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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 Up- rising (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 Janke 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 pasa 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 Emilijan Josimovic who was first President of the Technicians’ Society, prominent figure of that time, Rector of Licej 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 tehnikara 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.
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Formic Acid Electrooxidation On Carbon Supported Platinum Catalysts With Preferential Plane Orientation

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Pt-based nanocatalysts supported on Vulcan XC-72R carbon, were prepared by water-in-oil microemulsion method, with addition of various amounts of HCl in the water phase. Polyethileneglycol-dodecylether (BRIJ 30) was used as a surfactant, which influenced the Pt surface structure, along with HCl. Catalysts prepared with addition of 0, 15, 25 and 35 % of HCl during the synthesis, were electrochemically characterised in 0.5 M H2SO4 using cyclic voltammetry and CO oxidation. Formic acid electrooxidation was examined on all investigated catalysts, in terms of their electrocatalytic activity and stability. Platinum loading on carbon support was examined by Thermogravimetric analysis. Catalysts showed different features in hydrogen region, and slight differences in formic acid oxidation mechanisms.

Key words: nanoparticles, platinum, formic acid electrooxidation, microemulsion method

1. INTRODUCTION

Carbon supported platinum nanoparticles are known as good catalytic material for fuel cell applications, due to their electrocatalytic activity, high specific surface area, and good corrosion stability [1]. Catalytic activity of platinum nanoparticles can be increased by alloying platinum with another noble metal [2], by replacing the carbon support with an interactive metal-oxide support [3], but also by producing shape-controlled nanoparticles [4]. As electrochemical properties of nanoparticles are highly dependent on their surface structure, size, geometry and composition, synthesis of the shape-controlled nanoparticles provides a preferential plane orientation suitable for the investigated reaction. Formica acid can be used as a fuel in fuel cells, as a small organic molecule, that undergoes oxidation reaction at the anode catalyst surface. Control of shape of the nanoparticles used as catalysts for formic acid electrooxidation can be achieved through the water in oil microemulsiion synthesis method, with the addition of HCl as a capping agent in the water phase of the microemulsion [5]. Aim of this work was to investigate formic acid electrooxidation as a surface sensitive reaction, on catalysts with different surface structure.

2. EXPERIMENTAL

2.1. SYNTHESIS

Four Pt catalysts supported on Vulcan XC-72R were synthesized using the water in oil microemulsion method, with different amount of capping agent (HCl) incorporated in the water phase [6]. Briefly, a water in oil microemulsion with n-heptane as oil phase, 0.1 M H2PtCl6 with 0, 15, 25 ili 35 % HCl as water phase and polyethileneglycol-dodecylether (BRIJ 30®) as surfactant was prepared. Size of such formed micelles is...
determined by the water to surfactant molar ratio ($\omega_0=3.8$). The reducing agent, NaBH$_4$, was added in great excess. After reduction of the precursor H$_2$PtCl$_6$ to Pt took place, Vulcan XC-72R carbon support was added to the system, and the solution was stirred for several hours. This procedure is shown on Figure 1.

As a final step of the synthesis, acetone was added to destabilize the micelles and cause precipitation of synthesized catalysts. The precipitate was then washed with ultra-pure water (Millipore, 18 MΩ cm), and dried in N$_2$ atmosphere to remove the used surfactant from the powder. Nominal Pt loading in catalyst powders was 20%. Synthesized catalysts are labelled in further text in a way given in Table 1.

![Figure 1 - Illustration of the microemulsion synthesis process](image)

Table 1. Catalyst labels based on the amount of HCl used in the synthesis

<table>
<thead>
<tr>
<th>Concentration of HCl in the water phase, %</th>
<th>0</th>
<th>15</th>
<th>25</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

2.2. Thermogravimetric Analysis

The TGA analysis was performed (30–800 °C range) on an SDT Q600 TGA/DSC instrument (TA Instruments). The heating rates were 20 °C min$^{-1}$ using less than 10 mg sample mass. The furnace atmosphere consisted of air at a flow rate of 100 cm$^3$ min$^{-1}$.

2.3. Electrochemical Measurements

Electrochemical characterisation of prepared catalysts includes cyclic voltammetry experiments conducted on AUTOLAB potentiostate, in a three electrode compartment electrochemical cell. Glassy carbon disk (5 mm diameter) with 10 µl of prepared catalyst water suspension (2 mg/ml) applied on its surface was used as a working electrode, Pt wire was used as a counter, while saturated calomel electrode was used as a reference electrode. (SCE). All potential values shown in the results are given versus SCE. All experiments were performed on as prepared catalysts. 0.5 M H$_2$SO$_4$ was used as a supporting electrolyte, and potential sweep rate was 50 mV/s in all measurements. Basic voltammograms were recorded in a potential range from -0.2 to 0.55 V, in order to avoid the formation of Pt oxides, while the CO stripping experiments were recorded from -0.2 to 0.9 V. Formic acid electrooxidation was tested in 0.5 M HCOOH in 0.5 M H$_2$SO$_4$, from -0.2 to 0.8 V, for 100 cycles. Electrochemically active surface area (EASA) of working electrodes (Pt catalysts) was calculated based on the amount of charge used for the oxidation of CO$_{ads}$. All current density values were calculated using these EASA values.

3. RESULTS AND DISCUSSION

3.1. Thermogravimetric Analysis

Thermogravimetric analysis of catalyst powders revealed that Pt loading in catalysts A and D corresponds to the nominal Pt loading, while with catalyst B a minor loss of Pt is observed. In case of the catalyst C, higher amount of Pt than nominal is a consequence of a certain loss of carbon. These values were used in particle size calculations. TGA results are shown in Figure 2, and Table 2.

![Figure 2 - TGA curves for catalysts A, B, C and D](image)

Table 2. Pt loading in catalyst powders obtained by TGA analysis

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt loading, %</td>
<td>19.69</td>
<td>16.06</td>
<td>33.94</td>
<td>19.67</td>
</tr>
</tbody>
</table>

3.2. Electrochemical Measurements

3.2.1. Characterisation

Figure 3. represents CVs for all four synthesized catalysts, recorded in supporting electrolyte. CVs have two characteristic areas: hydrogen region, in the potential range from -0.2 to 0.06 V, and double layer region on higher potential value. It can be seen on the same figure that catalysts C and D (with higher amount of HCl used) have better
defined current peaks in the hydrogen region. These peaks belong to hydrogen desorption [7,8], at potential values of -0.14 and -0.02 V. Higher current densities in this area that catalysts C and D exhibit, suggest that their as prepared surface has less residual surfactant than catalysts A and B, thus their surface is cleaner. This fact indicates that the addition of HCl contributes to more efficient removal of the organics used during the synthesis from catalyst powder.

Figure 3 - Basic CVs of Pt catalysts A, B, C and D recorded in 0.5 M H₂SO₄ with the sweep rate of 50 mV/s.

Differences in the double layer region width can also be noted in Figure 3: catalysts A and B have a narrower DL region, compared to catalyst C, and especially to catalyst D. DL region width is associated to the size and distribution of Pt particles on carbon support. Pt particles in the case of catalyst D are obviously poorly distributed on the support, and are highly agglomerate, while Pt particles formed with lower use of HCl are better distributed on the support.

Further analysis of the CVs and comparison of current peaks in hydrogen area to the CVs of Pt monocrystals shows that the first peak found on -0.15 V corresponds to the (110) plane orientations, while the second peak (0.0 V) corresponds to (100) steps [6, 7, 8]. It is evident that catalysts C and D exhibit higher influence of (100) steps, compared to catalysts A and B.

Careful examination of CV that belongs to catalyst C reveals the presence of a shoulder at the end of the hydrogen region, in the potential range from 0.0 to 0.1 V. This can be attributed to (100) wide domains, and their presence indicated the cubic shape of Pt particles [6].

3.2.2. CO Stripping

After CVs were recorded in the supporting electrolyte, CO was chemisorbed for 5 min, at a constant potential of -0.2 V. CO was then oxidized and removed from the surface, and the positive-going part of the CVs, that represent the occurrence of this reaction, are given on Figure 4. Mathematical analysis of the CO oxidation current peaks revealed the EASA values, as well as the particle diameter values, presented in Table 3.

Figure 4 - CO oxidation at catalysts A, B, C and D, positive-going CV parts.

Table 3. Data on surface areas and particle diameters calculated based on CO stripping peak areas and Pt loading from TGA

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>EASA, cm²</td>
<td>1.70</td>
<td>1.30</td>
<td>1.17</td>
<td>0.65</td>
</tr>
<tr>
<td>Specific surface, m²/g</td>
<td>42.5</td>
<td>40.6</td>
<td>17.2</td>
<td>16.2</td>
</tr>
<tr>
<td>d, nm</td>
<td>6.6</td>
<td>6.9</td>
<td>16.3</td>
<td>17.2</td>
</tr>
</tbody>
</table>

CV of catalyst C (Figure 4.) exhibits the start of CO oxidation at lowest potential value (0.22 V). CO oxidation at catalysts A and B starts at around 0.35 V, and at catalyst D on more positive potential of 0.44 V.

Integration of CO peaks, assuming that 420 C/cm² corresponds to a monolayer of adsorbed CO, was the starting point for EASA and d calculations (Table 3.). [9, 10, 11]. These results show that catalysts with lower concentration of HCl (A, B) exhibit higher EASA, and have smaller particles than the catalysts with higher HCl concentration (C, D).

3.2.3. Formic Acid Electrooxidation

Formic acid electrooxidation was investigated on the synthesized Pt catalysts, as one of the most significant anodic reactions in low-temperature fuel cells [12]. Based on the CVs recorded 0.5 M H₂SO₄ + 0.5 M HCOOH, activity and stability of these catalysts for investigated reaction were considered.

Figure 5. represents the CV of formic acid electrooxidation on catalyst A, while the CVs recorded on other three catalysts follow the same form. Observing the anodic part of the CV curve, it can be concluded based on the curve shape, that the reaction follows a
dual mechanism with direct and indirect reaction path. [13].

The direct reaction path, reaction (1), leads to HCOOH dehydrogenation:

\[
\text{HCOOH} + Pt \rightarrow Pt - \text{HCOOH}_{\text{ads}} \rightarrow \text{CO}_2 + 2H^+ + 2e^- \quad (1)
\]

while the indirect path, reactions (2a-c), involves the formation of CO as reaction intermediate, which has to be removed from the catalyst surface for the reaction to be continued [13].

\[
\text{HCOOH} + Pt \rightarrow Pt - \text{HCOOH}_{\text{ads}} \rightarrow \\
\rightarrow Pt - \text{CO}_{\text{ads}} + H_2O \quad (2a) \\
Pt + H_2O \rightarrow Pt - OH_{\text{ads}} + H^+ + e^- \quad (2b) \\
Pt - \text{CO}_{\text{ads}} + Pt - OH_{\text{ads}} \rightarrow 2Pt + \\
\text{CO}_2 + H^+ + e^- \quad (2c)
\]

CO is known as a catalytic poison, which means that it strongly adsorbs on the Pt surface, which prevents the further continuation of the reaction, due to the decrease in the number of active sites on Pt surface. The anodic CV part shows the increase of current density at first, which corresponds to the direct reaction path of HCOOH oxidation. Simultaneously, CO$_{\text{ads}}$ is formed in the indirect reaction path, blocking the Pt surface, which leads to the presence of a current density plateau (0.28 – 0.50 V). The formation of OH$_{\text{ads}}$ species (reaction 2b) at more positive potentials enables the removal of CO$_{\text{ads}}$ (reaction 2c), and the oxidation current rises again, until a potential of Pt oxide formation is reached, which is manifested by a current peak (0.65 V).

Comparing the current densities of the two peaks, one that belongs to the direct to the one that belongs to the indirect reaction path, the share of one or another reaction path in the mechanism can be estimated. These values are taken from the CVs of each catalyst and illustrated in Figure 6.

**Figure 5** - Formic acid electrooxidation CV for catalyst A, recorded in 0.5 M H$_2$SO$_4$ + 0.5 M HCOOH with the potential sweep rate of 50 mV / s.

Figure 6 shows that the direct path is more dominant only in the case of catalyst D, while the indirect path that involves the formation of CO$_{\text{ads}}$ catalytic poison prevails, more or less, in the case of other three catalysts.

Pt surface poisoning with carbon-monoxide affects the electrode stability. The stability of the prepared catalysts was tested during 100 cycles. Initial activity of the catalysts was estimated by comparing the current values at 0.2 V of the first cycle. Initial catalyst activities are illustrated on Figure 7.

It can be concluded from Figure 7 that the highest initial activity exhibit catalysts B and D.

**Figure 6** - Illustration of the direct and indirect reaction path contributions in the mechanism of formic acid electrooxidation at synthesized catalysts.

**Figure 7** - Illustration of the initial activities of the prepared catalysts for formic acid electrooxidation.

Catalyst stability was determined by the comparison of current values at 0.2 V of the 1$^{\text{st}}$ and 100$^{\text{th}}$ cycle.

**Figure 8** - Illustration of the stability of prepared catalysts for formic acid electrooxidation reaction, during 100 cycles.
The ratios of current densities of the 1st and 100th cycle, are illustrated in Figure 8, in percentage. It is clear that, while catalysts B and D exhibit higher initial activity, they are less stable than catalyst C, which stands out as the most stable one of all prepared catalysts.

4. CONCLUSION

Based on the presented results, the following can be concluded:

- Water in oil microemulsion method, used to synthesize Pt catalysts, has proven to be a suitable method for the synthesis of carbon supported Pt nanoparticles with preferential plane orientation
- TGA revealed that Pt nanoparticles were successfully supported by Vulcan XC-72R, while the Pt loading was close to nominal except for the minor losses during catalyst cleaning procedures
- CVs recorded in supporting electrolyte on as-prepared catalysts show that Pt surface is successfully cleaned from the organics
- Catalyst C electrochemically exhibits the highest presence of (100) oriented planes, compared to other catalysts
- CO stripping method shows that particle size increases with the increase of HCl concentration in the microemulsion water phase, and that particle agglomeration is present. Also, EASA decreases with the HCl concentration increase
- CO oxidation starts at lowest potential value in the case of catalyst C, which can be related to the highest share of (100) planes which are the most active for this reaction
- Formic acid electrooxidation follows a dual mechanism on all four catalysts, indirect path is more dominant in the case of catalysts A, B and C, while the direct path has primacy in the case of catalyst D
- Highest initial activity exhibits catalyst B, while catalyst C is the most stable of the prepared catalysts, which is in accordance with the results obtained for CO stripping

Finally, catalyst C is the most perspective one for further investigations, thanks to its optimal combination of exhibited features (FAO stability, CO stripping activity, and the presence of (100) oriented planes that suggests that nanoparticles could have cubic shape)

REFERENCES

REZIME

OKSIDACIJA MRAVLJE KISELINE NA PLATINSKIM KATALIZATORIMA NA UGLJENIČNOM NOSAČU SA PREFERENCIJALNO ORIJENTISANIM RAVNIMA

Platinski nano-katalizatori na ugljeničnom nosaču Vulcan XC-72R sintetizovani su mikroemulzijom metodom, sa različitim sadržajem HCl u vodenoj fazi mikroemulzije. Kao surfaktant korišćen je polietilenglikol-dodeciletar (BRIJ30), čija je uloga da, zajedno sa HCl, utiče na strukturu površine platine. Katalizatori, koji su pripremljeni sa 0, 15, 25 i 35% HCl u vodenoj fazi, okarakterisani su elektrohemijski u 0,5 M H2SO4, cikličnom voltametrijom i oksidacijom CO. Aktivnost i stabilnost sva četiri katalizatora ispitana je za oksidaciju mravlje kiseline. Udeo platine u prahu pripremljenih katalizatora određen je termogravimetrijskom analizom. Katalizatori su pokazali različito ponašanje u vodoničnoj oblasti osnovnih voltamograma, kao i različitu aktivnost i stabilnost za oksidaciju mravlje kiseline.

Ključne reči: nanočestice, platina, oksidacija mravlje kiseline, mikroemulzije
Laser-induced Modification of 5x(Ni/Pd)/Si and (Ni/Pd)/Si Systems by Picosecond Pulses

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A study of morphological and composition changes of bimetallic (NiPd)/Si and 5x(Ni/Pd)/Si systems induced by laser pulses in picosecond time domain is presented. The effects of Nd:YAG laser, operating at 1064 nm wavelength with pulse duration of 150 ps, on a complex target were investigated. The laser-induced morphological and composition modifications have shown dependence on applied intensities and number of laser pulses. The results show an increase in surface roughness, formation of parallel periodic surface structures, appearance of hydrodynamic features and ablation of surface material. RBS analysis revealed that laser modification induced inter-mixing between the components of individual Ni and Pd layers, with indications of the formation NiPd intermetallic compounds. Interesting findings are the morphological changes include the formation of specific nanostructures in form of mosaic or parallel periodic structures.

Key words: thin films, laser modification, parallel periodic structure

1. INTRODUCTION

Laser processing of materials is a promising branch of modern science and technology applicable in a various field of industries. The laser-matter interaction is a complex process that depends on a large number of parameters [1, 2]. The main parameters that define the laser-induced modification of the solid surface are the type and nature of the material (chemical composition, structure, surface conditions), the characteristics of the laser radiation (energy density, pulse duration, power, number of accumulated pulses) and the nature of the surrounding environment (vacuum, controlled ambient conditions) [3]. The advantages of the material laser processing compare to other methods, including that the process is localized in a small area in a very short time with the possibility of the synthesis of new chemical compounds. Laser ablation attracts considerable attention as a relatively new technique of treating the material for producing stable nanoparticles and specific nanostructures [4, 5].

Alloys and thin layers based on nickel and palladium have specific physico-chemical and mechanical properties, such as high corrosion resistance, good stability, high strength and porosity [6]. Alloy NiPd possesses high catalytic activity and easily hydrogenated so lately used as an effective catalyst and material for hydrogen storage.

Excellent synergistic effect which occurs between Ni and Pd, makes NiPd alloy as a new generation of catalysts with completely different properties compared to individual Ni and Pd catalysts.

Generation of nickel oxide (NiO) can significantly enhance catalytic activity and resistance of Pd adsorption for carbon monoxide, due to adsorption of OH groups on the lower potential by increasing the number of activation centers for electrocatalytic reaction [7-9].

Modification of complex nickel-palladium samples with laser radiation in the picosecond domain is insufficiently researched area. This work included the study of the effects caused by changes in the chemical composition and morphology after irradiation of single NiPd and multilayer 5x(Ni/Pd) thin films with Nd:YAG laser beam. Effects of changes in the chemical
composition and morphology were observed depending on the pulse energy and number of accumulated pulses.

2. EXPERIMENTAL

The nickel-palladium thin films were prepared by the ion sputtering in BALZERS SPUTTRON II vacuum system. Single bimetallic NiPd and multilayer 5x(Ni/Pd) thin films were deposited onto polycrystalline silicon substrate. Single (NiPd) thin film was deposited by sputtering of the Ni(80%)-Pd(20%)/wt target with argon ions at energy 1.3 KeV and pressure in the chamber was 10^{-3} Pa. Multilayer 5x(Ni/Pd) structure was deposited by the alternately formed 10 individual Ni and Pd layers at the same vacuum conditions.

