locations for profitable commercial contents which requires restructuring of the existing urban entities. [24] In addition to repurposing of urban land, an expansion of cities is taking place. For the most part, such expansions are not planned, but haphazard, creating an inadequate spatial organisation of urban functions and systems. Dispersion, imbalance
and lack of connectivity of new urban areas are associated with negative social, environmental and economic influences. Key undesirable influences are linked to an increase in energy consumption, occupation of land and destruction of fertile soil, growth in greenhouse gas emissions, rise in air and noise pollution which in turn further degrades the quality of life in an urban environment. [25, 26, 27, 28, 29, 30, 31, 32, 33]

Since mid-50s in the 20th century, European cities have expanded by 78% on average, whereas the population has grown by 33%. Unplanned expansion of cities generates additional expenses for construction of local road networks [26] and new flows of goods, and additional movement of freight and passenger vehicles for the purpose of supply. Additional movements of vehicles and additional vehicle-kilometres exert negative effects on economic, environmental and social aspects to sustainability of an urban environment.

Relocation of large shopping malls to the city’s periphery reduces time and cost of supply, and traffic in crowded central zones is relieved of delivery vehicles. However, as peripheral city zones are accessible for individual transport only, moving shopping activities away from the place of residence may considerably increase the passenger vehicle-kilometre figure. [11] Given that motorised shopping trips are calculated as one half of vehicle-kilometres for the transport of goods in the city [34], these contribute significantly to urban transport CO₂ emissions. In this respect, in urban planning one should bear in mind that a delivery vehicle in a residential zone causes fewer problems than hundreds of passenger vehicles which would move towards shopping malls on the city’s outskirts to transport the same amount of goods. [35] On the other hand, shopping malls located in urban zones may supply consumers efficiently at acceptable costs to suppliers and logistical services providers, as well as be more accessible to local population.

Goods-transport centres, as logistical systems servicing national and international markets, have become a crucial element of the city economy. Big modern logistical and distribution centres have propensity towards concentration in the area of large urban environments. [36] Reasons for polarisation, i.e. concentration of logistical activities in large metropolitan cities are as follows: local market’s size and importance, vicinity of big infrastructure hubs, developed labour and commercial activities and systems markets. However, the cities are facing the issue of lack of space, and in urban plans logistical systems are being pushed out of city zones. Given that these systems involve movement of large numbers of freight and delivery vehicles, air and noise pollution and greenhouse gas emissions, and represent an eyesore in the city landscape, logistics is increasingly less present in central and urban zones, and there is a tendency to relocate them to suburban parts of the city. Such a dislocation and deconcentration, i.e. dispersion of logistical systems is referred to as logistic sprawl [37] or suburbanisation [38] of logistics and represents a global phenomenon [36, 39, 40].

Adequate planning of logistical systems is of particular importance for reduction in freight vehicle-kilometres. [37] As the freight transport generates 20-30% of total vehicle-kilometres and 16-50% of harmful emissions [41] in the city, many strategic decisions taken at regional, national and international levels pertain to freight transport. And yet, city logistics and urban freight transport system is not adequate. In most cities the use of urban city terminals, the logistical centres, when transporting goods is not required. Deliveries are organised from terminals often situated 80-150km away from the city centre.

5. CONCLUSION

Logistics industry is influenced by many global trends defining new requirements. On the other hand, competitiveness of a region and a city, as the champion of economic development, depends on availability and efficiency of logistical services. Environment and conditions are changing, hence only those cities which manage to adjust their logistics to the changes may expect prosperity and offer a competitive edge. In this respect, planning and city logistics management should be based on experience and assessments of social, economic, political, technological, environmental and other circumstances. Analyses of global trends point to requirements, importance, objectives, directions, measures and concepts of city logistics development.

In order to ensure economic development and improve quality of life in the city, cut costs and resource consumption, protect environment, ensure growth of security, better and more cost-effective use of land, protect and use more efficiently the existing infrastructure, etc, it is necessary to interconnect all logistical and economic entities, global trends and local resources.

In addition to knowledge of the city’s characteristics, identification of stakeholders, their requirements, objectives and mutual interactions, the success of city logistics solutions also depends on willingness to adjust to trends and ensure efficient fulfilment of new requirements. Therefore, city logistics planning and management requires an analysis of global trends and local conditions, collaboration of all parties involved, removal of all barriers and defining measures which will ensure compliance with existing and future requirements.

S. TADIĆ at al. GLOBAL TRENDS AND THEIR IMPACT ON CITY LOGISTICS...
REMARK

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GLOBAL TRENDS AND THEIR IMPACT ON CITY LOGISTICS

Promene privrednog i društvenog okruženja su sve dinamičnije, a opstanak na tržištu zahteva široku paletu i efikasnou realizaciju logističkih usluga. Konkurentnost regiona i grada, kao nosioca privrednog razvoja, zavisi od efikasnosti logističkih rešenja, a ona moraju biti prilagođljiva novim uslovima i zahtevima tržišta. U radu su prikazani neki od najznačajnijih globalnih trendova su aspektu uticaja na logistiku urbane sredine. U cilju definisanja održivih rešenja, analiza opisanih društvenih, ekonomskih, tehnoloških, ekološki i drugih trendova treba da bude sastavni deo planiranja i menadžmenta city logistike.

Ključne reči: globalni trendovi, uticaji, city logistika, planiranje, menadžment

REZIME

GLOBALNI TRENDOVI I NJIHOV UTICAJ NA MENADŽMENT CITY LOGISTIKE

Promene privrednog i društvenog okruženja su sve dinamičnije, a opstanak na tržištu zahteva široku paletu i efikasnou realizaciju logističkih usluga. Konkurentnost regiona i grada, kao nosioca privrednog razvoja, zavisi od efikasnosti logističkih rešenja, a ona moraju biti prilagođljiva novim uslovima i zahtevima tržišta. U radu su prikazani neki od najznačajnijih globalnih trendova su aspektu uticaja na logistiku urbane sredine. U cilju definisanja održivih rešenja, analiza opisanih društvenih, ekonomskih, tehnoloških, ekološki i drugih trendova treba da bude sastavni deo planiranja i menadžmenta city logistike.

Ključne reči: globalni trendovi, uticaji, city logistika, planiranje, menadžment


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Sustainable Management of Drinking Water Production Plant Pollutants

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Original scientific paper

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During the last two centuries, the origin of pollution substances that are jeopardizing environmental sustainability by devastating its structural elements, are a consequence of rapid techno-economic development. It is the unconditional accountability of the human population to recover the biosphere, through remediation and diminution of the existing, as well as prevention of future extermination of natural resources. One of the ultimate prerequisites for survival of all living beings is water. Anthropogenicity, it means it means providing enough drinking water in the same quantities for us, as well as for the future generations, applicable for all other natural resources. This essay puts the accent on the crucial aspect of water sustainability: sludge managing, from the water production plant, specifically drinking water, from the aspect of influence on structure, quantity, optional recycling and the most efficient disposal.