Deposition rate for Ni component was approximately 0.13 nm s^{-1}, while for Pd was about 0.17 nm s^{-1}, without additional heating the substrate during the deposition. First layer on the silicon was NiPdPd/Pd. Multilayer 5x(Ni/Pd) structure was deposited by the alternately formed 10 individual Ni and Pd layers at the same vacuum conditions.

Modification of samples 5x(Ni/Pd)/Si and NiPd/Pd were carried out by focused laser radiation in the air at the pressure of 1013 mbar and at standard relatively humidity. Laser irradiation of the samples was made by Nd:YAG laser (model EKSPALA SL212P) with following characteristics: wavelength 1064 nm, pulse duration 150 ps, frequency 10 Hz and energy per pulse up to 2 mJ. The laser beam was focused through a quartz lens focal length of 17 cm, where the beam came at a normal angle to the sample. The sample were modified at energies per pulse of 1 mJ and 2 mJ with 10 and 100 accumulated pulses at each used pulse energy.

Surface morphological changes induced by laser irradiation were analyzed with scanning electron microscopy SEM (TESKAN, MIRA3). Analysis of changes in the chemical composition for 5x(Ni/Pd)/Si and NiPd/Pd systems on some characteristic positions before and after laser-induced modification was done by Particle Induced X-Ray Emission – PIXE and Rutherford backscattering spectrometry - RBS.

Methods PIXE i RBS were made proton microbeam using an EN Tandem Vande Graaff accelerator in Ruđer Bošković Institute in Zagreb, while experimental details were described in the literature [10]. To achieve a satisfactory resolution of the detection for observed elements (Ni, Pd and Si) was used proton energy of 3.02 MeV for both analytical methods.

3. RESULTS AND DISCUSSION

Morphological characteristics of multilayer 5x(Ni/Pd)/Si structure were studied after irradiation by focused picosecond laser pulses with energies of 1 mJ and 2 mJ. Comparative view of modified 5x(Ni/Pd)/Si system with several SEM photographs is shown in Figure 1, for both used energy pulses after applied 10 and 100 accumulated pulses.

The modified areas had circular shape (Figure 1A1, 1B1, 1C1 and 1D1), with intensive morphological changes after irradiation with a great number of pulses and higher pulse energy. The main characteristics of laser-modified area were: (i) intense surface melting of the thin film (Figure 1A2 and 1C2) after action of 10 pulses, and the melting of Si substrates with appearance of the liquid phase at the surface (Figure 1B2 and 1D2) after 100 accumulated pulses, (ii) the formation of holes at the peripheral part of the irradiated area, which likely originate from the evaporation of molten material (Figure 1A3, 1B3 and 1C3) or partial ablation of thin films (Figure 1B3 and 1D3), (iii) the occurrence of hydrodynamic characteristics in the form of resolidified materials (Figure 1B2, 1B3 and 1D2), (iv) the formation of frozen wavy structure as a result of displacement of molten material from the center to the periphery (Figure 1B3), (v) removal/ablation material with increasing the number of pulses (Figure 1B3 and 1D3).

The shallow and relatively short surface cracks were observed on the Si substrate in the central part after irradiation with a large number of pulses, which are the result of the rapid cooling of the material after stopping laser action.

During the irradiation with a small number of pulses removal of a thin film likely occurs through the ablation process, however with increased pulse energy and the number of accumulated pulses the material is further removed by evaporation process due to achieving the high temperatures during the interaction of the laser pulses.
LASER-INDUCED MODIFICATION OF 5x(Ni/Pd)/Si AND (Ni/Pd)/Si...

Figure 1 - SEM microphotographs of the modified 5x(Ni/Pd)/Si system: (A1-A3) spot, center and periphery after 10 pulses for E = 1 mJ; (B1-B3) spot, center and periphery after 100 pulses for E = 1 mJ; (C1-C3) spot, center and periphery after 10 pulses for E = 2 mJ; (D1-D3) spot, center and periphery after 100 pulses for E = 2 mJ

Significant morphological changes were obtained by the interaction of laser radiation with 5x(Ni/Pd)/Si, which is caused by the formation of characteristic nanostructures in the form of mosaic and surface periodic structures (Figure 2A and 2B).

Figure 2 - SEM microphotographs of the modified multilayer 5x(Ni/Pd)/Si system with laser radiation E=1 mJ with100 accumulated pulses: (A) central part and (B) periphery of irradiated area

In the central part, where the ablation of thin film materials was dominant, on the Si substrate is observed a certain amount of redeposited thin film materials in the form of a mosaic-like structure with well-defined edges in preferential directions (Figure 2A). A mosaic structure was formed as a result of condensation and redeposition of ejected material as atoms, ions or small clusters in the central region of the polycrystalline Si substrate, where along the grain boundaries of crystal can be piled the previously ejected material. Periodic structure with a period of about 800 nm is the most pronounced after 100 accumulated pulses at lower pulse energy (Figure 2B). Thus formed parallel periodic structures occur mainly at the periphery, where the laser beam has lower intensity due to the Gaussian distribution of energy. The assumed mechanism of their formation involves interference incident beam of laser radiation with reflected surface wave on some surface imperfections.

From SEM images of the modified single (NiPd)/Si thin film after irradiation with 10 and 100 pulses at energies of 1 mJ and 2 mJ, it was found that beside of intensive surface melting, a great extent of the observed ablation material was appeared as partial exfoliation of the NiPd thin film (Figure 3A1, 3B1, 3C1 and 3D1). In the central part of the modified areas at lower pulse energy for any number of applied pulses are clearly visible the periodic structures with the distance between successive periods of about 10 microns (Figure 3A2 and 3B2). The periodicity is significantly greater than the wavelength of the applied laser radiation, the origin of the periodic structure is attributed the accumulation of molten material during cooling after stopping laser action. With the increasing number of pulses the periodic structure become enhanced, which is reflected in the deepening of the space between the period and more noticeable melting of the material at the top period. During the irradiation with a larger number of pulses (Figure 3B2) is recognized the formation of crystal grains on the top of periods, as a result of the material recrystallization. In one part of the modified area is registered not-so-well-defined periodic structure with a periodicity of about 1 μm, which is close to the value of the used wavelength (1064 nm). On the periphery of the modified area (Figure 3A3 and 3B3), irradiation with 10 and 100 pulses at energy of 1 mJ, visible edge effects are made from the rim of the accumulated material during irradiation as consequence of the molten materials and their movement from the center to the periphery of the irradiated area. With the increasing number of pulses the recrystallization of molten material at the periphery was observed, causing the formation of the grain structure in a thin film. Creating a grain structure is the result of lateral transfer of energy through the material in the vicinity of the irradiated area. Thermally activated diffusion, allows grouping of atoms in some preferential direction, increasing the size of crystal grains, which are relatively small in the deposited thin films.

The different morphological changes occur on the surface of the single (NiPd)/Si thin film after the pulse energy of 2 mJ (Figure 3C1 and 3D1). The melting of the NiPd thin film is even accompanied by the removal of thin film from Si substrate after action of 10 pulses. After detailed analysis of morphological changes in the central and peripheral region (Figure 3C2 and 3C3) it can be concluded that due to the different thermal conductivity of the components Ni, Pd, and Si, first step was occurrence of cracks in film and then appeared the exfoliation of NiPd thin film due to insufficient...
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MODIFIKACIJA (NiPd)/Si i 5x(Ni/Pd)/Si TANKIH SLOJEVA IZAZVANA...

adhesion. Silicon substrate does not conduct heat at the same rate as the metal thin film; part of the heat is retained at the border film/substrate causing separation film from the substrate [11].

Figure 3 - SEM microphotographs of the modified NiPd/Si system: (A1-A3) spot, center and periphery after 10 pulses for $E = 1 \text{ mJ}$; (B1-B3) spot, center and periphery after 100 pulses for $E = 1 \text{ mJ}$; (C1-C3) spot center and periphery after 10 pulses for $E = 2 \text{ mJ}$; (D1-D3) spot, center and periphery after 100 pulses for $E = 2 \text{ mJ}$

Microcracks in a thin film are quite long, but shallow radially oriented from the center to the periphery. The occurred of frozen wavy structure is more pronounced with increasing number of accumulated pulses, shifting more and more from the center to the periphery (Figure 3D2 and 3D3).

The changes of chemical composition and distribution of components into the 5x(Ni/Pd)/Si and (NiPd)/Si systems were studied PIXE and RBS techniques by a proton beam with a diameter less than 1 mm, in order to avoid the impact of increased roughness on accuracy results caused by laser processing. Positions for the RBS spectra are selected to cover all possible modification based on the contrast in PIXE maps of Si that are directly reflected in the change of the other components (Ni, Pd).

PIXE maps (Figures 4 and 5) represent the distribution of Si atoms in the modified areas; thereby induced morphological changes are clearly mapped through distribution of Si atoms. In the central part, the presence of a thin film material is registered. The blue color indicates a high concentration of Si atoms, which indirectly signified the ablation during laser processing. The bordering contour of the modified area is yellow-red color that is associated with a decrease in concentration Si atoms. This can be explained by the accumulation of thin film materials due to the relatively higher contents of Ni and Pd.

RBS spectra were taken after 10 and 100 pulses with energy of 1 mJ (Figures 4 and 5) at the several positions within the modified area and compared with the RBS spectra of unmodified systems. The spectra recorded in the unmodified part of 5x(Ni/Pd) Si sample (Figure 4A and 4B) shows the presence of two peaks with close energies, for Ni 1812 keV and Pd at 1887 keV. A broad peak formed in the energy interval from 900 to 1700 keV is attributed to Si.

At selected positions for applied 10 pulses (Figure 4A), the high intense peak corresponds to Ni and Pd without separability of the individual components.
This form of peak is associated with the fact that intense mixing of the components between Ni and Pd layers are occurred. High energy edge of Si is shifted towards lower energies indicating that the thickness of the Si substrate decreased, or that part of Si atoms diffused into a thin film. After the action of 100 pulses (Figure 4B) in the center is not recorded presence of Ni and Pd components, which would mean that only Si are present at the surface.

On the edge of the modified area, in the accumulated material are existed all components (Ni, Pd and Si) in a significant intermixing form, indicated from moving and lifting high-energy edge of Si in the RBS spectrum [12, 13].
In the RBS spectrum recorded for the case of action 10 pulses with the energy of 1 mJ at (NiPd)/Si (Figure 5A) can be seen the presence of components of Ni and Pd with about 30% of a lower concentration compared to an unmodified area. At the expected position of the edge, RBS spectrum was almost the same as in the unmodified areas, except the intermixing of components between thin film and Si substrate as the only observed effects in this case. Both RBS spectra from modified position (Figure 5B) after 100 accumulated pulses, show decreased intensity of the peak which corresponding to Ni and Pd, with the explanation that the sample in this area suffered significant ejection of material by the ablation or evaporation. The intensity of peak increases at the periphery due to the accumulation of material. After the action of any number of pulses and the peak towards lower energy has been observed, as well as the displacement of high-energy edge of Si, due to mutual intermixing of components most likely caused by thermally activated diffusion [13].

4. CONCLUSION

The work was included the study of the laser-induced surface modifications of the single (NiPd)/Si and multilayer 5x (Ni / Pd) / Si systems. Surface changes of the observed systems showed the dependence on the pulse energy and the number of accumulated pulses. At the given parameters of laser beam (pulse duration of 150 ps and wavelength 1064 nm) on the surface of thin 5x(Ni/Pd) and NiPd films but also on Si substrate appear the significant morphological, structural and chemical changes.

Morphological and structural changes of 5x(Ni/Pd)/Si and (NiPd)/Si samples induced with pulse energies of 1 mJ and 2 mJ include different features: (i) the ablation followed by surface melting of the material, conditioned by delivered pulse energy; (ii) the occurrence of holes caused by vaporization; (iii) the gathering of material with the formation of frozen wavy structure; (iv) the occurrence of hydrodynamic characteristics in the form of resolidified material; and (v) the exfoliation of thin film due to difference in thermal conductivity of the constructive components. By increasing the number of pulses on the observed systems, the concentration of Si atoms in the central part was increased, with the initial formation of the edge of the accumulated material for 10 pulses and its complete formation for 100 pulses. Results of the composition changes show in all cases after modification with any number of pulses, that intense mixing of the components can be caused by thermally activated diffusion with the possibility of formation of intermetallic compound between Ni and Pd.

5. ACKNOWLEDGMENT

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REZIME

MODIFIKACIJA (NiPd)/Si i 5x(Ni/Pd)/Si TANKIH SLOJEVA IZAZVANA PIKOSEKUNDNIM LASERSKIM ZRAČENJEM

Rad prikazuje proučavanje promena hemijskog sastava i morfologije kompaktnog (Ni/Pd)/Si i višeslojnog 5x(Ni/Pd)/Si tankog sloja posle modifikacije pikosekundnim laserskim zračenjem. Istraživanje je obuhvatio analizu efekata koji su izazvani delovanjem zračenja Nd:YAG lasera talasne dužine 1064 nm sa dužinom trajanja impulsa od 150 ps na kompleksnim uzorcima. Laserski izazvane modifikacije hemijskog sastava i morfologije zavise od energije predate sistemu i broja akumuliranih impulsa. Rezultati pokazuju povećanje površinske hrapavosti praćeno intenzivnom ablacijom i površinskim topljenjem materijala u modifikovanoj oblasti. Laserska modifikacija posmatranih sistema indukovala je intenzivno mešanje komponenti individualnih Ni i Pd slojeva, sa velikom verovatnoćom formiranja intermetalnih NiPd jedinjenja. Jedan od značajnijih rezultata površinske modifikacije je formiranje mozaične i paralelnih periodičnih struktura nanometarskih dimenzija.

Ključne reči: tanki slojevi, laserska modifikacija, paralelne periodične strukture
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Current Serbian Design Codes – Transfering from a Deterministic to a Semi-
Probabilistic Approach

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The Serbian design code for reinforced concrete structures is somewhat out-of-date in its approach to structural design. In this paper, a study into the possible transition to a semi-probabilistic approach is presented. Firstly, the implicit reliability indices in the current Serbian reinforced concrete design code are determined for three design situations - bending, axial compression and shear and for various cases within each of them. The implicit reliability indices show that the Serbian design code is more conservative than Eurocode 2, but that design for shear without stirrups has a significantly low reliability index (2.27). Secondly, a calibration procedure was implemented in order to obtain partial safety factors for a target reliability index of 4.8 (calculated as the average of the implicit reliability indices). The obtained partial safety factors are ready-for-use with the current Serbian design code and, as expected, are higher than those in Eurocode 2.

Key words: design codes, reinforced concrete, reliability index, code calibration

1. INTRODUCTION

The current Serbian design code for reinforced concrete structures is somewhat out-of-date in its approach to structural design. It prescribes only partial safety factors for actions and its adopted values lead to uneven reliability indices in different design situations. This leads to economically, technically and societally unsustainable practice. For this reason most nations worldwide have adopted semi-probabilistic design codes calibrated to a target reliability index which is valid for all types of structures and materials (e.g. the Eurocodes). This is what is widely known as Load and Resistance Factor Design (LRFD).

The aim of this study is first to determine the different implicit reliability indices in Serbian design codes for concrete structures. Then a target reliability index for a new semi-probabilistic code can be adopted and a code calibration procedure carried out to determine the partial safety factors for both material resistances and loads. This would enable comparisons with other more modern codes such as the Eurocodes and foster more modern advanced design procedures in Serbian engineering practice.

2. IMPLICIT RELIABILITY INDICES IN CURRENT SERBIAN DESIGN CODE FOR REINFORCED CONCRETE STRUCTURES

2.1. An overview of the PBAB 1987 design code

Since 1987 the design code for reinforced concrete structures has been the “Rulebook of technical norms for concrete and reinforced concrete” (PBAB, 1987). At the time of its introduction it was a modern code that brought the use of limit state design to Serbian structural engineering but after 27 years of its use it can hardly be said that it still mirrors current trends in reinforced concrete design.

The (PBAB, 1987) follows the standard design check procedure of limit state design:

\[ R_u \geq S_u \]  

where \( R_u \) is the ultimate value of resistance and \( S_u \) the ultimate value of load effects.

Similar to other semi-probabilistic codes it defines characteristic values of material resistances and loads. In design, material resistances are used with their characteristic values and partial safety factors are only prescribed for load effects. The Application guidebook
for PBAB 1987 (Aćić et al., 1989) states that the partial safety factors pertaining to material resistances are envisaged by the code, but are implicitly included in the load safety factors. The load partial safety factors depend on the limit state being checked (defined by reinforcement strain) and on the load actions on the structure. For a reinforcement strain exceeding 3% in the ultimate limit state (which means a yielding of reinforcement and a ductile failure) the safety factor for permanent actions is set to $\gamma_R=1.6$ and for variable loads (such as live loads, wind, snow) to $\gamma_R=1.8$. For negative ultimate reinforcement strains (reinforcement in compression and brittle fracture) the safety factors are increased to $\gamma_R=1.9$ and $\gamma_R=2.1$. For reinforcement strains between 3% and 0% the safety factors are linearly interpolated. If an additional accidental load acts on the structure or if there is a favorable effect of permanent load, the factors change again. These situations however, will not be discussed here in detail.

According to (PBAB, 1987) the load effects are to be determined using theory of elasticity. This implies that all sections reach their limit state simultaneously. Therefore, the limit state design according to (PBAB, 1987) deals only with resistances of member cross-sections while other limit states related to whole structure are not analyzed.

In this study a FORM analysis is carried out in order to determine the implicit reliability indices of the (PBAB, 1987) design code. Three different design situations are analyzed – failure of a cross-section in bending, axial compression and shear.

2.2. Bending of reinforced concrete members

In this study bending was analyzed on a $b/d=30/60$ cm rectangular cross-section.

When designing a cross-section in bending according to (PBAB, 1987), the procedure is as follows:

1) Assume an effective depth of the beam $h \neq (9/10)h_d$

2) Calculate the coefficient $k$ (equilibrium of bending moments) given by

$$k = \frac{h}{M_u}{F_b} \quad (2)$$

where $M_u$ is the ultimate value of bending moment ($=1.6M_s+1.8M_p$), $b$ the width of cross-section zone in compression and $f_b$ the design value of concrete compressive strength

3) The coefficient $k$ unambiguously determines concrete and reinforcement strains $\varepsilon_c$ and $\varepsilon_r$; they in turn define the lever arm of internal forces through the coefficient $\zeta$ (all values are tabulated)

4) Using the coefficient $\zeta$ calculate the necessary reinforcement area (equilibrium of axial forces)

$$A_\alpha = \frac{M_u}{\zeta \cdot h \cdot \sigma_v} \quad (3)$$

where $\sigma_v$ is the characteristic value of reinforcement yield stress.