Key words: water, sludge, pollutants, sustainable development, natural resources, drinking water production plant, sustainable solutions

1. INTRODUCTION

The processes by which pollutants can be transported and transformed after their emissions into the environment, in an international dictionary defines the term "the fate of pollutant". Distribution of pollutants shall be carried out through the biogeochemical cycles in which usually leads to their transformation, changes in physical and chemical form and the formation of compounds that can reduce, or completely lost rapidly increase the original toxicity. This is largely a function of the physical and chemical properties of the substance, the physical and chemical properties of the environment as well as the physical conditions they are exposed Very volatile pollutants will obviously be more likely to be transported through the atmosphere and will be more mobile in warm conditions and faster air flow, while they are transmitted over solubility of water and increased mobility will have a period of strong rainfall. Also, pollutants of land will be far more quickly move through the porous sand or porous structure than the fine-grained soil forms.( clayey soil forms).

Although clear differences between the spheres of the environment, many processes and mechanisms that control the fate of pollutants are common to all of them. In all spheres of transport substances can go by convection, advection and diffusion; the essence of chemical reactions is similar because the scope and speed of propagation of pollutants destined to their chemical and biochemical reactivity and the fact that all the spheres of the environment composed of the relative representation of the same major phases:

1) Inorganic phases
   - the gaseous phase;
   - the water phase;
   - the solid mineral phase

2) Organic phases (the gaseous phase, the liquid phase, solid phase)

As the origin of pollutants that threaten the sustainability of, the last two centuries is primarily the result of rapid techno-economical development, imposes unconditional human responsibility for recovery of the biosphere through the rehabilitation/reduction of existing deficit and preventing the forthcoming deficit of natural resources.

One of the priorities of the ultimate survival of all living forms of existence is water, in terms of anthropogenic course this means providing enough clean drinking water in the same amount to us and the coming generations, which is a definition of sustainable
development and applies to all natural resources. In order to carry out this complicated task requires a multidisciplinary approach which is still closed on one of the first Conference on the Protection of Environment, in Stockholm in 1972, then in Mar del Plata in 1977 in Rio de Janeiro in 1992 (Agenda 21) Beijing, 1996, in Paris in 1997, the Hague 2002 to Copenhagen 2012, continues to this day.

Sublimation activity on most waters is expressed through the EU Directive on Water 2000 (Framework Directive 2000/60 / EC) and directives (there are several, and will be listed in accordance with the discussion of concrete problems) on the rules and parameters of the quality of wastewater, waste streams the parameters of environmental pollution and their synergistic effects. [1, 2, 3, 5].

In this sense, it is recommended integrated water resources management, which includes many activities of which are in the area of the Western Balkan countries with the most relevant:

- Development and management of water must be based on a comprehensive partnership that includes users, planners and policy makers at all levels,
- Water has an economic value in all its aspects and therefore should be recognized as an economic good, including also the social character of water,
- mobilization of financial resources is a critical moment on which depends the proper management of water resources,
- it is necessary to introduce management measures which will reduce the need for water and give priority to customers higher value
- To facilitate the achievement of specific needs for water in rural and urban areas, to accept modern and successful agricultural management approaches and methods that will ensure the supply of farms with water, use of urban treated wastewater, storm water collected in cities, etc.,
- integral to manage surface and ground waters,
- promptly taken into consideration and provide studies and projects that protect the environment and to appreciate the impact of the spatial and particularly unfavorable weather in the distribution of water ecological system,
- meet the basic quantitative and health needs of humanity for water,
- sustainable water management, protection of ecosystems,
- understand and accept the new solutions and systems as existing demonstrate inadequate,
- manage water resources responsibly, continuous measurement and monitoring of relevant parameters and by involving the public.

As a response to the demands of sustainability, Serbia has made a National Sustainable Development Strategy which represents the attempt of implementation of recommended activities and related mandatory statutory legislation in the form of ecocentric concept.

2. SLUDGE MANAGEMENT – WATER POLLUTION

In this expert work, the emphasis is on the important aspect of the sustainability of water: management of sludge from water treatment plants, in this case, drinking water. The idea is to identify aspects of the impact on the composition of the sludge and the reduction of production and as cost-effective disposal. As one of the basic principles of sustainability, just prevent or at least reduce pollution at the source, it is a well-designed monitoring of the recipient / watercourse of unquestionable importance. Circulation of water on Earth represents the most comprehensive quantitative biogeochemical cycles on Earth as a dynamic moving system causes different paths of movement of hazardous substances in the environment. The origin of pollutants can be inorganic, organic or mixed. Once within the hydrosphere, hazardous materials may be subjected to a number of processes in which, or break down into CO2 and water, or remain unchanged, or, are transformed into new compounds. Reactions in hydrosphere include various chemical processes: precipitation, dissolving, acid-base reactions, hydrolysis, oxidation-reduction reaction. So, water pollution can roughly be divided into: chemical (acids, alkalis, various salts, pesticides, detergents, phenols, etc.), Physical (thermal / increase t, color, odor, radioactivity, suspended solids, sand, sludge); biological (bacteria, viruses, algae, barnacles, lignins, etc.). PCBs (polychlorinated biphenyls), for example, types of hazardous substances that can accumulate in sediments, because they represent a thick fluid, immiscible with water, which can sink to the bottom of aquifers and accumulate there as so-called "lumps, spots" of liquid.

Hundreds of tonnes of waste containing PCBs is accumulated in the sediments in the Hudson River in New York, subject to heated debate about how to remediate this pollution.

Pollutants can get into the water through diffuse and/or point sources of pollution (leachate from landfills, outpouring of sedimentary lakes / landfill toxic industrial waste, leaks from sewage systems, rinsing in soil, acid rain ...). Intentional release of hazardous substances into waterways appears as a problem in countries with underdeveloped criminal legislation in the field of environmental protection. As the characteristics of the raw water recipient depends on the selection of coagulation-floku and disinfectants
for processing drinking water to the prescribed norms. With the chemical composition of chemicals used and by-products of the process coagulation-flocculation sedimentation, with disinfection (pollution by DBP / disinfection by product), all this affects the composition of the wastewater plant, characterization and mass of sludge as a product of processing in which the concentrate sedimentary forms of matter participating.

Waste, contaminated water and untreated sludge are classified into liquid waste where inorganic mineral pollution manifested as dissolved mineral salts, acids, bases, sand, clay.