In this study three design cases are evaluated. The Case B1 is a design situation where minimal reinforcement area is required (0.2% of cross-section area, under-reinforced section). The Case B2 is defined as “simultaneous failure” in (PBAB, 1987) where both concrete and reinforcement reach their respective ultimate strains at the same time (3.5 and 10% respectively). The Case B3 stipulates the reinforcement ultimate strain of 3%, close to the so-called “balanced section” (over-reinforced section).

In (PBAB, 1987) the concrete compressive strength is defined by a concrete grade MB which is the 10-percentile of concrete compressive strength obtained by testing 20x20x20 cm cubes, given in MPa. This differs from the definition of concrete grade in (EN 1992, 2004) where a 5-percentile of concrete compressive strength obtained by testing 15x15x30 cm cylinders is defined as the characteristic value.

The provisions in (PBAB, 1987) further decrease this value by multiplying it with approximately 0.7 in order to take into account the difference between the strength achieved in structural members versus test specimens (Aćić et al., 1989). The factor by which the characteristic value is multiplied decreases from 0.683 for MB 30 to 0.55 for MB 60.

Given that in bending, the contribution of concrete to bending resistance is significantly smaller compared to the reinforcement the reduction of concrete compressive strength wasn’t varied with concrete grade in this study. In axial compression this variation in reduction of the characteristic value can be significant and is therefore investigated.

The reinforcement yield stress is defined as the 5-percentile of the reinforcement steel yield stress obtained by testing defined specimen as required in (EN 1992, 2004).

Basic variables for the design of the cross-section are given in Table 1. The ultimate bending moment is given by:

$$M_u = \gamma_g \cdot M_g + \gamma_p \cdot M_p \quad (4)$$

For this ultimate moment, the ratio of permanent to variable load was varied using a coefficient $\alpha=[0,1]$ and equation (5):

$$\gamma_g \cdot M_g = \alpha \cdot M_u \gamma_p \cdot M_p = 1 - \alpha \cdot M_u \quad (5)$$
The limit state equation for FORM analysis is as follows (Vrouwenvelder and Siemes, 1987):

\[ G = A_g \cdot \sigma_c \cdot b \cdot 1 - 0.55 \frac{A_g \cdot \sigma_c}{b \cdot h^{0.682} \cdot MB} \]  

\[ -M_g - M_F \]  

(6)

In all three design cases the only differing parameters are the reinforcement area, effective depth, permanent and live load. In this study the geometric quantities are viewed as deterministic values. This, of course, doesn’t mirror the reality, but is deemed sufficiently accurate for the given purpose. For the distribution of concrete compressive strength and reinforcement yield stress, a Log-normal distribution was selected, as recommended in literature (Vrouwenvelder and Siemes, 1987; JCSS, 2001).

For the distributions of the permanent and variable loads, the Normal and Gumbel distributions are selected, respectively. Their characteristic values are also selected according to (JCSS, 2001). This results in four random variables and for each variable two coefficients of variation (CoV) are selected according to (Vrouwenvelder and Siemes, 1987; JCSS, 2001).

This amounts to 16 combinations that are to be simulated using the limit state equation (6). For each combination a FORM analysis was carried out using the software VaP (developed by Markus Petschacher, PSP GmbH, Feldkirchen, Austria). In each combination of CoVs, four values of \( \alpha \) factor are analyzed – 0, 0.3, 0.6 and 1.0.

Table 2. Variables and their distribution parameters for FORM analysis of bending

<table>
<thead>
<tr>
<th>Property</th>
<th>MB (kN/cm²)</th>
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<td>Distribution</td>
<td>Log-normal</td>
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<td>Normal</td>
<td>Gumbel</td>
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<td>Prob. of exceeding</td>
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<td>0.50</td>
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<td>0.30</td>
</tr>
<tr>
<td>CoV 2</td>
<td>0.25</td>
<td>0.10</td>
<td>0.10</td>
<td>0.50</td>
</tr>
</tbody>
</table>

The distribution parameters of the variables for cases B1-3 are given in Table 2.

2.3. Axial compression of reinforced concrete members

In this study axial compression was analyzed on a square cross-section with \( b=50 \) cm. Second-order effects are not considered. When designing a cross-section in axial compression according to (PBAB, 1987), the axial forces equilibrium condition is given by:

\[ N_u = A_p \cdot f_b + A_s \cdot \sigma_c \]  

where \( N_u \) is the ultimate value of axial force (=1.9\( N_c^* + 2.1 \cdot N_p \)), \( A_p \) the concrete cross-section area and \( A_s \) the reinforcement area (= \( A_b \), where \( A_b \) is the reinforcement ratio)

In this study four design cases (C1-C4) are evaluated. The reduction factor to obtain the characteristic value of the concrete compressive strength from concrete grade depends on the grade and this dependency cannot be neglected for axial compression. Hence, in this study two concrete grades are analyzed – MB 30 and MB 60 and for each grade two reinforcement ratios are chosen – the minimum ratio of 0.6% and a sufficiently large reinforcement ratio of 3% (the maximum allowed being 6%). The basic variables for the design of the cross-section are given in Table 3. The ultimate axial force is analogous to Eq. (4) and the ratio of permanent to variable load \( \alpha \) is defined in the same way as in bending.

Table 3. Variables for design of cross-section in axial compression

<table>
<thead>
<tr>
<th>Case</th>
<th>b (cm)</th>
<th>(%)</th>
<th>( N_c ) (kN)</th>
<th>MB (kN/cm²)</th>
<th>( \sigma_c ) (kN/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>50.0</td>
<td>0.6</td>
<td>5725</td>
<td>3.0</td>
<td>40.0</td>
</tr>
<tr>
<td>C2</td>
<td>3.0</td>
<td>3.0</td>
<td>8125</td>
<td>3.0</td>
<td>40.0</td>
</tr>
<tr>
<td>C3</td>
<td>0.6</td>
<td>8850</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>3.0</td>
<td>11250</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The limit state equation for FORM analysis is as follows:

\[ G = A_g \cdot C \cdot MB + A_s \cdot \sigma_c - N_\gamma - N_p \]  

(8)

where \( C \) is the reduction coefficient for concrete compressive strength (0.683 for MB 30 and 0.55 for MB 60)

Table 4. Variables and their distribution parameters for FORM analysis of axial compression

<table>
<thead>
<tr>
<th>Property</th>
<th>f_b</th>
<th>( \sigma_c )</th>
<th>( N_c )</th>
<th>( N_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>Log-normal</td>
<td>Log-normal</td>
<td>Normal</td>
<td>Gumbel</td>
</tr>
<tr>
<td>Prob. of exceeding</td>
<td>0.95</td>
<td>0.90</td>
<td>0.50</td>
<td>0.02</td>
</tr>
<tr>
<td>charact. value</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CoV 1</td>
<td>0.15</td>
<td>0.05</td>
<td>0.05</td>
<td>0.30</td>
</tr>
<tr>
<td>CoV 2</td>
<td>0.25</td>
<td>0.10</td>
<td>0.10</td>
<td>0.50</td>
</tr>
</tbody>
</table>

The distribution parameters of the variables for cases C1-4 are given in Table 4. There are 16 combinations of CoVs and three values of \( \alpha \) factor are analyzed – 0, 0.5 and 1.0.
2.4. Shear in reinforced concrete members

In this study shear was analyzed on a 60 cm high T-section with a web width of 30 cm.

When designing a cross-section in shear according to (PBAB, 1987), there are several specific issues. Firstly the basic design check format for members in shear is:

\[ \tau_n = \frac{T_{ul}}{b \cdot z} \leq \tau_T \]  

(9)

where \( \tau_n \) stands for the nominal shear stress, \( T_{ul} \) for the ultimate shear force \((=1.6 \cdot T_g + 1.8 \cdot T_p)\), \( b \) for the section width, \( z \) for the internal lever arm \((=0.9 \cdot h)\) and \( \tau_T \) for the shear strength design value.

The design value of the shear strength is derived by dividing the mean value of the uniaxial tensile strength \( f_{um} \) by approximately 2.2 (PBAB, 1987). This means that, unlike bending and compression, in shear, a basic random variable isn’t the concrete compressive strength (with a 10-percentile), but the concrete uniaxial tensile strength \( f_{um} \) with its mean value. Also associated with the concrete tensile strength is the significantly larger coefficient of variation.

Unlike other modern design codes (PBAB, 1987) prescribes three different possibilities when checking Eq. (9). In the case S1 i.e. \( \tau_n < \tau_T \), no transverse reinforcement is required.

If \( \tau_n < 3 \tau_T \) (case S2) transverse reinforcement is required but a part of the shear force is assumed to be transferred by aggregate interlock. The reinforcement is calculated for the remaining nominal shear stress.

In this case the design procedure is as follows:

- **Reduction of the shear stress:**

  \[ \tau_{Ru} = 1.5 \left( \frac{T_{ul}}{b \cdot z} - \tau_T \right) \]  

(10)

- **Calculation of necessary stirrups to support the stress \( \tau_{Ru} \):**

  \[ \tau_{Ru} = \frac{A_u}{b \cdot e_u} \sigma_v \]  

(11)

where \( A_u \) is the area of reinforcement in one section (= number of legs x area of one stirrup bar) and \( e_u \) stands for stirrup spacing.

In case S3 \( 3 \tau_T < \tau_n < 5 \tau_T \) shear reinforcement is required but no reduction of the shear force is allowed. The case \( \tau_n > 5 \tau_T \) is not permitted.

In this case the design procedure consists only of calculating the necessary stirrups to support the nominal shear stress \( \tau_n \), using Eq.(11) replacing \( \tau_{Ru} \) with \( \tau_n \).

For a selected concrete grade MB 30 the mean value of the uniaxial tensile strength \( f_{um} \) is 0.24 kN/cm², the shear strength design value is 0.11 kN/cm², and the reduction factor 2.18 (PBAB, 1987). The ultimate shear force is analogous to Eq. (4) and the ratio of permanent to variable load \( a \) is defined in the same way as in bending.

In the case of \( \tau_n < \tau_T \), FORM analysis is carried out by using the following limit state equation:

\[ G = 0.9 \cdot f_{um} \cdot b \cdot h/2.18 - T_g - T_p \]  

(12)

In the case of \( \tau_n < 3 \tau_T \), the limit state equation is:

\[ G = 0.9 \cdot A_u \cdot h \cdot \sigma_v + 1.35 \cdot f_{um} \cdot b \cdot h - \]  

\[ -1.5 \cdot (T_g + T_p) \]  

(13)

and in the case of \( 3 \tau_T < \tau_n < 5 \tau_T \) the limit state equation is:

\[ G = \frac{0.9 A_u h \sigma_v}{e_u} - T_g - T_p \]  

(14)

Table 5. Variables for design of cross-section in bending

<table>
<thead>
<tr>
<th>Case</th>
<th>b (cm)</th>
<th>h (cm)</th>
<th>A_u (cm²)</th>
<th>e_u (cm)</th>
<th>T_u (kNm)</th>
<th>f_{um} (kNm²)</th>
<th>\sigma_v (kN/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>30.0</td>
<td>55.0</td>
<td>–</td>
<td>–</td>
<td>164.0</td>
<td>0.24</td>
<td>–</td>
</tr>
<tr>
<td>S2</td>
<td>1.57</td>
<td>12.6</td>
<td>35.0</td>
<td>0.24</td>
<td>327.0</td>
<td>0.24</td>
<td>40.0</td>
</tr>
<tr>
<td>S3</td>
<td>3.14</td>
<td>9.5</td>
<td>654.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>40.0</td>
</tr>
</tbody>
</table>

Basic variables for the design of the cross-section are given in Table 5. The distribution parameters of the variables for cases C1-4 are given in Tables 6. In cases S1 and S2 there are 8 combinations of CoVs while in case S3 there are 16 (two material resistances instead of one). Three values of \( a \) factor are analyzed – 0, 0.5 and 1.0.

Table 6. Variables and their distribution parameters for FORM analysis of shear

<table>
<thead>
<tr>
<th>Property</th>
<th>f_{um}</th>
<th>\sigma_v</th>
<th>T_u</th>
<th>T_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>Log-normal</td>
<td>Log-normal</td>
<td>Normal</td>
<td>Gumbel</td>
</tr>
<tr>
<td>Prob. of exceeding charact. value</td>
<td>0.50</td>
<td>0.90</td>
<td>0.50</td>
<td>0.02</td>
</tr>
<tr>
<td>CoV 1</td>
<td>0.20</td>
<td>0.05</td>
<td>0.05</td>
<td>0.30</td>
</tr>
<tr>
<td>CoV 2</td>
<td>0.40</td>
<td>0.10</td>
<td>0.10</td>
<td>0.50</td>
</tr>
</tbody>
</table>

3. CALIBRATING A PROBABILISTIC CODE TO A TARGET RELIABILITY INDEX

3.1. Overview of the implicit reliability indices in the PBAB 1987

Ten design cases were analyzed and the average reliability indices for each one are presented in Table
7. Also a “most-likely” reliability index is shown for each case, chosen on the basis of the most-likely coefficient of variation for each variable and most-likely α factor (as described in Table 7). Within the cases for each type of analysis (bending, axial compression, shear) the reliability index increases as the role of reinforcement increases (due to the lower CoV of reinforcement properties).

<table>
<thead>
<tr>
<th>Table 7. Average reliability indices for reinforced concrete structures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

<sup>a</sup> Most-likely β  
<sup>b</sup> α=0.3, CoV: 0.2, M<sub>s</sub>, M<sub>f</sub>, 0.1, 0.1, 0.5  
<sup>c</sup> α=0.5, CoV: 0.15, 0.05, 0.1, 0.1, 0.5  
<sup>d</sup> α=0.5, CoV: 0.2, 0.2, 0.1, 0.1, M<sub>s</sub>, M<sub>f</sub>, 0.5  
<sup>e</sup> α=0.5, CoV: 0.15, 0.05, 0.1, 0.1, M<sub>s</sub>, M<sub>f</sub>, 0.5  

The overall average reliability index is 4.83 while the value range is 2.27 - 6.17. It can be concluded that when designing reinforced concrete structures according to (PBAB, 1987) a higher reliability index is to be expected compared to the target reliability index of 3.8 used to calibrate (EN 1992, 2004). This is not valid for the design case of shear with τ<sub>r</sub>,τ<sub>τ</sub> (S1). This case requires correction of the design process since the obtained reliability index can be dangerously low. Also, it should be noted that in this study only member cross-sections are analyzed.

3.2. CodeCal software

Calibration of the partial safety factors is performed using the software CodeCal (Faber et al., 2003). CodeCal is specifically designed for the calibration of design codes according to (JCSS, 2001).

In this study calibration of partial safety factors to a target reliability index is performed for a design case consisting of permanent and one variable load as well as two material resistance variables.

The design equation is:

\[ z = \frac{\gamma_m}{\gamma_K} \cdot \gamma_G \cdot G_R + 1 - \frac{\gamma_Q \cdot Q_R}{\gamma_K} \]  \hspace{1cm} (15)

where \( z \) is the design variable, \( \gamma_m \) the partial safety factor for material resistance (i.e. \( \gamma_c \) concrete; \( \gamma_s \) – reinforcement), \( G_R \) the characteristic value of resistance variable, \( \alpha \) the coefficient representing permanent to variable load ratio, \( \gamma_Q \) the partial safety factor for permanent load, \( G_Q \) the characteristic value of permanent load, \( \gamma_f \) the partial safety factor for variable load and \( Q_L \) the characteristic value of variable load.

3.3. Calibration results and discussion

Code calibration is performed for a target reliability index of \( \beta_{\text{target}} = 4.8 \). Calibration is performed for two scenarios. In scenario 1 all of the partial safety factors are calibrated and in scenario 2 only factors \( \gamma_m \) and \( \gamma_Q \) (material resistance and variable load safety factors) while the permanent load safety factor is kept constant at \( \gamma_G = 1.35 \).

Calibration is performed for 32 combinations of material and load CoVs. The combinations are derived from two cases – bending and compression.

When analyzing bending, reinforcement is given a weight coefficient of 0.9 while concrete is given a weight coefficient of 0.1. In compression the situation is reversed and concrete is given a weight coefficient of 0.9 and reinforcing steel 0.1.

Shear isn’t analyzed because currently (PBAB, 1987) prescribes the use of a different material resistance variable for concrete shear strength (defined through a reduction of the uniaxial tensile strength) and not the concrete compressive strength.

In order to be able to apply the obtained partial safety factors to shear, it is necessary to formulate the shear strength as a function of the concrete compressive strength. This can be done via clause 51 of (PBAB, 1987) that defines the mean uniaxial tensile strength as:

\[ f_{\text{bzm}} = 0.25 \cdot M B^2 \tau \]  \hspace{1cm} (16)

This value should be viewed as being too conservative since a mean value of a material property is empirically defined by a characteristic value of another material property. The shear strength design value can then be formulated as:

\[ \tau_T = f_{\text{bzm}} 2.2 = 0.114 \cdot M B^2 \tau \]  \hspace{1cm} (17)
In this way, the obtained results are also applicable to shear.

The results of the code calibration are presented in Table 8.

### Table 8. Calibration of partial safety factors to \( \beta_{\text{target}}=4.8 \)

<table>
<thead>
<tr>
<th>1</th>
<th>Calibration of all partial safety factors</th>
<th>( \gamma_a )</th>
<th>( \gamma_b )</th>
<th>( \gamma_c )</th>
<th>( \gamma_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.62</td>
<td>1.33</td>
<td>1.29</td>
<td>1.67</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>2.31</td>
<td>1.33</td>
<td>1.29</td>
<td>1.77</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2</th>
<th>Keeping ( \gamma_c=1.35 )</th>
<th>( \gamma_a )</th>
<th>( \gamma_b )</th>
<th>( \gamma_c )</th>
<th>( \gamma_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.54</td>
<td>1.26</td>
<td>1.35</td>
<td>1.77</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>2.20</td>
<td>1.26</td>
<td>1.35</td>
<td>1.77</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3</th>
<th>EN 1992</th>
<th>( \gamma_a )</th>
<th>( \gamma_b )</th>
<th>( \gamma_c )</th>
<th>( \gamma_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.50</td>
<td>1.15</td>
<td>1.35</td>
<td>1.50</td>
<td></td>
</tr>
</tbody>
</table>

In comparison with (EN 1992, 2004) the calibrated safety factors are, as expected higher than in (EN 1992, 2004). As commented in (Jacobs, 2008) the calibration of Eurocode 2 yielded \( \gamma_i=1.30 \). This safety factor was multiplied by 1.15 in order to account for the uncertainty arising from the fact that concrete is tested on concrete from test specimens and not directly on the structure. The code (PBAB, 1987) already prescribes a reduction of the compressive strength by 0.7. If this factor were applied directly on the characteristic value (by increasing the partial safety factor), 0.7 could be eliminated from the design equations. In this way the partial safety factor for concrete would be \( \gamma_i=1.62/0.7=2.31 \) and \( \gamma_c=1.54/0.7=2.20 \) (for calibration scenarios 1 and 2, respectively).