Organic pollution are of plant, human or animal origin, and Water is the universal solvent, any water contamination is present in the form of solutions, suspensions and colloids, usually expressed in mg/l, in accordance with the physical and chemical characteristics of water (temperature, organoleptic properties, pH, redox potential, the content of gases: CO4, CO2, bicarbonates, carbonates, hardness, alkalinity, electrical conductivity, dissolved O, BOD, COD, TOC, ammonia, nitrites NO2 , nitrates NO3, j-ing phosphorus, metals ...).

To determine the degree of contamination of liquid waste is the most important content of organic matter and heavy metals, and the parameters that indicate the amount of oxygen dissolved, BOD, COD, TOC.

- The processes that consume oxygen, as one of the most commonly monitored parameters of organic pollution in the water, are:
- oxidation of organic matter:
  \[
  CH_{2}O + O_{2} \rightarrow CO_{2} + H_{2}O \quad (1)
  \]
- oxidation of nitrogen compounds (requires 3 moles of oxygen to convert 1 mole of ammonia via nitrite to nitrate, this phase lasts much longer than the previous, typical of waste water):
  \[
  NH_{3} + 1/2O_{2} \rightarrow NO_{2}^{-} + H_{2}O \quad (2)
  \]
- oxidation of iron, sulfur, other reducing agents:
  \[
  4Fe^{2+} + O_{2} + 10H_{2}O \rightarrow 4Fe(OH)_{3}(s) + 8H^{+} \quad (3)
  \]
  \[
  2SO_{3}^{2-} + O_{2} \rightarrow 2SO_{4}^{2-} \quad (4)
  \]

On this basis, it can be concluded that the degree of contamination of water defined amount of oxygen necessary for the degradation process carried out by aerobic heterotrophic (BOD), the amount of chemical consumed Oxygen Demand (COD), which increases with the presence of biodegradable substances in water, as well as the amount of dissolved oxygen in water. Oxygen consumption is in direct proportion to the temperature rise.

Thus, the division of water pollution in relation to any act of dissolved oxygen (ppm) at 200C looks like this [10]:

<table>
<thead>
<tr>
<th>Concentration (ppm)</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 8</td>
<td>GOOD</td>
</tr>
<tr>
<td>6,7-8</td>
<td>MILDLY contaminated</td>
</tr>
<tr>
<td>4,5-6,7</td>
<td>MODERATE contaminated</td>
</tr>
<tr>
<td>under 4,5</td>
<td>SEVERELY contaminated</td>
</tr>
<tr>
<td>under 4</td>
<td>HEAVILY contaminated</td>
</tr>
</tbody>
</table>

**Figure 1 - Curve showing the dependence of the temperature of the BOD in the function of time for three different temperatures (1 - Phase 2 - Phase)**

This is just one of the ways of looking at water pollution, but monitoring the recipient should implement complex and multifunctional, while in this paper provides priority possibilities to reduce and control pollution at the source of creation, in plant waste producers in the process of water clarification, and with an emphasis on sludge originating from dosing chemicals. Conventional methods of water treatment depending on its origin, capacity and characteristics include the removal of suspended particles processes of aeration, coagulation (destabilization of colloids), flocculation, sedimentation of suspended materials, and decantation for example, through in granulated sand filters, previous disinfection and disinfection.

Modern methods include physical, chemical and biological processes that include multiple degrees of processing, such as: Pretreatment through the equalization of the composition, flow equalization and primary processing through the procedures of neutralization, pH correction value, oxidation, flotation, sedimentation, removal of organic and inorganic substances with the help of modern equipment and environmentally appropriate chemicals; secondary treatment by aerobic and anaerobic processes of purification of biodegradable organic matter, tertiary treatment through denitrification, ion exchange, adsorption, reverse osmosis, in order to remove ions, odor...
inappropriate colors, non-biodegradable organic substances and final processing through disinfectant preventing the development of pathogenic microflora chlorination, ozonisation, UV irradiation. The goal of all these methods is the removal of harmful and toxic substances from the water and the achievement of the required quality.

With these processes, with the necessary addition of washing the filter installation and settling, leads to the formation of certain quantities of waste in the form of process wastewater and sludge, which must be managed in a sustainable way and return them to the recipient or applied to the soil so that they can accept the aforementioned ecosystems without the influence of a lasting or deferred devastation, but with a tendency of adopting the recommendations EEA for "3R" (reuse, reduce, recycling). To do so in a responsible manner is necessary to:

- examine the physical-chemical and biochemical composition of wastewater and sludge treatment, legally determined using a specific methodology that they contain toxic substances and to what concentration contain in relation to the existing regulation on the limit values
- make a characterization of the water bodies in which it intends to perform discharge as described in the laws in force (effluent, recipient);
- to characterize the soil in case of application of sludge and/or efficiency in terms of increasing agricultural potential of the land surface;
- to detect potentially hazardous substances both in the waste and the reception factor that will be made direct exposure from waste water treatment plants.

3. SLUDGES ON TREATMENT PLANT FROM DRINKING WATER

In this paper will be discussed sludges from conventional water treatment plants for human consumption with conventional clarification processes through the use of aluminum-based coagulants (aluminum sulphate Al2 (SO4) 3 and polyaluminium chloride PAC) and iron through the actions of sedimentation and filtration on granulated sand filters. Thus, one can say that the origin of the sludges is from ferric and aluminum. As the water content of the sludge from the water treatment plant is very large (up to 96% or more), dry matter consists of several mineral organic ingredients than the dominant presence of dissolved metal salts in the form of hydroxide originating in the coagulation base, the question of possible effects on the environment due to the presence of heavy metals and volatile and semi-volatile toxic substances (SVOC, VOC) at levels higher than allowed for transport in the environment. Depending on the characteristics, the sludge may be disposed in the raw state or be treated in an appropriate manner.

In Europe and the world is rapidly growing interest in the production of sludge disposal and recycling. In order to control potential risks introduced legislation at European and national level (the EU directive on urban waste water village replaced by Directive 98/15 / EC of smanjejnju content of undesirable pollutants in sludge restrict the use and increase the cost of subsequent treatment; Sewage Sludge; IPPC which promotes the principle of prevention and reduction of pollution at the source by using BAT techniques, Directive 86/278 / EEC on the use of sludge in agriculture, Directive 200/76 / EC on limit values for dioxins during the incineration of waste and sludge, etc.). Sludges are even bigger problem than wastewater because the impact of pollution in sludges evident, and pollutants in sludge in more concentrated form than in wastewater.

In Europe, production of dry sludge per capita is 90 g/day and is derived from primary, secondary and tertiary wastewater treatment. According to Directive 86/278 / EEC on the land intended for the cultivation of food products that are consumed raw, and in direct contact with the ground, is prohibited applications for 10ms period preceding the harvest and during the harvest itself, whereas when sludge is used on soils with a pH below 6, Member States, taking into account the increased mobility and accessibility of heavy metals plants, reduce the limit values set in accordance with Annex IA, as follows [1-6]:

<table>
<thead>
<tr>
<th>Element</th>
<th>The limit values mg/kg dm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6&lt;pH&lt;7</td>
</tr>
<tr>
<td>Cd</td>
<td>1-3</td>
</tr>
<tr>
<td>Cr</td>
<td>-</td>
</tr>
<tr>
<td>Cu</td>
<td>50-140</td>
</tr>
<tr>
<td>Hg</td>
<td>1-1.5</td>
</tr>
<tr>
<td>Ni</td>
<td>30-75</td>
</tr>
<tr>
<td>Pb</td>
<td>50-300</td>
</tr>
<tr>
<td>Zn</td>
<td>150-300</td>
</tr>
</tbody>
</table>

The tendency is that the sludge to obtain a commercial character and introduces the concept of sludge reference to the characteristics given in Table 2.

Directive 86/276 / EEC defines three types of sludge:

- sludge generated from the treatment plant of urban waste water;
- sludge from septic tanks and other similar installations for the treatment human bodily waste;
sludge generated from sewage treated and is different from the sludge under the first and second paragraph.

Tabela 2. Reference sludge

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter</td>
<td>6%</td>
</tr>
<tr>
<td>Organic matter</td>
<td>75% SM</td>
</tr>
<tr>
<td>Zink</td>
<td>1000mg/kg</td>
</tr>
<tr>
<td>Copper</td>
<td>500mg/kg</td>
</tr>
<tr>
<td>Nickel</td>
<td>40mg/kg</td>
</tr>
<tr>
<td>Mercury</td>
<td>3mg/kg</td>
</tr>
<tr>
<td>Cadmium</td>
<td>3mg/kg</td>
</tr>
<tr>
<td>Lead</td>
<td>200mg/kg</td>
</tr>
<tr>
<td>Nitrogen (total)</td>
<td>3.5% SM</td>
</tr>
<tr>
<td>P2O5</td>
<td>3.5% SM</td>
</tr>
<tr>
<td>K-O</td>
<td>0.2% SM</td>
</tr>
</tbody>
</table>

For cost effective sludge emphasis is on reducing weight and toxic characteristics of the sludge at the source of creation that would be cheaper and, if possible, completely avoid the further processing procedures.

- In this sense, are defined in legislation and analysis of silt, which include the following parameters:
  - mass fraction of dry matter expressed in %;
  - mass fraction of total organic carbon in the dry matter of sludge expressed in %;
  - pH value of the sludge;
  - mass fraction of oxygen in the total dry matter of the sludge in %;

Tabela 3. Factor for PCDD /PCDF

<table>
<thead>
<tr>
<th>POLIHLOORAVNI DIBENZODIOKSIINI</th>
<th>FAKTOR</th>
<th>POLIHLOORAVNI DIBENZOFURANI</th>
<th>FAKTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,3,7,8-tetraCDD</td>
<td>1,0</td>
<td>2,3,7,8-tetraCDF</td>
<td>0,1</td>
</tr>
<tr>
<td>1,2,3,7,8-pentaCDD</td>
<td>0,5</td>
<td>1,2,3,7,8-pentaCDF</td>
<td>0,05</td>
</tr>
<tr>
<td>1,2,3,4,7,8-heksaCDD</td>
<td>0,1</td>
<td>1,2,3,7,8-pentaCDF</td>
<td>0,5</td>
</tr>
<tr>
<td>1,2,3,6,7,8-heksaCDD</td>
<td>0,1</td>
<td>1,2,3,4,7,8-heksaCDF</td>
<td>0,1</td>
</tr>
<tr>
<td>1,2,3,7,8,9-heksaCDD</td>
<td>0,1</td>
<td>1,2,3,6,7,8-heksaCDF</td>
<td>0,1</td>
</tr>
<tr>
<td>1,2,3,4,6,7,8-heptaCDD</td>
<td>0,01</td>
<td>1,2,3,7,8,9-heksaCDF</td>
<td>0,1</td>
</tr>
<tr>
<td>oktaCDD</td>
<td>0,001</td>
<td>1,2,3,4,6,7,8-heptaCDF</td>
<td>0,01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,2,3,4,7,8,9-heptaCDF</td>
<td>0,01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>oktaCDF</td>
<td>0,001</td>
</tr>
</tbody>
</table>

content of heavy metals in sludge dry matter:
- cadmium, copper, nickel, lead, zinc, chromium and mercury, expressed in mg / kg,
- the content of the following polychlorinated biphenyls in sludge dry matter, expressed in mg / kg: 2,4,4’-trihlorobifenil, 2,2’, 5,5’-tetrahlorobifenil, 2,2’, 4,5,5’-pentahlorobifenil, 2,2’, 3,4,5,5’-heksahlorobifenil, 2,2’, 3,4,4’, 5,5’-heptahlorobifenil.
- content of polychlorinated dibenzodioxins / dibenzofurans in the dry matter of sludge expressed in mg / kg TCDD equivalents.

Methods of analysis are:
- Determination of heavy metals is performed after thorough digestion acids. The reference method of analysis of heavy metals is atomic absorption spectrometry. The limit of determination of heavy metals used methods may not exceed 10% of the limit of detection.
- The reference method for determining the content of polychlorinated biphenyls and polychlorinated dibenzodioxins/dibenzofurans is gas chromatography.
- The formula for calculating the TCDD equivalent is:

\[
\text{TCDD equivalent} = \Sigma (A_i \times F_i) + \Sigma (B_i \times F_j),
\]

where:

- TCDD equivalent in mg / kg of dry matter of sludge,

And the mean value of the mass content of each PCDD calculated as the arithmetic mean of the balance obtained from at least two measurements in mg / kg of dry matter of sludge, \( F_i \) factor of a particular PCDD given in Table 3.

Unlike the permissible heavy metals content of the reference sample, Table 4 presents the permissible content of heavy metals in a representative sample of sludge.