Further harmonization is possible with (EN 1992, 2004) so that a better comparison can be made. The current code (PBAB, 1987) defines the characteristic value of the concrete compressive strength as a 10-percentile obtained on 20x20x20cm cubic samples whereas Eurocode 2 defines this characteristic value as a 5-percentile obtained on Ø15x30cm cylindrical samples. If the concrete grade is to be converted to a 5-percentile value and a Ø15x30cm cylindrical sample it should be multiplied by 0.84-0.93 for the percentile difference (for a Log-normal distribution and CoV0.15 and 0.25) and by 1/1.2 for the sample size difference (PBAB, 1987) which means a new \( MB^{10}=0.9\cdot MB/1.2=0.75\cdot MB \).

### Table 9. Partial safety factors for MB defined as in (EN 1992, 2004)

<table>
<thead>
<tr>
<th>1</th>
<th>Calibration of all partial safety factors</th>
<th>( \gamma_a )</th>
<th>( \gamma_b )</th>
<th>( \gamma_c )</th>
<th>( \gamma_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.22</td>
<td>1.33</td>
<td>1.29</td>
<td>1.67</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>1.74</td>
<td>1.33</td>
<td>1.29</td>
<td>1.67</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2</th>
<th>Keeping ( \gamma_c=1.35 )</th>
<th>( \gamma_a )</th>
<th>( \gamma_b )</th>
<th>( \gamma_c )</th>
<th>( \gamma_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.16</td>
<td>1.26</td>
<td>1.35</td>
<td>1.77</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>1.66</td>
<td>1.26</td>
<td>1.35</td>
<td>1.77</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3</th>
<th>EN 1992</th>
<th>( \gamma_a )</th>
<th>( \gamma_b )</th>
<th>( \gamma_c )</th>
<th>( \gamma_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.50</td>
<td>1.15</td>
<td>1.35</td>
<td>1.50</td>
<td></td>
</tr>
</tbody>
</table>

a – without compressive strength reduction
b – with compressive strength reduction

In this way the partial safety factors for concrete can be computed as \( \gamma_c^{1,EN}=0.75\cdot1.62=1.22 \) and \( \gamma_c^{2,KN}=0.75\cdot1.54=1.16 \). The aforementioned factor of 0.7 can now be applied to calculate the final value of partial safety factors that are compatible with concrete grade as defined in (EN 1992, 2004), Table 9.

### 4. CONCLUSIONS

In this paper, a study of limited scope into the implicit reliability of current Serbian design codes is presented. From the analyses and calculations carried out the following conclusions can be drawn:

- The current Serbian reinforced concrete structures design code is, in most cases, too conservative. This is evident in the achieved reliability indices. The average reliability index for bending, compression and shear is higher than the target reliability index of 3.80 for (EN 1992, 2004).
- The exception to these findings is a design case which has a dangerously low reliability index: shear with the nominal shear stress lower than the shear strength (no transverse reinforcement required). The average achieved reliability index is 2.27.
- In the current Serbian design code for reinforced concrete structures (PBAB, 1987) the use of safety factors for loads is unnecessarily complicated. Their values are tied to reinforcement strain and dependent on the types of load acting on the structure. This is a complicated approach prone to errors in engineering practice.
- It is possible to calibrate a semi-probabilistic code to target reliability indices implicit in the current code. Partial safety factors are calibrated either for direct use with (PBAB, 1987) or for use with material properties harmonized with (EN 1992, 2004).
- The calibrated partial safety factors are higher than those in the (EN 1992, 2004), as is expected due to the higher target reliability index.
- The use of the partial safety factors obtained in this study can facilitate Serbia’s transition to the Eurocodes for practicing engineers and designers.

### REFERENCES

REZIME

TRENUTNI SRPSKI PROPISI ZA PRORAČUN - PRELAZAK SA DETERMINISTIČKOG NA POLU-PROBABILISTIČKI PRISTUP

Srpski propis za proračun armiranobetonskih konstrukcija je relativno zastareo u svojim pristupima. U ovom radu sprovedena je analiza mogućnosti prelaska na polu-probabilistički pristup definišući i parcijalne faktore sigurnosti i na strani nosivosti. Prvo su određeni indeksi sigurnosti, implicitno sadržani u važećem propisu, za tri proračunske situacije – savijanje, centrični pritisak i smicanje i za nekoliko slučajeva u okviru svake situacije. Izračunati indeksi sigurnosti pokazuju da je važeći srpski propis konzervativniji od Evrokoda 2 osim proračunske situacije smicanja bez armature koji ima izuzetno nizak indeks sigurnosti (2.27). U drugom delu je primenjen postupak kalibracije radi dobijanja parcijalnih koeficijenata sigurnosti za ciljani indeks sigurnosti od 4.8 (dobijen kao srednja vrednost implicitnih indeksa sigurnosti). Rezultujući parcijalni koeficijenti sigurnosti su, očekivano, veći nego oni u Evrokodu 2, a moguća je njihova direktna upotreba uz važeći srpski propis.

Ključne reči: propisi za proračun, armirani beton, indeks sigurnosti, kalibracija propisa
Optimization of Membrane Structures through Incremental Application of Snow Loads

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DRAGAN S. KOSTIĆ, University of Niš,
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Faculty of Civil Engineering and Architecture, Niš

Membrane structures are one of the most attractive structural systems used today. They are characterized by their double curved form, large spans and extremely low self-weight. Besides these favorable properties, they also have certain imperfections. Their thermal properties need to be significantly improved. Large deflections that occur under external loading are much higher in comparison with other structures and structural materials. However, these large deflections allow for the possibility of optimizing the membrane structures through the method of applying the loads during calculation. This paper presents a research done on this topic. The research is done as a numerical experiment on one structure, loaded with four different calculation snow loads. The methods for applying the calculation snow loads that are currently used are analyzed, and a new method of applying calculation load step-by-step is proposed. Parametric analysis and comparison of results showed that a certain level of optimization can be achieved. The directions of further research that would provide higher levels of optimization are also discussed.

Key words: membrane structures, optimization, snow load, numerical model, incremental method

1. INTRODUCTION

Membrane structures are very popular globally since their emergence in the mid-twentieth century. They achieved their popularity primarily due to their esthetics, whose main characteristics are the unusual form, minimalism and white color. Practical implementation of membrane structures in our country has started fairly recently. There are now several structures constructed in this structural system, and a few more significant structures are planned to be covered by membranes [1]. The situation in the region is similar as in Serbia; there are only a few constructed membrane structures. It is evident that there is a lot of unexploited potential for application of this contemporary structural system in our country. At present, professional contribution to the development of membranes in our country comes primarily from the theoretical field; therefore, a more comprehensive promotion and construction of new membrane structures is certainly necessary.

Considering that this structural system is relatively new, it has not yet been completely researched. The areas being actively researched are: making of a spatial curved structure from planar sections [2-4], thermal properties of membrane structures [5,6] as their main deficiency at the moment, and optimization of membrane calculation [7-9] as a complex mathematical problem.

The form of the membranes was most thoroughly researched as their primary characteristic [10-13]. In order for the membrane to be stable, it is necessary for it to have a double curved form with a negative Gaussian curvature. In addition, it has to be constantly under tension, even during the most unfavorable loads. The cause for these special stability requirements is their low stiffness.

Similar to the case of cable networks which are not stabilized with additional elements, membranes have a negligible compressive and bending strength [14]. Due to their low thickness of around 1 mm, and a span of...
several tens of meters, membranes are considered spatial-surface elements. Because of low thickness, their self-weight is extremely low, around 1 kg/m².

Two materials most often used for building membranes are the so called PVC and PTFE materials [15]. The former has a carrier polyester core with a protective layer on both sides made of PVC (polyvinyl chloride), and the latter a carrier fiber-glass core with protective PTFE (polytetrafluoroethylene) layers. Their characteristics differ, but they function in similar ways. These materials undergo elasto-plastic strain under tension, which leads to large deformations of membrane structures under external loads [16]. Maximum deflections of membrane structures are not precisely defined by the standards, but in practice, deflections of even 1/10 of the span are acceptable, which are unacceptable for classical structures. Since there is no strict limit for maximum deformation, contact between the membrane and other structural elements as a result of such deflections needs to be prevented [17]. The relationship between the strain and load intensity is nonlinear.

Figure 1 – Membrane structure “SkySong”

Membrane structures are still relatively expensive, since they in most cases only cover an area, and do not enclose it completely. Even though they are less costly than the structures made using traditional building materials (concrete, timber, steel), their service life is shorter as well, amounting to 10-30 years. The cost of membranes corresponds to their image of being used for prestigious structures, most often, public ones. They are most widely used within sports events structures, such as stadiums, halls, swimming pools and Formula 1 tracks, but also on the structures where an impression of exclusiveness is desired, such as shopping malls, hotels, research centers and structures for special purpose. The total price of membrane structures depends on several factors. Most of the budget is spent on manufacturing the membrane material itself, transport, support structure (most frequently a steel one), design costs and assembly. With respect to the external calculation loads, the calculation specifies maximum forces acting upon the membrane, and based on this, the type of membrane material required for the specific structure is selected. The type of the membrane material is determined according to the tensile strength [18].

The anticipated external load is therefore important for specifying the cost of the membrane structure as it directly affects the selection of the membrane material type. It would be desirable that the external load is low, because then a lower strength membrane material could be used, which is also a cheaper solution. The external loads are however strictly defined by the standards so it is not allowed to reduce the intensity of external design load. This paper presents a part of the research which revealed that it is possible to reduce stress in a membrane by using the method of incremental applying of the snow load, and consequently to reduce the cost of the entire structure.

2. METHODOLOGY

The basic idea motivating this research is to convert one of the deficiencies of membrane structures into an advantage. High strain occurring in membranes under external loads is of a much higher intensity than in other structural systems, which may significantly change the form of the structure itself. The research indicated that this change of form can lead to optimization of the membrane when applying the snow load.

The loads acting on membrane structures do not differ from those acting on other types of structures. Two most important external loads are caused by snow and wind. Which of these two loads will be critical depends on the location of the structure, i.e. climate conditions characteristic for the location. Seismic actions do not have significant effects on membrane structures because of their low weight, so they are most often ignored. Temperature differences and variations are also ignored, since membranes present almost no barrier to the transfer of heat. Point loads are significant and ought to be taken into consideration in calculation. Membranes are particularly sensitive to puncturing, so care should be taken to prevent it. In addition to external loads, internal tension loads introduced through prestressing are also present.

The national code [19], as well as the European codes [20], define, depending on various factors, which calculation load should be used for structures. For snow load, one of the most important factors is the pitch of the roof plane. In the national code, for the pitch exceeding 60° there is no load application, while for the roof pitch lower than 20° the load is 0,75 kN/m², and in between, the load intensity increases for 0,05 kN/m² at each 5°. In the European codes, the roof pitch
is defined in similar terms, except that for the pitch lower than 30° the designed load intensity is 0,8 kN/m², for the pitch higher than 60° there is no load, and between 30 and 60° the values decrease in a linear fashion. The aim of this research is to show that calculation snow load can be reduced since membranes undergo considerable deflection under external load, i.e. increase the roof plane pitch. The same effect is present in all other structures, but it is so small that it is ignored.

Figure 2 – Appearance and layout of the structure, divided into finite elements

In order to examine to what extent the mentioned effect is important for calculation of the membranes, the research is continued by experimenting on the models. The numerical experiment method was used. Four numerical models were made, which were completely identical in terms of structure, but loaded with different calculation models of snow load. The model structure is conical, which along with the form of hyperbolical paraboloid is one of the most frequently used for construction of membranes. The layout is circular, having a 14 m diameter, with fixed supports. The central opening has a 3 m diameter, located at the height of 4 m in relation to lower supports, and it is also fixed.

Modeling and calculation were performed on Sofistik 2012 software, employing Finite Elements Method. Geometrically nonlinear analysis was used. The warp direction of the structure was set radially, while the weft direction was set tangentially. For formfinding, prestressing forces in both main directions were applied, whereby the force of the warp was twice as high as that of the weft. As it is usual for such membrane forms, the forces were not constant, but lower in the lower part of the structure. Thus, prestressing forces of the warp ranged between 3 to 6,5 kN/m, and in the weft from 1,5 to 3,25 kN/m. PVC membrane 1 mm thick was used. The modulus of elasticity in both directions was 600 N/mm². The shear modulus was 30 N/mm². The Poisson coefficient was 0,4 in both directions.

Model 1 was loaded with 0,8 kN/m², across its entire surface area. This is the most common case in practice, because it is the simplest way of applying the load, and it is also favoring safety, since the roof pitch is not taken into account. Model 2 was loaded with 0,8 kN/m², not across the entire surface but only up to the 45° pitch. Such case is also common in practice, because by loading one part of the structure more than foreseen by the standards, and by not loading the central part, the total load is approximately equalized, as if the roof plane pitch was not taken into consideration. The advantage of such approach is that there is no need to measure the pitch of every section of the membrane, yet it takes the pitch into consideration, to a certain extent. Model 3 was loaded in strict adherence with the standards. The pitch of every finite element of the structure was measured, and the appropriate intensity load was applied in accordance with it. Model 4 was loaded using the method which, according to the knowledge available to the authors of the paper, had not been used in practice up to now. The load was applied in increments of 0,1 kN/m². After each step, the pitch of all finite elements was measured, and if it was necessary to add a load lower than 0,1 kN/m², then this exact value was added, and if it was needed to add a load higher than 0,1 kN/m², then 0,1 kN/m² was added. The procedure was repeated until the entire structure was loaded with appropriate load. Applying the load in increments is not a novelty per se, but the control of roof pitch at every step is. In case of a structure which has small deformations, the difference between Model 3 and Model 4 would not exist, or it would be negligibly small. Exactly for this reason such method of application of calculation load was not researched or implemented up to date.

Figure 3 – Loading of four models
3. RESULTS AND DISCUSSION

Five key parameters were analyzed for all four models. These parameters are:
1. Total applied load
2. Maximum deflection
3. Maximum tension force in warp
4. Maximum tension force in weft
5. Maximum force in the support

Total applied load is one of the input parameters, and all the other parameters partially depend on it. Maximum deflection is one of the parameters monitored in each calculation of membrane structures. Maximum forces in warp and weft determine which type of membrane material will be used. When designing the membrane structures, the permissible stress method was used, so these forces are multiplied with certain safety coefficients, and on that basis the necessary tensile stress of the membrane was determined. The maximum force in the supports determines the dimension of the support structure, so it is desirable that it be the lowest possible. The results for each of the models, according to the mentioned parameters are given in the diagrams.

![Figure 4 - Parameter of the total load of the models](image1)

![Figure 5 - Parameter of the maximum deflection of the models](image2)

![Figure 6 - Parameter of the maximum force in warp](image3)

![Figure 7 - Parameter of the maximum force in weft](image4)

![Figure 8 - Parameter of the maximum force in supports](image5)

It is obvious that according to any of these four parameters, Model 4 has the lowest values. Model 1 and Model 2, even though most frequently implemented in practice, can be characterized as uneconomical. Their advantage is reflected in the fact that the design load is applied in a simplest way. The process of load application for Model 3 lasts slightly longer, but such an approach is more rational, and in strict adherence to the appropriate standards. Model 4 implements an innovative approach to load application, which is most time consuming, but obviously provides the best results. Also, it is more realistic. To illustrate the
improvement achieved using this procedure, Model 4 was compared with Model 3. The results are provided in Figure 10 showing percents by which Model 4 is better.

Figure 9 – Strain of the membrane structure under the action of external load

Figure 10 – Optimization achieved for Model 4 in comparison to Model 3, in percents

According to the monitored parameters and the proposed method of structure loading, an optimization in the range 2-7% was achieved, in comparison to the best existing loading model. Optimization of 7% was achieved in the total load, which is not one of the structural parameters, so it has the least importance. Maximum deflection is one of significant parameters, because it is important to control maximum deflections for each individual structure which will be constructed. The maximum forces in the membrane in warp and weft have a direct influence on which type of membrane material will be used for the specific structure. Based on the obtained values, the membrane type to be used is determined. There are five types of membranes which differ according to their tensile strength, thickness and weight, whereby type 1 is the thinnest and has the least tensile strength. The characteristics of five types of PVC membranes are displayed in Table 1. The membrane type directly determines the cost of the entire structure which leads to a clear conclusion that it is desirable to make the membrane forces as low as possible. If optimization allows for the usage of a lower membrane type, financial saving can be considerable.

Reduction of maximum force in the support for Model 4 will mean reduction of support structure dimensions, which in turn results in the total cost reduction. The last three parameters, therefore, have a direct impact on the cost of the material selected for construction of the structure. Optimization achieved by the proposed load method using these three parameters, in comparison to the currently existing best loading method is between 2 and 3%.

The obtained optimization percentage is certainly not negligible, especially from an investor’s perspective. The effect of this optimization on the total cost is not identical, when percentage is considered, but it is certain that some savings will appear in the total cost of the structure as well, when the proposed loading method is applied during design.

The presented results represent the case study of a characteristic membrane structure. The next step in this research will be an analysis of several different models of structures. Firstly, the saddle form membrane structures will be dealt with, and afterwards the more complex forms occurring in practice. Simultaneously, one should examine how the value of the increments affects the final degree of optimization. It is logical to expect that smaller increments would bring about a higher degree of optimization. Also, the structures with
a higher curvature will, in all probability, yield better results for the proposed loading method, due to the higher pitch of the plane. Another factor affecting the final results is the size of finite elements, so it should be further researched. Eventually, one should devise a way for speeding up the application of loads according to the proposed procedure, because it can take considerable time unless economically conceived.

4. CONCLUSION

This paper researched the potential of optimization of membrane structures through the change of the method of application of calculation snow load. Such optimization results in the reduction of the total cost of the structure. The research results indicated that it was possible to achieve a certain degree of optimization. The research was conducted on the models of the same structure which were loaded in different ways. A new loading method was proposed, which comprises loading in increments and not all at the same time. In this way, large deflections occurring in membranes under external loads in actual situations are taken into consideration. The total load, maximum deflection and maximum forces in the membrane and supports parameters were analyzed. An optimization of 2-3% of the parameters used for design of membrane and support structure was achieved for the analyzed structure, by applying the proposed loading method. A further research will be directed towards an analysis of other forms of structures, and of factors which could have an impact on the additional increase of membrane optimization. Also a method for speeding up of load application in steps will be researched, because it is very time consuming at the moment. The proposed method of membrane optimization is undemanding and does not require additional software for designing, so it could very quickly be practically implemented.

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REZIME

OPTIMIZACIJA MEMBRANSKIH KONSTRUKCIJA INKREMENTALNIM NANOŠENJEM PRORAČUNSKOG OPTEREĆENJA SNEGOM

Membranske konstrukcije su jedan od najatraktivnijih konstruktivnih sistema koji se danas koristi. Njih karakteriše dvostruko zakrivljena forma, veliki rasponi i izuzetno mala sopstvena težina. Osim ovih pozitivnih karakteristika, one imaju i neke nesavršenosti. Pre svega, njihova termička svojstva treba da budu značajno unapređena. Zatim, ugibi koji se javljaju pod spoljašnjim opterećenjima su veliki u poređenju sa drugim konstrukcijama i konstruktivnim materijalima. Međutim, upravo zbog velikih ugiba otvara se mogućnost za optimizaciju membranskih konstrukcija kroz način nanošenja proračunskog opterećenja. U radu je prikazano istraživanje koje se bavi upravo ovom temom. Ispitivanje je izvršeno kao numerički eksperiment na jednoj konstrukciji, sa četiri različita proračunskih modela opterećenja snegom. Analizirani su načini opterećenja koji se trenutno primenjuju i predložen je novi metod opterećivanja u koracima. Parametarskom analizom i komparacijom rezultata utvrđeno je da je moguće postići određeni stepen optimizacije. Diskutovano je i u kom smeru treba nastaviti istraživanja da bi se postigla veća optimizacija.

Ključne reči: membranske konstrukcije, optimizacija, opterećenje snegom, numerički model
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Operational Mine Planning and Coal Quality Control: Case study Tamnava West

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In contemporary mining industry is very difficult to achieve production targets and profit without investing effort in detailed excavation planning. It is especially true for deposits with complex geological structure and production technology, as is the case for many coal mines in Serbia. The majority of coal production is used for generation of electricity in power plant. This fact is the main reason why production objectives of coal mine and power plant are strongly connected. Due to the variability of the coal quality, operational mine planning (as a part of coal homogenization process), is of critical importance for managing successful coal quality control and meeting criteria of power plant.

This paper presents model for operational planning and coal quality control process, and investigates its impact on overall production performance. In order to evaluate proposed approach, a case study is conducted on open pit Tamnava West field. Successful operational mine planning is almost impossible without use of highly specialized software packages. For that reason in presented case study operational mine planning is done using Minex and SUKU software packages.

Key words: operational planning, geological modeling, quality control, mining block and cut, stockyard.

1. INTRODUCTION

Modern mining is characterized by continuous worsening of production conditions. This is particularly evident when considering the fact that the deposits on which exploitation is carried out are often, small in size, with poor quality, with complex structure and geometry, often in locations that have unfavorable infrastructure, or in regions with significant political instability.

In the vast majority, mining projects, that guarantee the realization of profits, are a thing of the past. Successful business in conditions of limited resources is impossible without analysis of the technical and economic parameters and detailed planning of all possible scenarios of production.

Due to availability of the coal resources and their price stability, coal is and will retain its important role in power production in Europe and worldwide [1]. In Serbia, coal is the most important fuel in the production of electricity, accounting for 65% of the power production [2].

This fact is the main reason why production objectives of coal mine and power plant are strongly connected. A power plant owner is interested to know in advance the quality of coal to be burnt, which should meet maximal efficiency of power plant and the environmental regulations. The coal quality control between the mine site and the utility plant is a complex problem owing to the variable nature of coal properties (heating value, sulfur, ash) even within the same coal seam. In order to ensure a normal and efficient operation of the power plants fed with coal it is necessary to reduce the variation of the coal. This reduction is achieved through coal homogenization
process. More about homogenization process can be found in the work of many authors [3, 4, 5, 6].

Coal homogenization can be conducted at two places: at the mine site and at the stockyards [2]. Homogenization of coal in mine site can be achieved at:

- mining block (production of one excavator on one bench),
- The connecting conveyors (production of all excavators on different benches).

At the stockyards coal homogenization is usually done by mixing of coals with different quality.

For the management of the coal homogenization process at the mining block level or on stockyard is especially important to have enough in situ data, and to conduct quality operational planning. The importance of operational planning for coal quality control is stressed by Stevanović et al. [7].

2. OPERATIONAL PLANNING AND COAL QUALITY CONTROL MODE DEVELOPMENT

Successful operational mine planning is almost impossible without use of modern software packages [8]. In presented case study operational mine planning is done with Minex and SUKU software packages.

Minex is the recognized as one of world leading software for integrated geology and mine planning solutions. It is comprehensive tool specialized for coal and other stratified deposits.

Minex covers almost every part of geological modeling and mine planning process and it provides a fast and powerful set of modules for surface and underground mines. In this study all geological modeling and design of benches are done in Minex software.

SUKU is custom made software package developed at University of Belgrade - Faculty for Mining and Geology. Through its integrated modules SUKU combines geological, technological and operational constrains and it is specialized for operational mine planning and coal quality control management in a coal mines with continuous technology.

Development of technological model and operational planning presented in this paper are done by SUKU.

Model development for operational planning and coal quality control for the Tamnava West open pit consists of 4 steps (Figure 1):

- Geological database and modeling,
- Development of technological model,
- Operational planning for coal quality control in mine site,
- Operational planning for coal quality control in stockyard.

Figure 1 - Model of operational mine planning and coal quality control

3. CASE STUDY

The case study is conducted on open pit Tamnava West field. Tamnava West is a part of Kolubara coal basin, and it operates under governance of Electric Power Industry of Serbia (EPS). Currently, Tamnava West is a biggest surface coal mine in Serbia, with capacity of 13 million tons of coal per year. The excavation technology of Tamnava West is based on continuous mining equipment. Coal and interburden is excavated with 4 Bucket wheel Excavator-Conveyors-Crushing Plant systems (ECC), and 2 Bucketwheel Excavator-Conveyors-Spreader systems (ECS) that are engaged on overburden excavation. General technological scheme of open pit Tamnava West is presented on Figure 2.
3.1. Geological database and modeling

In order to prepare and import data to Minex, the data sets had to be transformed in several steps. Borehole data where obtained from BpUBS (Integral database of Serbian Coal Basins). This database stores all exploration drilling data from Kolubara Coal Basin, such as: basic information about drill hole (collar data), complete lithology and assaying data, geotechnical, hydrogeological, and geophysical data. This system can perform export of data to the different formats for use in mining and geological software like Minex.

Nevertheless, it was necessary to clean, integrate and do numerous levels of logical control and verification over this set of data before import into the Minex database:

- Checking of all 213 drill holes logs,
- Checking of all lithological intervals (11298 records), followed by lithological and ply/rock parting coding,
- Checking sample intervals, individual ply analysis and composite assays (5109 records, average sample length is 0.8m),
- Checking drill hole collar coordinates to eliminate any obvious errors in location.

In this study is analyzed only portion of Tamnava West mine since it has sufficient geological exploration data, necessary for production planning and operational management of coal quality in next 5 years, Figure 3.

Drill holes that had less than 86% recovery through any coal seam, were discounted and not included for coal modeling. The 11298 lithological records where coded based on Minex lithology code, followed by code. The minimum mineable thickness thresholds have been set at 0.5 meters for coal seams and rock partings within coal seam as well. Total of 5109 drill hole samples are taken from the 185 drill holes, 4045 coal samples and 1064 rock partings samples (dominantly clay). Coal sample analysis was conducted for Moisture, Ash, Lower Calorific Value (LCV) and Upper Calorific Value. After preliminary statistical analyses the 367 sample where rejected based on correlation between Ash and LCV (Figure 4).
In next stage geological model was developed using the Minex software package. Structural model, is based on the "Splitting" and "Father and Son" technique with the grid mesh size of 25 m by 25 m, scan distance was 35,000 m for General Purpose interpolation, and also for Inverse Distance, with power of 2. A total of 25 coal sub-seam plies, 46 partings (14 sandstone and 32 clay), clay basement, interburden sandstone and overburden river sediments have been modeled within a stratigraphic section up to 98 m thickness.

The Tamnava West deposit consists of one seam that is divided in two correlated seam plies with interburden sandstone. These two seam plies are divided into lower and upper units by clay and sandstone partings (maximum up to 9 sub-seam plies).

The individual plies maintain relatively constant thickness over the strike length, while most of the variation takes place in the inner rock parting material mainly clay (Figure 5).

3.2. Technological model development

Case study, is based on already existing long term production planning. In this regard, pit limits, geometry of benches or technology, was not a part of interest for this research.

Design of pit benches is one of the most important and critical phases in mine planning of pit production. It’s a part of long term planning, and if done inappropriately can have significant impact on overall pit performance. This is especially true for continuous mining technology where pit benches are usually irregular surfaces (not horizontal planes). Many factors have influence on design of pit benches and main are:

- capacity requirements
- geotechnical conditions
equipment limitations and
coal quality control.

All these factors were analyzed for bench design in case of Tamnava West. Special attention was paid to the aspect of selective excavation. In this way the first step of quality control is performed. Bench surfaces designed in this manner allow less dilution effects and greater recovery of reserves. For the case of Tamnava West minimal minable thickens of coal seam was set to 0.5 m.

The final design of benches is done in Minex. Although Minex has module for bench design, due to complex nature of bench geometry for Tamnava West, final bench design is done semi automatically. 3D model of benches is created in the form of grid, and as such is suitable for integration with created geological grid model as well as with technological and operational constrains. This integration is performed in SUKU software package. In the first phase, Minex geological model and designed benches were exported in CSV (comma separated value) file format, suitable for import to SUKU.

In order to make operational planning of coal production and management of coal quality control, it is necessary to know what each excavator at a certain moment is excavating. The main precondition for planning on this level is discretization of each coal bench on mining blocks.

Bench discretization to mining block level is performed in two steps:

- Bench area is divided in the direction of operations advancing, on the parts that correspond to the width of the mining blocks (strips). This width is the same for each coal bench and depends on the characteristics of bucket wheel excavator (BWE) engaged on that bench (it matches the actual width of the block which is excavated by particular excavator).
- Bench area is divided parallel to the direction of excavation advancing. This division simulates the advancing of each excavator in the mining block, i.e. mining block length. Block length is the unique value of each bench and is related to technological capabilities of engaged excavator on the specific bench.

Figure 6 presents general principle of discretization to mining block level for portion of coal field, at which the case study is conducted.

In this way, geometric framework necessary for the consideration of the qualitative characteristics and production planning for the mining blocks, is formed. In the next step it is necessary to join the geological characteristics with the geometric framework produced in previous step, and calculate reserves for each coal bench and each mining block.

Discretization on the mining blocks for one excavator strip is shown on Figure 6. For operational planning, this representation of mining blocks (arranged in one excavator pass) is very important because it provides the efficient way of operational planning for each BWE in advance.

Single mining block is shown on Figure 7, since geometry of a mining block is connected with geological model it is possible to calculate the reserves of coal and waste, as well as the quality achieved by excavating the each block on each bench.

For all four designed coal benches, of open pit Tamnava West, the same process is performed. During the discretization, technological features of the equipment engaged on each bench were considered. For this purpose SUKU has a module that implements all technical characteristics and technological constrains for each equipment included in coal excavation system. That means that data for all bucket wheel excavators, conveyors, and stockyard reclaimers on open pit, in this case for Tamnava–West were supplied.

SUKU representation of mining block, with geological characteristics is shown on figure 7. Representation includes all lithological seems and it’s colored according to LCV for each seam.
Discretization of geological model on mining blocks is suitable for both long and short range production planning, but it can’t provide answers regarding current excavation within simulation runs.

For that purpose, discretization of model needs to be further conducted, to the level of excavator’s cuts. The reason for this is excavation technology of bucket wheel excavator (BWE) which is based on individually excavation of one cut. In this sense every mining block is divided in several cuts, and BWE excavation is conducted from top cut Figure 8. Technology of BWE is very well explained by many authors[9, 10].

\[
LCV_{\text{low}} = \frac{LCV_1 \cdot h1 + LCV_2 \cdot h2 \cdot x}{h1 + h2 \cdot x}, \quad (\text{kJ/kg})
\]

LCV1 – lower calorific value of coal sub-seam 1
LCV2 – lower calorific value for clay sub-seam
h1 – height of coal sub-seam
h2 – height of clay sub-seam
x – part of clay sub-seam (%)

Capacity of BWE is usually greatly affected by excavation controlled by coal quality. For successful production plan both criteria (quality and capacity) must be met.

Using SUKU software, each mining block is divided in excavator (mining) cuts. With SUKU modules for simulation and reporting, it is possible to keep track of quantity (waste and coal) and quality (lower caloric value, moisture, sulfur content) on the level of excavator cut. Three variants of mining block divided in excavator’s cuts and reports based on that division is shown on Figure 9. Presented example refers on mining block shown on Figure 7.

As can be seen from Figure 7, selected mining block comprises from 16 seams of coal and waste. LCV significantly varies within sub-seams. All this suggest that selective excavation must be conducted in order to achieve desirable LCV within coal mining cuts. Mining block selected as example, is divided in 4 mining cuts (2 variants) and in the third variant, block is divided in 3 mining cuts (Figure 9). Choosing the best variant depends on many factors and the most
important are required coal quality and quantity, as well as excavation performance of other BWE’s engaged on coal excavation system.

By combining geological model with geometry of benches and cuts, technological model is developed. In SUKU discretization of mining blocks in to mining cuts, can be done automatically or manually. Automatic discretization is faster, but manually provides more control.

The best option is to perform automatic mode discretization, followed by optional manual fine tuning for selected blocks. In any case it’s clear that specialized software SUKU is very practical solution for the development of technological model.

Figure 9 - Mining block divided in excavators cuts (3 alternatives)

3.3. Operational planning for coal quality control on mine site

In order to define operational plan of excavation it is necessary to compute capacity of BWE during the analyzed period. The capacity depends largely on the technical characteristics of specific BWE and on defined geometry of bench and cuts. SUKU generated dataset with calculated capacity for set of mining blocs (and specific BWE) is shown on diagrams (Figure 10).

By discretization of specific numbers of mining blocks, on the same bench, into mining cuts and by calculating capacity of BWE engaged on excavation of that bench, operational plan for some period (shift, day, week, etc) can be defined. Operational plan for three of four BWE’s engaged on Tamnava West coal excavation system is presented on Figure 10. At the area selected for analysis fourth BWE (SRs 630) was engaged in excavation of interburden sandstone seam, and its production didn’t affect performance of coal production. For every excavator two diagrams are presented.

First diagram shows capacity for observed BWE (t/h) and on second diagram coal quality parameter (LCV, kJ/kg) are shown. The presentation of coal quality parameters is possible because geology and later technological model, was the basis for defining the operational plan.

The diagrams show great variability regarding excavators both capacity and quality (LCV) performance. This is expected if we take into account the complex structure of the coal seam in the mine as well as complex technological model that derives from it.
Figure 10 - Operational plan for three excavators

With bench conveyors excavated coal from each BWE is transported to the connecting conveyors. Simulation of coal production on connecting conveyors is shown on Figure 11. Coal on connecting conveyors represent aggregation of coal production of all active excavators.

For this reason variations in capacity and quality are much less.

Figure 11 - Coal production performance on connecting conveyors

3.4. Operational planning for coal quality control in stockyard

By bench and connecting conveyors system, excavated coal is transported to the stockyard. The characteristics of the incoming material flow on stockyard are in function of the geological conditions, bench and cuts design, technological constrains of equipment and developed operational plan for mine site. Bed blending on stockyards has two main objectives: buffering and homogenizing. Stockyard transforms the characteristics of the incoming material flow in an outgoing material flow, whose characteristics are defined by customer specifications.
Coal homogenization process is performed by stockpiling the run of mine (ROM) coal in layers, in their correct proportions, in the same stockpile, then reclaiming across the full face. In any blending pile the attenuation on variability depends on the equipment used and the way coal is stocked and reclaimed [11].

The main factors influencing blending efficiency are the pile size or its mass and the number of layers used to build pile. The aim in the homogenization process is to narrow down the standard deviation of the distribution. A measure of the quality of the homogenization process is defined by the homogenization efficiency (HE). In simplified terms, and subject to certain statistical assumptions, the resultant homogenizing effect is calculated as the variability of the incoming coal on pile (e. g. LCV) and the variability of the outgoing coal from pile [12]:

\[ HE = \frac{\sigma_{in}}{\sigma_{out}} \cong (0.5 \pm 0.7) \cdot \sqrt{n} \quad (2) \]

where \( n \) is the number of layers. By grouping exploitation mining blocks and forming a pile, the average grade of this pile is closer to the planned mean if compared to the grades of each individual block which comprise the pile. This phenomenon of variance reduction is well known and it is referred to as the volume-variance relationship [12, 13]. SUKU has incorporated module for the operational planning and quality control of delivered coal on stockyard. Thanks to integrated structure of SUKU it is possible to perform simulations of incoming and outgoing material flow on stockyard.

In this example incoming material flow on stockyard is presented on Figure 11, and simulation for outgoing material from stockyard is shown on Figure 12.

As can be seen on diagram of outgoing material, variability of LCV is further reduced relative to the incoming material from connecting conveyor. Moreover, outgoing coal from stockyard has LCV in range 6700 kJ/kg ± 5%.

![Simulation of outgoing material from stockyard](image)

Figure 12 - Simulation of outgoing material from stockyard

Analyzed stockyard is of type “strata” and the goal of delivering coal within specified range (6700 kJ/kg ± 5%) is achieved with 15 layers (Figure 13).

![SUKU visualization of stockyard section](image)

Figure 13 - SUKU visualization of stockyard section

4. CONCLUSION

In today mining industry is very difficult to achieve production targets and profit without giving special attention and effort in detailed mine planning. It is especially true for deposits with complex geological structure and production technology, as is the case of Tamnava-West coal mine. The coal quality control management is of vital importance for successful production since coal mine and power plant objectives are strongly connected.

Coal quality control is complex and comprehensive problem which depends of many factors and elements of production system:

- geological in situ data should be credible and with sufficient amount,
- geological model should provide realistic interpretation of real structural and qualitative characteristics of deposit
- long, short and operational planning should incorporate all production goals and constraints: capacity and quality requirements, geotechnical conditions, equipment limitations etc.
- discipline should be kept on high level thought every step of production process.

Operational mine planning is mandatory part of coal quality control management. Successful operational mine planning is almost impossible without use of modern software packages. Minex was the software tool used for geological modeling and bench design. For operational planning and coal quality control in mine site and on stockyard SUKU is used.

This paper presents approach for operational mine planning and coal quality control. Using SUKU specialized modules, simulation of whole coal production process is simulated. It’s important to emphasize change in variability of coal LCV during the entire flow of coal. For presented example and from generated diagrams it’s clear that the goal of delivering coal within specified range (6700 kJ/kg ± 5%) was not possible without stockyard.
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REZIME

OPERATIVNO PLANIRANJE RUDNIKA I KONTROLA KVALITETA UGLJA: PRIMER TAMNAVA ZAPADNO POLJE

U savremenoj rudarskoj industriji vrlo je teško postići ciljanu proizvodnju i profit bez ulaganja velikog napora u detaljno planiranje otkopavanja. To je naročito tačno za ležišta sa kompleksnom geološkom strukturom i tehnologijom proizvodnje, kao što je slučaj sa mnogim rudnicima uglja u Srbiji. Najveći deo proizvodnje uglja se koristi za dobijanje električne energije u termoelektranama. Ova činjenica je glavni razlog uske povezanosti ciljeva proizvodnje rudnika uglja i termoelektrane. Usled promenljivosti kvaliteta uglja, operativno planiranje kopa (kao deo procesa homogenizacije uglja), je od ključnog značaja za uspešno sprovođenje kontrole kvaliteta uglja i ispunjavanja kriterijuma termoelektrane.