### Table 4. Limit values for heavy metals

<table>
<thead>
<tr>
<th>Heavy metals</th>
<th>Limit values for heavy metals expressed in mg / kg of dry matter of a representative sample of sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>5</td>
</tr>
<tr>
<td>Copper</td>
<td>600</td>
</tr>
<tr>
<td>Nickel</td>
<td>80</td>
</tr>
<tr>
<td>Lead</td>
<td>500</td>
</tr>
<tr>
<td>Zinc</td>
<td>2000</td>
</tr>
<tr>
<td>Mercury</td>
<td>5</td>
</tr>
<tr>
<td>Chromium</td>
<td>500</td>
</tr>
</tbody>
</table>

### Table 5. Limit values for organic substances

<table>
<thead>
<tr>
<th>Organic substances in sludge</th>
<th>Permitted content of organic substances in the sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polihlorovani bifenili (PCB):</td>
<td>in mg / kg of dry matter of sludge</td>
</tr>
<tr>
<td>2,4,4’-trihlorobifenil</td>
<td>0.2</td>
</tr>
<tr>
<td>2,2',5,5'-tetrachlorobifenil</td>
<td>0.2</td>
</tr>
<tr>
<td>2,2',4,5,5'-pentachlorobifenil</td>
<td>0.2</td>
</tr>
<tr>
<td>2,2',3,4,5,5'-hekschlorobifenil</td>
<td>0.2</td>
</tr>
<tr>
<td>2,2',3,4,4',5,5'-heptachlorobifenil</td>
<td>0.2</td>
</tr>
<tr>
<td>Polihlorovani dibenzodioxini/dibenzofurani (PCDD/PCDF)</td>
<td>100 mg TCDD ekvivalenta* per kg of dry matter of sludge</td>
</tr>
</tbody>
</table>

* TCDD equivalent is the sum of the contents of individual polychlorinated dibenzodioxins/dibenzofurans expressed in ng/kg and factors, and calculated according to the formula previously demonstrated

Table 5 shows the permitted content of organic substances in Table 6 - permissible content of heavy metals in a representative sample of the soil.

### Table 6. Limit values for heavy metals in a representative sample of soil

<table>
<thead>
<tr>
<th>Heavy metals</th>
<th>Limit values for heavy metals expressed in mg / kg of dry matter of a representative sample of sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH soil in 1 M solution KCl</td>
<td></td>
</tr>
<tr>
<td>pH&gt;6.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.5</td>
</tr>
<tr>
<td>Coper</td>
<td>40</td>
</tr>
<tr>
<td>Nickel</td>
<td>30, 50</td>
</tr>
<tr>
<td>Lead</td>
<td>50, 70</td>
</tr>
<tr>
<td>Zinc</td>
<td>100, 150</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.2, 0.5</td>
</tr>
<tr>
<td>Chromium</td>
<td>50, 75</td>
</tr>
</tbody>
</table>

The use of sludge that could cause exceeding the permitted levels of heavy metals in the soil.

### 3.1. Examinations

Executed significant test of 26 treatment plants of drinking water from surface waters II class in Florida. The sludge is usually disposed of in a short period in the lagoon system which is usually located at the facility. Finally, sludge is being disposed of in a landfill (dump). As the disposal of the produced sludge from water treatment plants for drinking expensive it was difficult, it was suggested exploitable options.

Questions have been raised regarding the potential impact of used sludge on the environment. In order to assess the potential risks applications of sludge from the treatment process for drinking water in the soil, the University of Florida’s Department of Environmental Engineering Sciences has made an agreement with the Florida Center for Solid and Hazardous Waste Management to execute the characterization of sludge from treatment of drinking water from water plants in Florida. The method of work was:

During a period of four months (May 2001 – August 2001), samples were taken from water supply systems throughout the country. Samples of sludge from the treatment of potable water collected from the bed of drying or stock from 26 water supply facilities. Large number of tests was performed to characterize the materials [9].

For chemical characterization analyzes were carried out of the total content of metals and organic substances. Where it was possible, were compared to the results of the overall analysis of the target limit values for land (SCTLs). It should be noted that these values are not regulatory standards, but a set of useful targets.
in the assessment of the best ways of ecological waste management.

Furthermore, these goals are taken voluntarily by those wishing to apply eco application of solid waste in zemljisje, as parameters for risk assessment. Test-process synthetic precipitation leaching sludge (a synthetic precipitation leaching procedure (SPLP test) is also carried out to determine the leaching of pollutants: heavy metals (aluminum, arsenic, barium, cadmium, chromium, copper, iron, lead, manganese, mercury, molybdenum, nickel, selenium, silver, sodium, zinc) and organic components (volatile compounds, semi-volatile compounds, pesticides) and inorganic components (fluorides, chlorides, sulfates, suspended particles).

The concentrations of chemicals detected in extracts SPLP (acronym for leachate muddy water obtained by the synthetic procedure leaching, acid sludge digestion), were compared with FGGC (abbreviation for concentration limits of municipal wastewater effluent) to assess the potential risks releases.

3.2. Results

Complete results of all analyzes the total sludge and SPLP extracts from the treatment process for drinking water are summarized. Metals in all 26 samples of sludge were measured both total and after conversion to liquid leaching method, while nine samples analyzed for organic compounds including on volatile, semi-volatile compounds and pesticides [9].

1. For the analysis of total metals in the sludge, most concentrations were below the detection limit, or you have detected, but not in concentrations above the permitted limit values corresponding to the pure land.

However, all the samples of aluminum and ferric sludge showed arsenic exceeding the allowable limit. The seven samples of lime sludge exceeded the limit (0.8 mg/kg), 1 sample is above the threshold limit industrial lot of arsenic (3.7 mg/kg), and conc min - 8.53 mg/kg, max - 16.89 mg/kg, and an average value of 11.32 mg/kg, while the pH value at the aluminum sludge samples oscillated below the recommended 6.5-8.5. It is believed that the cause of the occurrence of larger amounts of As, may be due to the content of the Al-sulphate as a technical mixture.

Another metal that has occasionally crossed the border barium. One of the 5 samples of aluminum sludge and 3 out of 20 samples of lime sludge exceeded the set limit values (direct exposure). Copper was also detected above the set limits sctl in one of the analyzed samples ferric sludge.

As expected, all the samples of aluminum sludge had an Al concentration higher than allowed in the direct exposition (on the basis of direct exposure), while all samples ferric sludge had higher with concentration of iron than allowed, also for direct exposure.

2. In the VOC analysis of samples collected in 9, only two target VOC compounds (acetone, and methylene chloride), 74 possible, the consistently was present in the samples. Nijedna od koncentracija ne premašuje postavljene limite. Ovi analiti se obično koriste za čišćenje laboratorijskog posuda (i organskih eksrakata) u laboratorijama.

3. In none of the analysis of samples of the total sludge were found Swatch components, and pesticides (nitrogen-phosphorus and organochlorine) were not present to the limit of detection in any of the samples uzoraka.

4. SPLP leaching test is performed to determine whether it will be leachate heavy metals (Al, As, Ba, Cd, Cu, Fe, Pb, Mn, Hg, Mb, Ni, Na, Se, Ag, Zn) for all selected samples. The results were compared with FGGC limits for effluent. In three samples leached extracts (1 of aluminum sludge from a 2-ferric sludge) leach manganese was over values FGGC while oce-dnim water / extracts of lime sludge has not been any overruns. Also, in most leached samples of aluminum sludge and in two samples of ferric sludge were exceeded limit values for Al, and all the ferric sludge samples had higher concentrations of Fe (all relating to limit values FGGC).