U ovom radu predstavljen je model za operativno planiranje kopa (kao deo procesa homogenizacije uglja), kao i njegov uticaj na ukupne performanse proizvodnje. Za bolje razumevanje predstavljen je primer na površinskom koku Tamnava Zapadno polje. Uspešno operativno planiranje rudnika je skoro nemoguće bez upotrebe specijalizovanih softverskih paketa. Iz tog razloga je prikazani primer operativnog planiranja kao urađen korišćenjem programskih paketa Minex i SUKU.

Ključne reči: operativno planiranje, geološko modeliranje, kontrola kvaliteta uglja, bagerski blok i rez, deponija
The Application of Mathematical Transformation in Order to Define EDGES of Pluton Valja Strž

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The Timok Magmatic Complex (TMC) belongs to the East Serbian and is the largest volcanic area in our country. The largest pluton in this area is Valja Strž. This pluton is situated in the northwestern part of the complex. Applying different methods of mathematical transformation on aeromagnetic data facilitated outlining of pluton edges in subsurface of surrounding rocks. In this paper we used mathematical transformation on anomaly values of the magnetic field, obtained from processing of aeromagnetic data. In order to detect the edges of pluton Valja Strž we used following set of mathematical transformation: first vertical derivative, the total horizontal derivative, tilt derivative, upward continuation, and combination of upward continuation and tilt derivative. Results of application of mathematical transformation showed that outspread of the pluton Valja Strž in the subsurface is larger than it’s extend on the surface.

Key words: The pluton Valja Strž, aeromagnetic data, anomaly values of the magnetic field, mathematical transformation, edges

1. INTRODUCTION

Potential fields are physical (vector) fields; whose forces are challengers, gradients of their potentials, and like those fields, among others are gravity and magnetic fields [1]. These fields, as their potentials, are mathematically defined and they are in the appropriate relations. Mathematical transformation of potential fields implies the application of different procedures, and allows obtaining the data for better interpretation. Application of mathematical transformation allows retaining or enhancing spectral (frequency) components of the useful signal, and weakening components of interference. The transformations could not give new information, but could indicate certain characteristics of the fields such as compressing or completely excluding of the other, which were covered. Mathematical transformations could be applied to the measured or anomaly values.

In this paper we present the theoretical background of some techniques of mathematical transformations, as well as their practical application on anomaly values of magnetic field, obtained on the base of aeromagnetic measurements. Aeromagnetic data were obtained during the investigating in north part of Timok Magmatic Complex (TMC), the area which is mostly located north and northwest from Bor.

Anomalies of magnetic fields are subject to a mathematical transformation in order to obtain exact responses from the total signal respectively reduces unwanted responses. Using different methods of mathematical transformations on anomaly values of the total magnetic field in the horizontal plane we obtained the edges of the Valja Strž pluton, which cause magnetic anomalies. For defining the edges of pluton we used next mathematical transformation: first vertical derivative, total horizontal derivative, tilt derivative, upward continuation and combination upward continuation with tilt derivative.

2. THEORETICAL BACKGROUND OF MATHEMATICAL TRANSFORMATION

The first vertical derivative (VDR) represents a change of the total magnetic field (T) in the vertical direction (z) and can be expressed as:
\[ VDR = -\frac{\partial T}{\partial z} \] (1)

The first vertical derivative underlines shallower, near the surface, causes of anomalies. For first vertical derivative is characteristic that it is positive over the source, has zero over the edges and is negative outside of a vertical side source of anomalies [2, 3].

The total horizontal derivative (THDR) used for determination edges of shallower (near the surface) source of magnetic anomalies and can be defining as:

\[ \text{THDR} = \sqrt{ \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 } \] (2)

where

\( T \) – magnetic field,
\( \frac{\partial T}{\partial x}, \frac{\partial T}{\partial y} \) are first-order derivative of the total magnetic field (T) in x and y directions [4].

The total horizontal derivative has maximal value over the edges and zero is over the body which caused anomalies [2, 3, 5].

The tilt derivative (TDR) can be expressed as [2, 6]:

\[ \text{TDR} = 0 = \arctan \left( \frac{\frac{\partial T}{\partial x}}{\frac{\partial T}{\partial z}} \right) \] (3)

\[ \frac{\partial T}{\partial h} = \sqrt{ \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 } \] (4)

where

\( T \) - magnetic field, \( \frac{\partial T}{\partial x}, \frac{\partial T}{\partial y}, \frac{\partial T}{\partial z} \) are the fist-order derivatives of the magnetic field \( T \) in the x, y and z directions.

The TDR is positive when lying over the source structure, and negative outside the source region, where the vertical derivative is negative. The TDR passes through zero above or near the edge, i.e. where the vertical derivative is zero and the horizontal derivative is maximal [2, 7].

Unlike the already mentioned transformation (VDR, THDR), the technique tilt derivative (TDR) generally gives good results when defining the edges of the source of anomalies, both the smaller and at larger depths.

Also, this procedure enables determination of the presence of subtle deeper sources which are often covered in the large responses of shallower sources [2].

Upward continuation (UP) transforms the magnetic field measured on one surface to the field that would be measured on another surface father from all sources. The procedure upward continuation diminishes the effects of the anomalies of shorter wavelengths. The effect of upward continuation process on the fields can be understood by examining the continuation operator in wavenumber domain. The operator of upward continuation has a form [8, 9]:

\[ F = e^{-|k|z} \] (5)

where

\( |k| = 2\pi\lambda \) - is wavenumber,
\( \lambda \) - is full wavelength,
\( z \) - continuation level.

3. FIELD EXAMPLE

The Timok magmatic complex (TMC) belongs to the East Serbia and this complex represented one of the largest volcanic regions in Serbia. The volcanic activity developed in roughly three phases. The volcanism began in the Turonian and finished in lower Senonian [10]. In the final phase of volcanism is followed by intrusive phase, during which impression in plutonic rocks occurred, mostly diorite and monzoniite constitution [10]. In this area the largest plutonic intrusive is Valja Strž. This pluton located in the northwestern part of TMC (Figure 1), was discovered in an area of over 20 km² [10].

Figure 1 – Geological map of the study area with position of survey area

The Valja Strž pluton has irregular extended shape which direction is northwest-southeast. Length of
pluton is about 8.5 km, its maximum width in the northern part is about 3 km, while the southern part narrows [10]. The western margin of pluton Valja Strž is tectonic, and to the south is impressed on the Lower Cretaceous limestones and Upper Cretaceous sediments that metamorphoses at contact, where mostly introduced into Senonian volcanic rocks, which metamorphoses weak [10].

The aeromagnetic survey, north part of TMC was done in period March 24th to June 18th 2006 (source “Dundee Precious Metals Inc.”, now “Avala Resources Ltd.”). Total Magnetic Intensity (TMI) data were acquired from aeromagnetic measurements. This data require processing and preparation for work. The processing of magnetic data involved correction for diurnal variations, leveling, defining dimension of grid, decision on interpolation methods, calculated normal field values, calculated anomaly values of total magnetic field intensity, microleveling and reduction to the pole [11]. As a result of processing we got the map of total magnetic field anomaly reduced to pole. In this paper we give a part of the map which showing the positive magnetic anomaly (Figure 2).

The anomaly has direction north northwest - south southeast. The maximal anomaly values in this zone exceed 1700 nT. The anomaly is most likely caused by the presence of the Valja Strž pluton. The shape and size of anomaly suggest that this pluton has large outspread underneath surface.

In order to define the position of pluton and its boundaries in the horizontal plane on map of magnetic field anomaly reduced to the pole (Figure 2) we used next mathematical transformations: first vertical derivative, total horizontal derivative and tilt derivative.

The results obtained by applying VDR on the available aeromagnetic data are illustrated in Figure 3. It can be observed that positive values are located over the source, negative outside of a vertical side source of anomalies and zero over the edges of anomalies source. In Figure 3 zero contours are shown by black color and that contours shown edges of anomalies source in horizontal plane, and in this case edges of the Valja Strž pluton.

The results obtained by applying THDR are illustrated in Figure 4. The maximal values are located over the edges of anomalies source.

The results acquired by TDR are illustrated in Figure 5. This technique gives good results not only in defining the source of the anomaly near the surface, although at larger depths. The TDR facilitate to delineate the edges of source in larger depths which are covered by other source. The TDR is positive when lying directly above the source structure and is negative outside the source region. The TDR passes through zero above it or near its edges. In Figure 5 zero contours marked with black lines and they define edges of source in horizontal plane, i.e. edges of Valja Strž pluton.

In order to verify whether the cause of this anomaly has regional significance we used the technique upward continuation for level 100 m (Figure 6) and 500 m (Figure 7).
Using technique UP for different levels it can be concluded that the source of this anomaly has regional significance, i.e. pluton Valja Strž has widespread distribution in width and/or depth.

For defining the maxima weigh of Valja Strž pluton in subsurface we used combination UP and TDR for level 100 m (Figure 8) and 500 m (Figure 9). In Figures 8 and 9 zero contour level marks with black lines which delineate edges of anomalies source in horizontal plane, i.e. edges of Valja Strž pluton.
4. CONCLUSION

In order to define position and edges of Valja Strž pluton on map of magnetic field anomaly reduced to the pole we applied different mathematical transformations: first vertical derivative, total horizontal derivative, tilts derivative, upward continuation, and combination of upward continuation with tilts derivative. Based on the results of applying different methods of mathematical transformations it has been found that pluton has a larger distribution than it has been known until now, and most of the plutonic rocks are covered and not visible on the surface of the field. The Valja Strž pluton in subsurface continues its extension to the north and south, with the extension to the south far greater than extension to the north. It was also found that in the depth the pluton has great distribution.

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REZIME

DEFINISANJE GRANICA PLUTONITA VALJA STRŽ PRIMENOM MATEMATIČKIH TRANSFORMACIJA

Timočki magmatski kompleks (TMK) predstavlja najveće vulkansko područje u našoj zemlji, a nalazi se u istočnoj Srbiji. Na prostoru TMK, kao najveći intruziv, izdvaja se plutonit Valja Strž, koji se nalazi u severozapadnom delu kompleksa. Primenom različitih postupaka matematičkih transformacija na aeromagnetske podatke definisane su potpovršinske granice plutonita prema okolnim stenama. U ovom radu, matematičke transformacije su primenjene na anomalne vrednosti magnetnog polja, koje su dobijene kao rezultat obrađe aeromagnetskih podataka. Da bi se definisale granice plutonita u horizontalnoj ravni primenjeni su sledeći postupci matematičkih transformacija: prvi vertikalni izvod, ukupni horizontalni izvod, izvod nagiba, analitičko produženje polja naviše i postupak nastao kao kombinacija analitičkog produženja polja naviše sa izvodom nagiba. Rezultati primene matematičkih transformacija pokazali su da je rasprostranjenje plutonita Valja Strž u potpovršini daleko veće od njegovog rasprostranjenja na samoj površi terena.

Ključne reči: plutonit Valja Strž, aeromagnetski podaci, anomalne vrednosti magnetnog polja, matematičke transformacije, granice
Properties Improvement of the Al 7075 Alloy Castings

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The microstructure and the mechanical properties of the samples obtained by conventional vertical continuous casting and electromagnetic casting of 7075 aluminium as-cast alloy were investigated. The better quality, more homogeneous alloying elements distribution and hence the microstructure and better mechanical properties were obtained in sample cast with electromagnetic field (EMF) compared with sample cast without EMF. The microstructure was analyzed by optical microscope and the variation of alloying elements, Zn and Mg, through the sample cross section was examined by chemical analysis. The mechanical properties of samples cast with and without electromagnetic field were determined using computerized materials testing machine Zwick/Roel Z 100.

Key words: 7075 aluminium alloy, alloying elements, mechanical properties

1. INTRODUCTION

Electromagnetic casting (EMC) is the technology developed as by combining the magneto hydrodynamics and casting technique. Electromagnetic casting provides the opportunity which has never been achieved by conventional casting process. At the beginning, the application of electromagnetic casting has been aimed to obtain the better ingot surface, due to the reduced contact pressure between the mould and the metal. The reduced contact pressure is the result of potential force acting, as a horizontal component of Lorentz force density, which is being balanced by static pressure of the molten metal, thus resulting in the formation of the convex surface meniscus, i.e. the decrease of the metal/mold contact surface and their friction [1-6]. The other component of the Lorentz force density is a rotational component, resulting in a forced convection in the molten metal, enabling enhanced flow of the melt and homogeneous bulk distribution of alloying elements [7-11]. The recent researches show that combining the main operating parameters of electromagnetic field, such as frequency and strength of electromagnetic field, this process can efficiently eliminate the other defects of as cast ingots. In this way, the great savings in energy and time can be achieved. Knowing the microstructure-mechanical properties correlation, it is possible to obtain preferred ingot properties by controlling the main operating parameters and at the same time to avoid needs for additional operations, such as machining and prolonged homogenization. The research here is aimed to establish the possibility to obtain better quality of ingots at the very start of the production process through the proper combination of the main operating parameters.

2. EXPERIMENTAL

The chemical composition of the used EN AW 7075 alloy is shown in Table 1.

Table 1. Chemical composition of alloy EN AW 7075

<table>
<thead>
<tr>
<th>Element</th>
<th>Zn</th>
<th>Mg</th>
<th>Cu</th>
<th>Mn</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content %</td>
<td>5.51</td>
<td>2.29</td>
<td>1.45</td>
<td>0.13</td>
<td>0.19</td>
<td>0.14</td>
</tr>
</tbody>
</table>

The experimental equipment consists of medium frequency induction furnace with 100 kg capacity. There is a drainpipe, at the bottom of the furnace, with graphite crystallizer that is intensively cooled with
water. The low frequency magnetic field is placed around the crystallizer itself. The testing samples were taken out of ingots with a diameter of 80 mm, obtained by vertical continual casting. The casting temperature was in the range of 710-720°C and the average casting speed was 1.5 mm/s. The frequency of electromagnetic field was 30 Hz. The microstructure and the frequency of the electromagnetic field are closely related. The sample 1 was obtained from the ingot casted without the presence of electromagnetic field to enable the evaluation of the field effect on the microstructure at sample 2, obtained from the ingot casted in the presence of electromagnetic field with the frequency of 30 Hz.

The microstructure of samples was examined by optical microscopy using the image analysis device Leica Q500MC, after the usual metallographic preparation and etching in Keller’s reagent (revealing morphology of Al segregation-solid solution and intermetallic phase). The content variation of key alloying elements, Zn and Mg, was determined by chemical analysis of the samples taken from the cross section of both ingots, obtained with and without the electromagnetic field influence.

3. RESULTS AND DISCUSSION

Comparing the microstructure of sample 1, obtained without the field effect and of sample 2, obtained with the effect of electromagnetic field, it is obvious that the structure of sample 1 is more dendritic then the structure of sample 2, which is finer and with more emphasized cells.

![Figure 1 - Microstructure of sample cross section: sample 1 (a) and sample 2 (b), Keller’s reagent, 500x](image)

The characteristic microstructure appearance at the cross section of samples cast under different conditions is shown in Figure 1.

As it can be seen, the cellular/dendritic morphology is the result of Al segregation from the solid solution during the solidification process. Nevertheless, the morphology of the samples cast without the electromagnetic field effect, Figure 1a, is more dendritic, in comparison with distinctive cells at Figure 1b, obtained with the electromagnetic field influence. The variation of elements content through the entire cross section was examined using chemical analysis. The figure 2 shows the distribution of alloying elements Zn and Mg along the radius of ingots. During the casting without electromagnetic field influence due to unequal conditions of solidification, the large inhomogeneity of alloying elements distribution can be seen.

![Figure 2 - Content of Mg element (a) and content of Zn element (b) along radius of samples with different casting conditions](image)
On the surface of ingots the content of alloying elements is significantly higher than in the center. The application of the electromagnetic field reduces the undercooling because the contact line between mold and metal is smaller, as the result of potential force, a horizontal component of Lorentz force density acting. In this way the inhomogeneity of alloying elements distribution is reduced. Knowing the microstructure-mechanical properties correlation the following tests are related to determining the mechanical properties of the sample 1, which was obtained without influence of electromagnetic field, and sample 2, which was obtained under the influence of electromagnetic field. For mechanical characterization, the Zwick/Roell Z 100 device was used. The mechanical properties, tensile strength, Rm, yield strength, Rp, and elongation, A, were obtained by tensile testing of samples. The measured values of mechanical properties are shown in the table 2.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rp, N/mm²</th>
<th>Rm, N/mm²</th>
<th>A, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>201.63</td>
<td>229.88</td>
<td>3.73</td>
</tr>
<tr>
<td>2</td>
<td>216.35</td>
<td>243.60</td>
<td>5.94</td>
</tr>
</tbody>
</table>

Comparing the obtained results of mechanical properties, it can be concluded that sample 2, cast under the influence of electromagnetic field, has higher values of mechanical properties, Rm, Rp and A, than sample 1, cast without of electromagnetic field influence. Having in mind the microstructure-mechanical properties correlation the obtained results are in agreement.

4. CONCLUSION

The results presented in this paper show the evident influence of the electromagnetic field during casting aluminium alloy 7075. The electromagnetic casting has advantages over conventional casting in terms of obtaining the uniform fine-grained microstructure, and consequently better mechanical properties of an ingot made of the Al alloy 7075. The sample obtained by electromagnetic casting process, with a frequency of 30 Hz, have finer and more homogenous microstructure than the sample obtained without electromagnetic field influence, as it was evident on the microstructure figures. Besides, the inhomogeneity of alloying elements through the entire cross section is reduced in sample 2, cast with influence of electromagnetic field.

5. ACKNOWLEDGEMENT

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REZIME

POBOLJŠAVANJE OSOBINA ODLIVAKA OD ALUMINIJUMSKE LEGURE 7075

U radu je prikazana mogućnost dobijanja homogenije mikrostrukture i ravnomernije raspodele legirajućih elemenata Zn i Mg u aluminijumskoj leguri EN AW 7075, prilikom livenja u prisustvu elektromagnetnog polja. Ispitana su i mehanička svojstva uzoraka koji su odliveni bez i sa elektromagnetnim poljem. Rezultati pokazuju da se livenjem u elektromagnetnom polju postižu prednosti u odnosu na klasičan postupak livenja aluminijumskih legura.

Ključne reči: Al legura 7075, legirajući elementi, mehanička svojstva
Changes In The Surface Layer Of The cBN Tool During The Hardened Steel Turning

The paper presents the results of experimental research in turning of hard-to-machine steels of 60-62 HRC hardness, using tools made of polycrystalline superhard materials based on cubic boron nitride (cBN). Modeling of temperature distribution was performed in the cutting tool using the finite element method (FEM). Research results of tool wear in tool's surface indicate the presence of oxidation process and changes in physical-mechanical properties in tool's surface layer. Oxidation of the surface layer, directly next to the contact zone of tool chip, leads to the increase of its hardness and decrease of its strength, which ultimately results in the occurrence of microfracturing of tool composite and thereby rapid tool wear.