5. Results for SPLP VOC leaching test with ZHE (Zero Headspace Extraction), only two target VOC components have been detected in the leached samples. Acetone was consistently present in all samples leached, while the methylene chloride was once detected in a single sample. Sample concentrations exceed the allowable limits for effluent. However, the origin of these compounds is probably laboratory character.

6. None of the Swatch compounds not detected in the leached samples. Pesticides (nitrogen- phosphorus and organochlorine pesticides), were not found in any sample during SPLP leaching test.

7. Inorganic ions such as chloride and sulfate were found in some of the leach samples, the concentration of these ions was FGGC below the limit values. The concentration of TDS (total dissolved particles) in all 28 SPLP extracts over the allowed concentration limit for TDS (500mg/l), with one exception. Fluorides have not been found in any of the SPLP extrakata.

Also, another test characteristics of the sludge from the treatment of drinking water with aluminum sulphate in similar conditions of raw water [7], as well as work on the same subject [8], were able to consolidate the reuse of sludge from the treatment process
for drinking water originating from the aluminum base coagulant, in the following ways:

- using advanced eutrophication in areas where the reaction of the sludge with phosphorus stops mentioned process and to the land and / or in aqueous media since the sampled and tested part of the land and / or bottom of a water body, to anticipate the potential synergistic effects;
- re-use as a coagulation agent in the plant for treatment of municipal wastewater, also with the accompanying analysis.

3.3. One manufacturing facility in JKP BVK

Also, there is a perception in the process of processing the drinking water production plant on the location "Bele vode", that belongs to the company JKP "Belgrade Waterworks and Sewerage". The comparison was made in the balance of production of sludge on the basis of stoichiometric budget through the use of two aluminum coagulant, Al-sulphate and PAC / SACH P-Al (OH) a Clb (SO4) C, in the period from 02.01.2013. god - 31.01.2013. as from 13.02.2013. god - 13.03.2013. god. in raw river water flow of 300 l / s and similar terms by parameters of raw water (NTU, pH, t, el. conductivity, etc.). Was taken as a starting point the number of suspended solids in raw water to which are added the amount of coagulant all equalized through mass balance, whereby in the first case, added: Al2(SO4)3, PAA, and CuSO4, and in the second case: SACH P - Al (OH) a Clb (SO4) C, PAA and CuSO4.

The amount of the produced sludge was about 38% below the PAC than with Al-sulfate, which can be seen from the attached budget:

\[ MR = [(SM + MO1 + MO2 + + PAA) kg] \times Q \times DT - [(MO1 + MO2 +) \times Q \times DT] \]

where are they:
- MR - sludge from the treatment of river water;
- SM - particulate matter expressed in kg;
- MO1 - alkali metal salt coagulant Al as Al2(SO4)3;
- MO2 - sulphate Cu as CuSO4;
- PAA - polliektrolit;
- Q - the quantity of raw river water (flow);
- DT - part time;
- mo1 - residual parameter MO1 in clean water;
- mo2 - residual parameter MO2 in clean water,

wherein by means of mass balance of these parameters brings the same units of measurement.

When the budget for the PAC - Al(OH) aClb (SO4) c, instead of stoichiometric MO1, PAC brings in the same unit of measurement of other parameters, while the budget for the sludge in well water uses a similar form:

\[ MB = [(SM + Fe) \times Q \times DT] - [Fei \times Q \times DT] \]

Where:
- MB - sludge from the treatment of well water;
- SM - suspended particles;
- Feu - iron in raw well water as an input parameter;
- Fei - iron in pure(treated) water as the output parameter;
- Q - the volume / flow of well water;
- DT - part time.

Thus the total sludge process is the sum of MR and MB:

\[ M = MR + MB. \]

Thus, in this period of thirty day, and the average flow of river water of 300 l / s with the quantity of sludge treatment with a PAC is 33.4 t, where it is translated to the stoichiometric aluminum - 0.526 tons of aluminum, aluminum sulfate treatment while the amount of sludge tridestodnevni perid in the previous month and similar conditions, at a flow rate of 300 l / s is 53.3 t, where he also translated the stoichiometric aluminum -5.24 tons of aluminum. This is shown in Tables 7 and 8.

### Table 7. 02. – January 31, 2013, river water (treatment of aluminum sulfate)

<table>
<thead>
<tr>
<th>Dose mg/l</th>
<th>Al2(SO4)3 Consumption kg/ms</th>
<th>CuSO4 Consumption kg/ms</th>
<th>PAA Consumption kg/ms</th>
<th>SM mg/l</th>
<th>SM kg/ms</th>
<th>Q l/s</th>
<th>Q m3/ms</th>
<th>Δt dan</th>
<th>M t</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>33660</td>
<td>1000</td>
<td>186</td>
<td>23.7</td>
<td>18429</td>
<td>300</td>
<td>777600</td>
<td>30</td>
<td>53,3</td>
</tr>
</tbody>
</table>

### Table 8. 13.02. – 13.03.2013. RIVER WATER (Treatment PAC-om, ρ PAC 1.23kg / dm3, the dry mat.18,7%, the content of Al in PAC-u 5.35%)

<table>
<thead>
<tr>
<th>PAC Consumption kg/ms</th>
<th>PAC The amount of dry matter (18,7%) kg</th>
<th>CuSO4 Consumption kg/ms</th>
<th>PAA Consumption kg/ms</th>
<th>SM mg/l</th>
<th>SM kg/ms</th>
<th>Q l/s</th>
<th>Q m3/ms</th>
<th>t dan</th>
<th>M T</th>
</tr>
</thead>
<tbody>
<tr>
<td>52556</td>
<td>9827</td>
<td>831</td>
<td>77,8</td>
<td>29,3</td>
<td>22745</td>
<td>300</td>
<td>777600</td>
<td>30</td>
<td>33,4</td>
</tr>
</tbody>
</table>
Total sludge in 2012 as the manufacturing plant of water treatment process was 857.3 t of which 785 t from the processing of river water, and 72.28 t from well water at an average flow rate of 376 l/s of raw river and 310 l/s raw well water. In these calculations output parameters are ignored because the weight to zero, so as not to affect the amount of sludge more than 0.03%.

4. CONCLUSION

Given the slightly higher cost of PAC in relation to Al-sulfate, compared with the costs of waste products (transport, the potential treatment of sludge and waste water, etc.). Benefit in favor of polyaluminum chloride as a coagulant in the processing of river water observed from the aspect of quantity and waste characterization using parameter concentrations of residual aluminum, it is quite certain. This does not mean anything, except that the sustainable management of waste products from the plant for the production of drinking water, implies management (professional selection, monitoring and control) of technical chemicals that are used in the technological process of processing raw water into drinking water. Also, it is necessary a detailed examination of waste products, particularly sludge, not only for characterization, but also to control the presence of hazardous components and defining the origin and trends disposition of pollutants.

REMARK

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REFERENCES


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REZIME

ODRŽIVO UPRAVLJANJE OTPADNIM PRODUKTIMA IZ POSTROJENJA ZA PROIZVODNju VODE ZA PIĆE

Kako je poreklo zagađujućih supstanci koje ugrožavaju održivost životne sredine devastirajući njene strukturalne elemente, u poslednja dva veka prevashodno iz antroposfere, kao posledica rapidnog tehnokonomskog razvoja, nameće se bezuslovna odgovornost čoveka za opravak biosfere - kroz saniranje/umanjenje postojećeg i sprečavanje nastupajućeg deficita prirodnih resursa. Jedan od ultimativnih prioriteta opstanka svih živih formi egzistencije je voda, u antropogenom smislu svakako to znači obezbeđenje dovoljno čiste pijaće vode u istoj količini kako nama tako i nastupajućim generacijama, što predstavlja definiciju održivog razvoja i važi za sve prirodne resurse. U ovom radu akcenat je na bitnom aspektu održivosti vode: upravljanje muljem od postrojenja za prečišćavanje vode, u konkretnom slučaju, vode za piću u funkciji prepoznavanja aspekata uticaja na sastav i smanjenje količine produkcije, mogućnostima ponovnog iskorišćenja i/ili ekonomičnijeg zbrinjavanja.

Ključne reči: voda, mulj, zagađujuće supstance, održivi razvoj, prirodni resursi, postrojenje za proizvodnju pijaće vode, antropogeno zagađenje, održiva rešenja
Fire Detectors Arrangement in Objects with Slope Roof

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Fire detectors present very important elements of all real time fire protection systems. Their assortment, type and arrangement in object present very important task in sense of fire protection system design. This task is often regulated by proper standards. However, some special cases where some changes in standards and design are necessary and obligated, could be found. This paper has written to presents simulation results of heat and smoke detectors reactions in case of object with slope roof.

Key words: fire, arrangement, simulation, object, slope, roof

1. INTRODUCTION

The main purpose of fire protection systems is to provide reliable warning for user in order to avoid human victim and material properties destruction. The design of fire protection systems purports cognition of enormous numbers of facts related to object purpose, objects dimensions, objects ambient conditions, detectors type, and lot of other factors. The final and the most important results of the fire protection systems design are the right choice of fire detectors and their proper arrangement inside the object because fire presents very unpredictable and hard controlled occurrence, such as presented on figure 1.

![Figure 1 - An example of fire in the house with slope roof](http://www.todayshomeowner.com/video/home-fire-safety-and-energy-efficiency-tips/)

Fire detectors could be divided on several ways, according to the way of response, reset possibilities, montage possibilities, the way of resetting, number of states and others.

Fire detectors arrangement into an object is defined according to the proper rules and standards (for example, BS (British Standard), NFPA (National Fire Protection Association), НПБ 88-2001 (Нормы пожарной безопасности), DIN VDE 0833-2 and others). Generally, in the ideal case, the needed fire detectors arrangement and number could be gained as a quotient between supervised surface and detector`s supervised surface.

There are lots of other factors that should be considered, such as shape and slope of the roof, barriers, girt, walls positioning, installation positioning, wholes into the walls positions, room height etc. Detectors should be easy visible and accessible, because of its testing and repairing.

The reduction of the range between detectors leads that the system sensibility becomes higher. But, in many cases, the increment of fire detectors number over some optimal limit brings small gain according to the price of the system.

According to noted facts, it is important to find an optimal relation between performance increments and price needed for that.

It is obvious that the problem of fire detectors choice and their arrangement depends of many different factors that could be found in the particular design task for some particular object. Before considering about many special factors, it is important to start from some the most general recommendations. Some of them are presented in table 1.
Table 1. Recommendations for detector’s choice (table source: Blagojević, D. M.: Alarm systems)

<table>
<thead>
<tr>
<th>Detectors type</th>
<th>Application</th>
<th>No application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization detectors</td>
<td>Best for flammable fires</td>
<td>Ambient with smoke, fumes or dust</td>
</tr>
<tr>
<td>Optical detectors</td>
<td>Best for smouldering fires</td>
<td>Ambient with smoke, fumes or dust</td>
</tr>
<tr>
<td>Multi sensors (optical+thermal)</td>
<td>Detector of general purpose</td>
<td>Ambient with smoke, fumes or dust</td>
</tr>
<tr>
<td>Linear(beam)</td>
<td>Huge and high rooms</td>
<td>Ambient with smoke, fumes or dust</td>
</tr>
<tr>
<td>Thermo differential</td>
<td>Ambient with smoke, fumes or dust</td>
<td></td>
</tr>
<tr>
<td>Thermal, fixed temperature (58 °C)</td>
<td>Ambient with smoke, fumes or dust or with fast temperature changes</td>
<td>Ambient with temperatures above 43 °C</td>
</tr>
<tr>
<td>Thermal, fixed temperature (78 °C)</td>
<td>Ambient with smoke, fumes or dust or with temperatures above 43 °C</td>
<td>Ambient with temperatures above 70 °C</td>
</tr>
</tbody>
</table>

This paper has written to present simulation results of heat and smoke detectors in house with slope roof for different burner’s positions in order to confirm theoretical noted facts given by proper standards and regulates [1, 2, 3, 6, 8].

2. THE ARRANGEMENT OF FIRE DETECTORS IN SPECIAL CASES

As a special cases for fire arrangement, it could be considered stairs, girts, galleries, objects with slope roof, downcast or duplicate roofs and similar cases.

The basic rule for fire detectors arrangement in the rooms with slope roofs is that the arrow of detectors is set in the vertical plane of the top-the highest point of the room. According to some rules, as the slope roof could be considered roof with slope that is bigger than 15°, while in general case, it is need to observe relation $h/a$, as it is presented on figure 2. If that relation is bigger than 0.2, the roof is considered on the same way as slope roof.

For western standards, the rules for detectors arrangement are quite different. The recommendation of those standards is that detectors should be positioned on the top point of the room with minimal distance from vertical wall of 50 cm. For example, the recommendations of the NFPA 72 standard are simpler then European standard. According to general recommendation, fire detectors should be positioned on that way that the complete distance of tilts from detectors is less than 0.9 m. If below the roof exist some girts then the relation between gilt’s depth and roof’s height with one side, and relation of distance between girts and roof’s height must be observed [1, 2, 10].