Key words: turning, tools, cBN, oxidation, tool wear

1. INTRODUCTION

Machining of hard-to-machine materials requires the use of cutting tools to satisfy the requirements from the process aspect, which occur when cutting. There's a great number of references that include researches related to the use of superhard materials (SHM) in machining of the material with high hardness. The authors [1, 2] in their researches analyse the impact of composition, hardness of tools and workpieces, and the elements of machining modes on tool life and quality of machined surface as well. The authors [3, 4] study the impact of tool wear on the change of cBN tool geometry, especially the crater impact on the rake surface of the tool. When it comes to cBN tool wear, it includes three basic mechanisms: (1) chemical tool wear, caused by interaction between the workpiece material and oxidation; (2) forming of coatings on the tool surface under high temperatures, and (3) abrasive tool wear [5]. The state of the cutting tool surface layer is greatly affected by the heat generated in the cutting zone. In effort to increase tool life it is necessary to determine the border of the heat influence zone. Many phenomena that occur in this zone are connected to the change of chemical composition and mechanical properties of the tool material surface layer and are the consequence of oxidation.

These processes are expressed during machining of steel and high-hardness alloys using tools made of polycrystalline superhard material (PSHM) based on cubic boron nitride (cBN), because the machining is done without the cooling process when the temperature in the cutting zone rises up to 1200°C [6].

Depending on their composition, different composites interact with oxygen, which leads to chemical processes. The experimental researches in the area of oxidation of PSHM based on cBN-kiborit showed that oxidation occurs at the temperature of 800°C [7]. Further temperature increase leads to the intensive
oxidation of materials, the transpiration of boron oxide and the removal of free nitrogen.

The oxidation process of PSHM-elbor RM occurs at the temperature of 1000°C, in order to have a linear character of change in the 1000-1300°C interval. Thermal analysis shows the complex mechanism of the oxidation processes formation, because the other particles of tool material form AlB$_2$, Si$_3$N$_4$ when reacting with oxygen. In the contact zone of tool and the processed material B$_2$O$_3$ is formed and its percent grows with the increase of cutting speed [9].

Having a chemical reaction with oxygen, the components of the composite form oxides with which they disturb bonds in the material. As a result, the probability of the material fracturing is increased on account of cBN particles detachment.

The structure of oxidated composite and its mechanical properties differ from the structure of the initial cBN. A very important segment in tool wear refers to the change of its chemical structure and mechanical properties [10].

The results of experimental researches are presented in the paper. The experimental researches are concerned with the processes of changing the chemical composition and mechanical properties of the surface layer of cBN-kiborit tool, which occurred during the turning of hardened steel.

2. CONDITIONS OF CONDUCTING AN EXPERIMENT

Hardened steel S1220 with 60-62 HRC hardness and 90mm diameter was machined on a lathe PH 42-CNC. The lathe knife was used and it consisted of a holder (S1530), a washer (hard metal K30) and a cutting plate (cBN), as shown in figure 1 and its characteristics listed in Table 1. The plates are mechanically attached to the system D, with the back rake angle γ= -10° and end clearance angle α= 10°. The electronic microscope AG-EVO-Zeiss was used to analyse the influence of processes occurring in the tool - workpiece contact during cutting.

The Scratch Test was used to evaluate the mechanical properties of the surface layer of tool composite, using the method of indentation with an indenter. Scanning was performed over the tool rake surface in the radial direction from the cutting edge on the contact surface part.

Table 1. Thermophysical properties of tool elements

<table>
<thead>
<tr>
<th>Material</th>
<th>Hard metal K30</th>
<th>PSHM on cBN base</th>
<th>Steel S1530</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda ), W/mK</td>
<td>54</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>( \rho ), J/kg</td>
<td>470</td>
<td>760</td>
<td>500</td>
</tr>
</tbody>
</table>

Machining was performed according to the modes of cutting given in table 2. Measuring was done at an indenter load of 100 cN on the scanning track of 720 m. For the comparison with the contact surface, the measurements were simultaneously performed under identical conditions on the part of the tool surface 3mm away from the cutting edge.

![Figure 1 - Model structure of cutting (a) and contact (b) surfaces: (1) cutting plate, (2) washer, (3) holder](image)

Modeling of the heat load in the tool during the cutting process was performed using FEM. During the turning with a massive lathe knife, the heat transported through the cutting edge-workpiece-tool chip system is rapidly stabilized, so the temperature of the contact surface slightly changes.

Consequently, assuming that the cutting temperature does not depend on the time, it is possible to set up first-order boundary conditions on the tool contact surface: \( u(x, y, z) = T_r \), where \( T_r \) is mean temperature of the tool’s tip. The given temperature \( T_r \) and the environment temperature are set at 20°C as the initial data. Boundary conditions are used on the free surface of the cutting plate (1), the washer (2) and the holder (3):

\[
\alpha_r \cdot (\theta_n - \theta_c) = \lambda_r \left( \frac{\partial \theta}{\partial n} \right) \tag{1}
\]

Mean values of the heat transfer coefficient for the given elements of the tool model are taken according to the recommendations [6]: \( \alpha_1 = \alpha_2 = 50 \, \text{W/m}^2 \cdot \text{K} \) and \( \alpha_3 = 20 \, \text{W/(m}^2 \cdot \text{K}) \).

Investigations of heat impact on the change of chemical composition and mechanical properties of the tool surface layer in the process of its wear are performed on the cutting plates of PSHM based on cBN: with titanium and silicon nitride (cBN + 10 % TiN + 30 % Si$_3$N$_4$), tantalum and silicon nitride and carbide (cBN + 15% TaN + 15 % Si$_3$N$_4$ + 10 % SiC) and silicone nitride (cBN + 3 % Si$_3$N$_4$).

The cutting time, needed to reach the corresponding value of the tool flank wear VB, is taken as a criterion to check the impact of the tool wear in the exploitation process, the change of chemical composition and the mechanical properties of the tool material.
3. RESULT AND DISCUSSION

The boundary zone of heat load influence is determined by the temperature gradient in the zone that borders with the cutting zone. Its value is affected by thermophysical properties of tool material – thermal conductivity and thermal capacity. With the decrease in the value of the temperature gradient value and increase in the cutting temperature, the change in the tool material structure and properties will expand to a larger volume of the composite.

Chemical reactions with the workpiece material occur during the machining at cutting speed of \( V = 1.5 - 3 \) m/s on the tool contact surface [11]. The interaction mechanism, during which a liquid phase on the tool contact surface is formed, has a significant role. That the processes associated with oxidation of tool material are also included in the tool wear mechanism is shown by the analysis of the tool made of PSHM based on cBN tool wear regularity. For the specified conditions of modeling: temperature 1200°C, cutting speed \( V = 2.35 \) m/s and feed \( S = 0.1 \) mm/o (e.g. table 2), the temperature distribution in the cutting tool is modeled and a survey is given in fig. 2 and fig. 3.

Table 2. Consistency of cutting tools on cBN base

<table>
<thead>
<tr>
<th>Composite</th>
<th>Cutting mode</th>
<th>Wear ( (B_L) ) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( cBN+TiN+Si_N_4 )</td>
<td>1.5 m/s</td>
<td>9 mm</td>
</tr>
<tr>
<td>( cBN+TiN+Si_N_4 )</td>
<td>2.35 m/s</td>
<td>5.33</td>
</tr>
<tr>
<td>( cBN+TaN+Si_N_4+SiC )</td>
<td>2.35 m/s</td>
<td>10</td>
</tr>
<tr>
<td>( cBN+Si_N_4 )</td>
<td>1.5 m/s</td>
<td>13.33</td>
</tr>
<tr>
<td>( cBN+Si_N_4 )</td>
<td>2.35 m/s</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Based on the results shown in fig. 3, it can be concluded that the temperature gradient along the X-axis on the tool part, in contact with the chip, is about 140 K/mm. The border temperatures of 1100°C and 950°C are present within 0.175mm and 0.27mm distance from the cutting edge. The model of temperature distribution provides the basis for further analysis of impact on the change of chemical composition and mechanical properties of the tool surface layer.

The cutting tools contact surfaces, after machining of hardened steel S1220, are shown in fig. 4. The region of brittle fracture on the flank is present in tools based on \( cBN+TiN+Si_N_4 \) (ph.4), which indicates a greater strain in the tool rake surface and insufficient strength of the composite during exploitation under high temperature conditions.

![Figure 2 - Temperature distribution on the tool contact surfaces](image-url)

![Figure 3 - Temperature distribution in the tool measured from the cutting edge](image-url)
Figure 4 - Tool contact surface after the machining of S 1220 (V= 2.35 m/s): a, b - cBN + TiN + Si₃N₄; Bₗ=0.30 mm; c, d - cBN + TaN + Si₃N₄ + SiC; Bₗ = 0.35 mm; e - cBN + Si₃N₄; Bₗ=0.25 mm

Chemical composition of the cutting tools contact surface is determined by an X-ray spectroscopy analysis. Figure 5 shows the position of the measuring zones on the tool rake surface, where the determined chemical composition is given in the tables 3-5. Increased amount of iron and oxygen on the tool surface is associated with the adhered particles of the machined material and products of interaction between the contact materials. Investigations [9] show that the chemical reaction in the cBN-(Fe, Ni, Cr) system leads to the formation of compounds (Fe, Ni, Cr)ₓByOz. Oxygen on the cutting tool surface also occurs as a result of oxidation of the cBN composite chemical elements at high temperatures. The region where these processes intensively occur is at 0.3mm distance from the cutting edge.

Table 3. Chemical composition (%) of the rake surface of the composite tool cBN + TiN + Si₃N₄

<table>
<thead>
<tr>
<th>Con. zone</th>
<th>B</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>Si</th>
<th>Ti</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.07</td>
<td>20.57</td>
<td>10.44</td>
<td>7.71</td>
<td>10.14</td>
<td>11.72</td>
<td>4.69</td>
</tr>
<tr>
<td>2</td>
<td>6.53</td>
<td>10.37</td>
<td>7.18</td>
<td>3.29</td>
<td>9.85</td>
<td>8.20</td>
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<tr>
<td>3</td>
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<td>8.08</td>
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<td>14.54</td>
<td>11.64</td>
<td>3.75</td>
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<td>4.93</td>
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<td>15.29</td>
<td>8.58</td>
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<tr>
<td>6</td>
<td>19.92</td>
<td>3.94</td>
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<td>25.22</td>
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<td>37.77</td>
<td>4.34</td>
<td>13.78</td>
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<td>10</td>
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<td>5.01</td>
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<td>21.75</td>
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<td>37.70</td>
<td>4.96</td>
<td>12.14</td>
<td>7.75</td>
<td>2.14</td>
</tr>
</tbody>
</table>
Table 4. Chemical composition (%) of the rake surface of the composite tool cBN + TaN + Si₃N₄ + SiC

<table>
<thead>
<tr>
<th>Con. zone</th>
<th>B</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>Si</th>
<th>Fe</th>
<th>Ta</th>
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<td>6.82</td>
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<td>15.88</td>
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<td>3.78</td>
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<tr>
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<td>7.77</td>
<td>11.51</td>
<td>1.39</td>
<td>18.84</td>
</tr>
</tbody>
</table>

Table 5. Chemical composition (%) of the rake surface of the composite tool cBN + Si₃N₄

<table>
<thead>
<tr>
<th>Con. zone</th>
<th>B</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>Si</th>
<th>Fe</th>
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<tbody>
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<tr>
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<td>28.28</td>
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<td>50.71</td>
<td>6.26</td>
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<td>7.18</td>
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<td>4.48</td>
<td>2.01</td>
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<td>10.18</td>
<td>55.14</td>
<td>3.96</td>
<td>0.78</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Figure 6 - Diagram of oxygen distribution (%) on the tool rake surface: a – cBN + TiN + Si₃N₄; b – cBN + TaN + Si₃N₄ + SiC; c – cBN + Si₃N₄.

Low oxygen content was observed at the X=180-200 μm distance from the cutting edge in all of the analysed tools. That can be explained by the fact that the tool area interacts with the air. Besides, the liquid phase of the products of contacting materials interaction, which also contains oxygen, is delivered to this area.

To evaluate the character of the relationship between the exploitative tool indicators and the oxygen amount on the rake surface, it is also necessary to consider the change in oxygen amount on the cutting edge as a function of the cutting time. As the cutting time for considered tools is different, the characteristic – wear speed is determined as a ratio between the flank wear VB and the cutting time. Computing values are shown in table 6.

The analysis results indicate the correlation between mean oxygen content on the tool rake surface and the speed of its wear. Based on carried out investigations, under conditions of hardened steel cutting at high cutting speeds, the composite with high super-hard phase cBN content and tools with low cBN content and addition of TiN and Si₃N₄ (< 15 %) content have the longest tool life.

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The data of oxygen content on the tool surface lead to a conclusion that increased tool life of the cutting tools with the composite cBN + TaN + Si$_3$N$_4$ + SiC compared to the tools with low cBN content is linked to the lower intensity of oxidation processes in the cutting zone.

<table>
<thead>
<tr>
<th>Composite</th>
<th>Relative average oxygen content</th>
<th>Tool wear speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>cBN + TiN + Si$_3$N$_4$</td>
<td>3.28</td>
<td>180</td>
</tr>
<tr>
<td>cBN + TaN + Si$_3$N$_4$ + SiC</td>
<td>0.85</td>
<td>27</td>
</tr>
<tr>
<td>cBN + Si$_3$N$_4$</td>
<td>0.51</td>
<td>25</td>
</tr>
</tbody>
</table>

Figures 7, 8 and 9 show the diagrams of change in the tangential resistive force magnitude, which occurs in scanning the tool surface measured from the main cutting edge.

Based on figs. 7-9 and the data given in table 7, it is possible to evaluate the influence of exploitation conditions on the change of mechanical properties of the surface layer of superhard composites. In the interval of uniform wear (0.1 mm < $B_L$ < 0.3 mm) the change of force $F_{\tau}$ is not observed. The change in the force $F_{\tau}$ is more expressed in the tool wear interval $B_L$ = 0.32 – 0.35 mm.

At the distance of $X > 200$ pm from the cutting edge the force $F_{\tau}$ decreases, reaches its minimal value at $X = 240$–270 m (tool of cBN + TiN + Si$_3$N$_4$) and $X = 340$–420 m (tool of cBN + TaN + Si$_3$N$_4$ + SiC).

Such character of change in the force $F_{\tau}$ as the function of $X$-coordinate is present in the tools that have reached the critical value of the flank wear $V_B$, when the fracturing of the tool occurred. It is important to note that the $F_{\tau}$ force decrease is linked to local increase in micro-hardness, that is, the smaller penetrating of the indentor in the tool surface.

The length of contact between the chip and the tool rake surface during machining with $S=0.1$ mm/o amounted approximately to ~ 80 m. In this way, located outside the contact zone is the tool area, where the significant change in mechanical properties of the composite is noticeable.

Based on computing-experimental evaluation, the surface layer temperature of the cutting tool of PSHM based on cBN during machining at the speed of $V = 2.35$ m/s in considered areas reaches $T = 1000$ – 9500 C and $T = 860$–780 ° .
The changes in the physical-mechanical properties in the tool surface lead to rapid wear of the cutting tool.

The tool based on cBN + 3% Si₃N₄ shows the longest tool life during the hardened steel machining. The changes in mechanical properties in the surface layer haven’t been observed during the exploitation using this tool.

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REZIME

PROMENE U POVRŠINSKOM SLOJU ALATA OD CBN PRI STRUGANJU KALJENOG ČELIKA

U radu su prikazani rezultati eksperimentalnog istraživanja obrade struganjem teškoobradljivih čelika tvrdoće 60-62 HRC sa alatom od polikristalnog supertvrdog materijala (PSTM) na osnovi kubnog bornitrida (cBN). Izvršeno je modeliranje raspodele temperature u reznom alatu primenom metode konačnih elemenata (MKE). Rezultati istraživanja habanja površine alata ukazuju na prisustvo procesa oksidacije i promene fizičko-mehaničkih svojstava u površinskom sloju alata. Oksidacija površine alata, neposredno uz kontaktu zonu alat-strugotina, dovodi do povećanja njihove tvrdoće i smanjenja čvrstoće, što u krajoj meri dovodi do pojave mikrokrzanja alatnog kompozita a time i ubrzanog habanja alata.

Ključne reči: struganje, alat, cBN, oksidacija, habanje
Development of Multifunctional Reconfigurable Desktop Machine Tool with Hybrid Kinematics

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Faculty of Mechanical Engineering, Belgrade

This paper presents a desktop reconfigurable machine tool with hybrid kinematics for four types of machine tools, with a description of the applied mechanism and established modular system for their configuring. The postprocessor for five-axis machining presented in this paper is applied to the kinematic structures with table-tilting with two rotations (B,C). The paper also presents the calculation of the position of actuators $p_1$ and $p_2$ when the machine works with hybrid kinematics. Verification of postprocessor is realized on virtual prototype in CAD/CAM environment and experimentally on an available 3-axis machine tool. Experimental results confirmed the configured postprocessor which can be used for machine tools programming.

Key words: configuring, reconfigurable machine tool, postprocessor

1. INTRODUCTION

Research in the field of multifunctional and reconfigurable machine tools is intense and has a lot of completed results [1-4]. The subject of this work is the development of a reconfigurable desktop machine tool with serial and hybrid kinematics. The term concept of reconfigurable machine tool in this paper refers to a system of constituent elements (modular system) by which multiple machine tools can be configured. Each of these machines is a new kinematic structure.

Basic functional requirements for the development of multifunctional and reconfigurable desktop machine tool with hybrid kinematics were: (1) make low-cost desktop machine tool, (2) establish a modular system for configuring four different machines, (3) control implemented on PC Linux platform with open architecture, (4) use step motors for feed drives, (5) machine is should be programmed using G-code, (6) ensure accessibility and safety at work, and (7) machine is seen as a resource for research and education. In this paper we have chosen the concept of machine shown in Figure 1.

![Conceptual model of machine tool](image)

Figure 1 - Conceptual model of machine tool

The basic machine is 3-axis desktop milling machine with portal construction, with VXYZ structure. Using additional 2-axis rotary/tilting table (B,C) in front of the machine frame, such machine becomes five-axis milling machine, with WCBVXYZT structure [5]. By fixing of B-axes in $B=0^\circ$ or $B=90^\circ$ and keeping C axes active, such machine becomes a four-
axis controlled, and can be used for turning operations as well. The fourth possible conception assumes basic machine with hybrid kinematics, i.e.: two-axis parallel module M2, for realization of movement of point P in plane (X, Y) via passive translation module (X, Y), whereas Z axis remains serial. At this basic machine, two-axis rotary/tilting table remains, and in this way we obtain 5-axis machine with hybrid kinematics, which is discussed in this paper in more details.