Figure 2 - An example of the room with slope roof with marked dimensions

3. SIMULATION MODEL

Simulation model for this paper was created in PyroSim software, version 2016. PyroSim is a power graphical user interface for the Fire Dynamics Simulator (FDS). FDS models can predict smoke, temperature, carbon monoxide, and other substances during fires such as different fire situations and scenarios [11].

Simulation model used for this purpose implied object with slope roof with dimensions 20 m x 40 m x 5.5 m. The fire source was modelled as burner with dimensions of 1 m x 1 m and HRR (Heat release rate per area) of 50, 250 and 500 kW/m². The burner’s positions were in the corner of the room (the first scenario) and in the middle of the room (the second scenario). The positions for smoke and heat detectors in the objects were according to noted rules. Simulation model in PyroSim with arrangement of detectors and burners are presented on figures from 3 to 6.

Figure 3 - 3D object in PyroSim with marked burner position in the corner and positioned smoke detectors
The reaction temperature for heat detectors was 75 °C (for both simulation models) and the response time index (RTI) was 100 m³s⁻¹, while the activation threshold for smoke detectors was 3.28 % of obscuration (for both simulation models).

Smoke detectors were positioned in one row in vertical plane of the top roof’s point, while heat detectors were positioned in two rows.

4. SIMULATION AND SIMULATION RESULTS

The simulations were realized on laptop Lenovo IdeaPad G50-80 80E502F3YA, with Intel Core i5-5200U processor (2 cores, 2.20GHz, 3MB cache), DDR3L memory controller (up to 1600MHz), Intel Turbo Boost 2.0 (2.70GHz) and 8GB of DDR3 RAM. The simulation time was set on 300 seconds for every simulation. The duration of complete simulation on computer could take some time, depended of simulation model complexity, simulation numerical options, simulation graphical options and hardware computer configuration.

Simulation results for smoke detectors from the first scenario, where the burner was in the corner of the room, and the burner’s HRR were 50, 250 and 500 kW/m² are presented on figures from 7 to 12.

Simulation results for smoke detectors from the second scenario, where the burner was in the middle of the room, and the burner’s HRR were 50, 250 and 500 kW/m² are presented on figures from 13 to 18.

At the same way, simulation results for heat detectors from the first scenario are presented on figures from 19 to 24 while simulation results for heat detectors from the second scenario are presented on figures from 25 to 30, for the same burner’s positions and HRR [4].
Figure 9 - Simulation results for the nearest smoke detector for burner with HRR of 500 kW/m²

Figure 10 - Simulation results for the farthest smoke detector for burner with HRR of 50 kW/m²

Figure 11 - Simulation results for the farthest smoke detector for burner with HRR of 250 kW/m²

Figure 12 - Simulation results for the farthest smoke detector for burner with HRR of 500 kW/m²

Figure 13 - Simulation results for the nearest smoke detector for burner with HRR of 50 kW/m²

Figure 14 - Simulation results for the nearest smoke detector for burner with HRR of 250 kW/m²

Figure 15 - Simulation results for the nearest smoke detector for burner with HRR of 500 kW/m²

Figure 16 - Simulation results for the farthest smoke detector for burner with HRR of 50 kW/m²
Figure 17 - Simulation results for the farthest smoke detector for burner with HRR of 250 kW/m²

Figure 18 - Simulation results for the farthest smoke detector for burner with HRR of 500 kW/m²

Figure 19 - Simulation results for the nearest heat detector for burner with HRR of 50 kW/m²

Figure 20 - Simulation results for the nearest heat detector for burner with HRR of 250 kW/m²

Figure 21 - Simulation results for the nearest heat detector for burner with HRR of 500 kW/m²

Figure 22 - Simulation results for the farthest heat detector for burner with HRR of 50 kW/m²

Figure 23 - Simulation results for the farthest heat detector for burner with HRR of 250 kW/m²

Figure 24 - Simulation results for the farthest heat detector for burner with HRR of 500 kW/m²
5. DISCUSSION

Realized simulation results for the first and the second scenario for smoke detectors presented on figures from 7 to 18 showed that for complete time of 300 seconds every detector will have an alarm reaction. Of course, that depends from the burners HRR and burn material. In any case, theoretical approach for the problem of the object with the slope roof is correct. The complete results for times needed for smoke detectors activation for both scenarios are presented on figure 31.

Realized simulation results for the first and the second scenario for heat detectors presented on figures...
from 19 to 30 showed that for complete time of 300 seconds every detector will not have an alarm reaction because none heat detector will react. That was, in real, possible for fires of TF2 and TF3 types, with high concentration of grey and black smoke. It took very short time for fire detectors in HD position for the first scenario or HD04 to react in the case with burner of 500 HRR but it still couldn’t reach the response limit of detector (75 °C).

If the time for simulation was longer, the temperature limit of 75 °C probably would be broken. It can be seen that the simulated object was empty-with more or less other objects (desks, chairs, cupboards or other objects with different fire properties) inside this object with slope roof and the temperature of fire would be much higher than temperature realized by simulation.

Smoke detectors were arranged in one row in vertical plane of the highest object’s point. Heat detectors were arranged in two rows in two different planes according to the standards. Simulation showed that, for heat detectors, greater number of heat detectors bring very small or even none effect in sense of faster reaction on temperature. For heat detectors with different properties (different RTI or less temperature limit response from let say, 50 °C, reactions would be more intensive.

6. CONCLUSION

Realized simulation results showed and justified potential smoke and heat detectors arrangement for object with slope roof and their reaction times, where all detectors were positioned according to valid rules.

Simulation results for this and every other simulated object could realize were precious information such as the optimal positions for heat detectors, smoke detectors, carbon monoxide detectors, flame detectors and other fire installations, potential evacuation situations and many other benefits on very accurate, relative fast and, what is the most important, safe way.

It simulation software must is obvious according to its benefits that simulation software must be standard “tool” for fire protection engineering and other similar problems. This paper was written to propound usage of simulation software and to confirm theoretical tasks by simulation for fire detectors arrangement in special occasions [2, 5, 7, 9, 10].

**REFERENCES**


REZIME

RASPORED DETEKTORA POŽARA U SLUČAJU OBJEKTA SA KOSIM KROVOM

Detektori požara predstavljaju veoma važne elemente svih sistema za zaštitu od požara koji rade u realnom vremenu. Njihov odabir, tip i raspored u objektu predstavlja veoma važan zadatak u smislu projektovanja sistema za zaštitu od požara. Ovaj zadatak je često regulisan odgovarajućim standardima. Međutim, postoje specijalni slučajevi gde su promene u standardima nužne i obavezne. Ovaj rad je napisan da prikaže simulacione rezultate reakcija detektora toplote i dima u slučaju objekta sa kosim krovom.

Ključne reči: požar, raspored, simulacija, objekt, kosina, krov
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