For the machine that is the subject of analysis in chapter 2, we present the established system of the constituent elements for its configuring. Chapter 3 presents postprocessing for the 5-axis machine tool with hybrid kinematics. Checking of the postprocessing calculations as well as workspace are also shown. Verification of the postprocessing calculations and configurated posprocessor for machine were realised using machining test by machining of a four-sided pyramid on the available CNC machine tool, and it is shown in Chapter 4.

2. CONFIGURATOR OF ONE CLASS RECONFIGURABLE MACHINE TOOLS

Analysis of the basic modules of the 5-axis machine tools enabled the establishment of a modular system with reconfigurable hardware, which makes the basic concept of machine tool. Modules are shown in Figure 2 in the form of morphological matrix.

Figure 2 - Configurator for one class of reconfigurable machine tools

Integral part of this matrix are representations of realization of modular system: base, translatory axes, rotary tables, main spindle, tailstock and 2-axis parallel mechanism as well as a part of the building program for machine tools of types S3D, S4D, S5D and H5D.

Passing through morphological matrix in Figure 2 and by completion of appropriate modules required for the basic functions of machines, a building program of possible machine tools was obtained. In Figure 2, the building program shows four examples of configured machine tools. Figure 3 shows more detailed view of the chosen sample of the building program from Figure 2, which includes and tags the controlled axes.

Figure 3 - Samples of CAD models from Figure 2

These are the initial concepts of four machines: S3D (3-axis), as the main portal machine, S5D (5-axis), as the classic 5-axis portal machine, S4D (4-axis) as a typical example of the 4-axis portal machine and H5D (5-axis), as the main configuration with hybrid kinematics. Tag S indicates machine with serial kinematics, and tag H indicates machine with a hybrid (serial and parallel) kinematics. Desktop machines in building program shown in Figure 3 have the following characteristics:

- They are equivalent, since they can be configured from the same group of the modules and according to same program of building, i.e., according the same configurator.
- In the case of machining the shorter workpieces by using rotary tables, machine of H5D type is suitable: Long strokes of tool carrier are not needed, while the feedrates of tool axis will be large enough to follow rotations (simultaneous or one-by-one) of tables.
- For 4-axis machining S4D is the best and most suitable machine. With sufficiently fast rotary table or equipped with additional spindle, it can work as a lathe, with appropriate tool holder interface which is blocked.
- 3-axis machine tool (S3D) is the initial for the other three machines from Figure 3.
Frame of the rotary/tilting table is mounted with its length aligned to cross direction of the machine in order to fit into the S3D conception of the machine, and such machines have basic structural formula WCVB XYZT.

3. POSTPROCESSING CALCULATION

Programming of machines with serial kinematics of WCBVXYZT type in some CAD/CAM software environment is routine after preparation of suitable postprocessor [6]. On the other hand, postprocessors for machines with parallel and hybrid kinematics are not so often. Therefore, there is no need for repeating the postprocessing calculations, characteristics of postprocessors for machines with serial kinematics. Instead, such calculations will be formalized and used for further formal checking and completion of program (written in G code), which will be executed on machines from Figure 3. Reason: If the machine of H5D type is used, then further postprocessing calculations for hybrid kinematics of this machine will be made in its control system, in order to make execution of interpreted G-code, created for machine WCVBXYZT (SSD), executable on the machine H5D as well. From this reason reconfiguring of the hardware from Figure 3 should be followed by reconfiguring of the software (control system), in order to establish one real sample of the machine from reconfiguring, with plan that includes the machine with hybrid kinematics (shown in Figure 4) as well. The formalism for postprocessing calculations for five-axis machine tools from Figure 3 is explained in further text, as well as the description of one test of validity of such calculations.

3.1. Formalism for postprocessing calculations for WCBVXYZT type of five-axis machines

For this kind of calculations preparing of the model is required. Basic preparation is shown in Figure 4, and it starts from establishing of coordinate systems of the basic machine (O_B), of the tool (O_T) and of the subsystem with parallel kinematics (O_M).

Postprocessing calculations for subsystem with serial kinematics, in basic system O_B, are described in this chapter. Kinematic model and important tags are shown in Figure 5. Coordinate system of the machine (O_M) is added in this model. In this system, the basic system, O_B, is established, with its origin in the center of the rotation of both tables. Coordinate system of the program is O_W and it is connected with the workpiece (WP).

Further discussion refers to the case in which the coordinate system of the workpiece, used in programming, is parallel with the systems of the machine. For zero point (G55, for example, in Figure 5), only one translation is required, for correct operation of the machine according to interpreted program, with preparation of the fixture and blank material on the table made in such a way. Workpiece coordinate system (OW) does not match with the basic coordinate system of the machine, and this is denoted by vector \( \overrightarrow{r}_i \) in OW system, in which given program is valid. Coordinate system of the tool (T) has its origin in O_T.
for each pose of the machine along tool path, described by command GOTO/ \( \vec{r}_f \) , \( \vec{a} \), according to APT format.

Coordinate systems in these calculations are:

Coordinate system of the machine 
\( \mathbb{O}_M( X_M, Y_M, Z_M ) \) and table \( \mathbb{O}_T( X_T, Y_T, Z_T ) \),
coordinate system of the workpiece 
\( \mathbb{O}_W( X_W, Y_W, Z_W ) \), and coordinate system of the tool 
\( \mathbb{O}_T = T_T( X_T, Y_T, Z_T ) \). Coordinates of the vectors used for orientation of the tool (\( \vec{a}_n, \vec{a} \)), vectors (\( \vec{r}_T, \vec{r}_w, \vec{p}, \vec{x} \)) and translation matrix for \( \vec{v} \) [\( T_T(\vec{v}) \)] are:

\[
\begin{align*}
\vec{a}_n &= \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad \vec{a} = \begin{bmatrix} a_z \\ a_y \\ a_x \end{bmatrix}, \quad \vec{r}_n = \begin{bmatrix} y_l \\ y_r \\ y_c \end{bmatrix}, \quad \vec{r} = \begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix}, \quad \vec{p} = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}, \\
\vec{x} &= \begin{bmatrix} x \\ y \\ z \end{bmatrix} ; \\
\begin{bmatrix} x \\ y \\ z \end{bmatrix} [ T_T(\vec{v}) ] &= \begin{bmatrix} 1 & 0 & 0 & v_x \\ 0 & 1 & 0 & v_y \\ 0 & 0 & 1 & v_z \end{bmatrix} .
\end{align*}
\]

Other: \( \vec{v} = \{ v_x, v_y, v_z \}^T \) is arbitrary given vector of translation, \( T \) is tool, \( W \) or \( WP \) is workpiece.

Postprocessing calculations can be, for each of these poses, described in this way: from its reference position, using rotations of tables, machine makes direction of programmed unit vector of the tool axis (\( \vec{a} \)) on \( \vec{a}_n \), the only one available on the machine. Then, using translatory axes, it governs the tool tip (\( T_T \)) to its inclined programmed position, after already realized rotations of tables. Tables are rotating first for \(-C\), and then for \(-B\).

Let \( \text{Tr}(\vec{v}) \) denote a translation for vector \( \vec{v} \) and \( \text{Rot}(\vec{o}, \phi) \) denote rotation for angle \( \phi \) around unit vector \( \vec{o} \) in a positive direction, where \( \vec{o} \) is either unit vector \( \vec{i} \) of axes \( X_M-X_R \) of the machine, or unit vector \( \vec{j} \) of axes \( Y_M-Y_R \), or unit vector \( \vec{k} \) of axes \( Z_M-Z_R \).

Axis of table rotations on machine H5D, are parallel to \( Z \) and \( Y \) axis in coordinate systems of this machine. Angle of rotation has negative sign if this rotation is movement of the workpiece (with table). According to standard, angle \( A \) is rotation around the unit vector \( \vec{i} \), angle \( B \) around the unit vector \( \vec{j} \) and angle \( C \) around unit vector \( \vec{k} \). Rotations of the table and then translations of the tool can be formalized as direct kinematics of the machine using the following equations, respectively:

\[
\begin{align*}
\text{Tr}(\vec{r}_R) \cdot \text{Rot}(\vec{k}, -C) \cdot \text{Rot}(\vec{j}, -B) \cdot \text{Tr}(\vec{p}) \cdot \vec{a}_0 &= \vec{a} \\
\text{Tr}(\vec{r}_W) \cdot \text{Rot}(\vec{k}, -C) \cdot \text{Rot}(\vec{j}, -B) \cdot \vec{r}_0 &= \vec{r}_f \quad (1)
\end{align*}
\]

Form of the translation matrix \( \text{Tr}(\vec{v}) \) for arbitrary vector \( \vec{v} \) is already shown. Besides, rotation matrices around machine axes have ordinary form, inherent to homogenous coordinates.

In equation (1) \( \vec{p} \) denotes required movement of the tool, relative to the workpiece in \( \mathbb{O}_W \) system of the machine, while real required motions of machine axis, which will be written in a program, can be described by vector:

\[
\vec{g} = [X \ Y \ Z]^T.
\]

The second solution is a pair of angles of rotary axis. In our case these are angles \( C \) and \( B \). Solutions of equation (1) need to separately derived. Solution for inverse geometric problem, obtained in this way, will be implemented in the postprocessor.

However, in this case such formalism is used for checking of just interpreted G code in the control system with open architecture, configured for observed machine, one from Figure 3. With substitutions \( sC \) for \( \sin(C) \), \( cC \) for \( \cos(C) \), \( sB \) for \( \sin(B) \), \( cB \) for \( \cos(B) \), both of these solutions of inverse geometric problem can be written in compact form. The first part of the solution can be written as:

\[
B = \arccos(a_z), \quad B \in (0, \pi), \quad B \neq 0 \quad (2)
\]

\[
C = \arctan2(-\frac{a_y}{a_z}, \frac{a_x}{a_z}), \quad C \in [-\pi, \pi]. \quad (3)
\]

The second part of the solution, for positions of translatory axes of the machine \((X, Y, Z)\), after re-arranging, usually can be written in the following form:

\[
\begin{align*}
X &= x_R + p_x \\
Y &= y_R + p_y \\
Z &= z_R + p_z \\
X_T &= (x_T - x_R) \cdot cB \cdot cC + (y_T - y_R) \cdot cB \cdot sC + (z_T - z_R) \cdot sB \\
Y_T &= (x_T - x_R) \cdot sB \cdot cC + (y_T - y_R) \cdot cB \cdot cC + (z_T - z_R) \cdot sB \\
Z_T &= (x_T - x_R) \cdot sB \cdot sC + (y_T - y_R) \cdot cB \cdot sC + (z_T - z_R) \cdot cB \\
\end{align*}
\]

3.2. Checking of postprocessing calculations

Verification of the postprocessing calculations is shown in Figure 6. Centre of the tool holder is denoted by Main spindle. Distance between Main spindle and TT is tool length, here \( l = 100 \) mm. Then we observe the case when \( \vec{r}_R = 0 \), when \( \mathbb{O}_W \) is set exactly in \( \mathbb{O}_R \). Solid line shows programmed pose of the machine in the system \( \mathbb{O}_R = \mathbb{O}_W \), based on data from program in \( \mathbb{O}_W \) system. Dashed line shows the pose of the machine after execution of the movement according to solutions.
(2)-(4), for special case: $\vec{r}_e = [0,0,0]^T$, $\vec{r}_x = [25,50,75,1]^T$ and $\vec{r}_y = [30,5/3,30,5/3,30,5/3,1]^T$.

Results are as follows: 
$B = 54.73^\circ$, $C=135.0^\circ$, $X=30.619$, $Y=-17.678$, $Z=86.602$, $px=30.619$, $py=-17.678$, $pz=86.602$. 
Overlapping of X, Y, Z with px, py, pz, respectively, is a consequence of overlapped coordinate systems OW and OR.

The second kind of checking are postprocessing calculations in a control system. It has to be conducted in two parts. The first includes checking shown in Figure 6: whether the programmed unit vector of the tool axis ($\vec{u}$) after rotations for C, and then for B from (2) and (3), overlaps with $\vec{u}_0$, and whether translatory axes of the machine are in positions $[X \ Y \ Z \ 1]^T$, according to (4). In the second check, calculations of required positions of driving axis $p_1$ and $p_2$ of the machine $M_2$ (Figure 7) with parallel kinematics, are performed.

This is the second required kinematic model of the machine of H5D type. Solutions for inverse and direct geometry were obtained using this model for subsystem with parallel kinematics. This solution will be implemented in open architecture control system execution of required corrections, which are consequences of machine kinematics. After that, planning of the tool path becomes possible, and afterwards interpolations in real time. Model shown in Figure 7 is general for two-axis mechanism, which is, among modules for configuring of machines (Figure 2), denoted as 2-axis parallel mechanism $M_2$. 

This mechanism, embedded in such a way, via its platform P, shown in Figure 4, is used for driving of one passive translatory joint, for simultaneous movement of X and Y axis of the serial part of the machine. Data for the second postprocessing calculation are required positions of X and Y axis of the machine. Based on these positions it is possible to calculate positions $p_1$ and $p_2$ of driving axes $B_1$ and $B_2$, respectively.

Model shown in Figure 7 has a coordinate system which is suitable for (i) deriving of solutions of inverse and direct kinematic problem of this subsystem, but also for further compensations inherent for control systems for machines with parallel kinematics, and also for machines with hybrid kinematics (there are two rotary and two linear-parallel diving axis) and (ii) for embedding of subsystem in a whole system.
Subsystem $M_2$ is put in the machine H5D by simple mapping, shown also in Figure 7: $X_{M2} \equiv Y_{M}$ and $Y_{M2} \equiv X_{M}$, where $(X_M, Y_M)$ are axes of the active coordinate system of the machine (either with origin in $O_R$, as a centre of rotations of tables, or with origin in $O_M$, as a general case). Transformation from $X_M$ axis to $Y_{M2}$ axis assumes just translation, and from $Y_M$ to $X_{M2}$ just with altering of the sign (by rotation for $\pi$).

Because of this, for module $M_2$, model from Figure 7 will be translated in a third and fourth quadrant, Figure 4. This means that the general model is adapting to module $M_2$ in the following way: $x_{M1} = -x_{M2}$, $\varphi_1 = \varphi_2 = 3\pi/2$, $l_1 = l_2 = l$.

According to tags from Figure 7 following sums are made:

$$ r_{1R1} + r_{B1} + r_{1p} = r_p, \text{ for drive axes } p_1 \text{ and}$$

$$ r_{1R2} + r_{2B2} + r_{12} = r_p, \text{ for drive axes } p_2. \ (5)$$

Solution of the inverse geometric problem of module $M_2$ are positions of driving axes $(p_1, p_2)$, which satisfy equations (5), all for the position of the platform $P$ given by vector $r_p$. Calculation of this position is based on existing solution of the inverse geometric problem, given in (4), based on a program which controls operation of the machine. Under conditions given in Figure 7 ($l_1 = l_2 = l$ and $y_{R1} = y_{R2} = 0$), one can obtain solution of the inverse geometric problem for $M_2$:

$$ p_1 = (x_p - x_{R1}) \cdot \cdot \cdot + y_p \cdot s\varphi_1 - \sqrt{l_1}$$

$$ p_2 = (x_p - x_{R2}) \cdot \cdot \cdot + y_p \cdot s\varphi_2 - \sqrt{l_2} \ (6)$$

In (6) following substitutions were used:

$$ t_1 = l^2 - ((x_p - x_{R1}) \cdot \cdot \cdot + (y_p - y_{R1}) \cdot \cdot \cdot + y_p \cdot s\varphi_1)j^2 + (y_p - y_{R1}) \cdot \cdot \cdot - (y_p - c\varphi_1)j^2$$

$$ t_2 = l^2 - ((x_p - x_{R2}) \cdot \cdot \cdot + (y_p - y_{R2}) \cdot \cdot \cdot + y_p \cdot s\varphi_2)j^2 + (y_p - y_{R2}) \cdot \cdot \cdot - (y_p - c\varphi_2)j^2$$

$$ \varphi_1 = \cos(\varphi_1), \ s\varphi_1 = \sin(\varphi_1), \ s2\varphi_1 = \sin(2\varphi_1)$$

$$ \varphi_2 = \cos(\varphi_2), \ s\varphi_2 = \sin(\varphi_2), \ s2\varphi_2 = \sin(2\varphi_2)$$

Solving of direct geometric problem starts from system of equations (5), written in algebraic form. By subtracting the second equation from the first one, the following equation is obtained:

$$ s_1 \cdot x_p + s_2 \cdot y_p = s_3,$$

where:

$$ s_1 = 2(x_{R2} + p_2 \cdot c\varphi_2 - x_{R1} - p_1 \cdot c\varphi_1),$$

$$ s_2 = 2(p_2 \cdot s\varphi_2 - p_1 \cdot s\varphi_1),$$

$$ s_3 = x_{R2}^2 - x_{R1}^2 + p_2^2 - p_1^2 - 2x_{R1} \cdot p_1 \cdot c\varphi_1 + 2x_{R2} \cdot p_2 \cdot c\varphi_2.$$
The results for the drive axes are:

\[ p_1 = 308.732 \quad \text{and} \quad p_2 = 252.816 \]

Checking is done on the virtual prototype machine, in the CAD/CAM environment, taking a position and orientation according to the calculated coordinates \( p_1 \), \( p_2 \), \( Z \), \( B \), \( C \), where the tool takes the correct position and orientation to the workpiece, as can be observed in Figure 8.

\[
\begin{align*}
X &= p_3 = -20.412, \\
Y &= p_4 = -35.355, \\
Z &= p_5 = 115.470 \\
B &= 54.736^\circ, \\
C &= 135^\circ, \\
p_1 &= 308.732, \\
p_2 &= 252.816
\end{align*}
\]

Figure 8 - Checking result of postprocessing in the CAD virtual prototype

The shape and dimensions of the workspace by subsystem M2 are shown in Figure 9.

To work with rotary tables a part of the workspace is available; it is designated as a reserve for working with rotary tables: rotary tables are as a rule used for machining of workpieces with dimensions proportional to the dimensions of rotary table, in the middle of the workspace of the machine along axis \( Y_M \)

\[
\begin{align*}
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4. ONE EXAMPLE OF VERIFICATION POSTPROCESSING

For verification we have selected machining of pyramid, where during machining the position of the worktable remains constant for long time and the control is easier. Parts of the program for these positions have been performed separately, in the regime of 3-axis machining, on the horizontal machining center LOLA HMC500, with two manually controlled rotary axes added, Figure 11. Positioning by two manually controlled rotary axes is achieved by using fixture, in which the first axis is blocked (Figure 11a), while the other two axes are used to realize the orientation of the workpiece, axes B and C. If we observe the chosen machine (Figure 11b) as a machine rotated for -90° around X axis (Figure 11c), conceptually the machine of SSD type is obtained (Figure 11d). It is here used for checking the configured postprocessor for vertical 5-axis machine with structure WXYZBCT.

Program for machining is prepared using CAD/CAM systems and the obtained G code using configured postprocessor. Since the workpiece is four-sided pyramid, tool orientation is achieved using four separate tilting the workpiece for angles B and C which were obtained in the G code, after postprocessing tool path from the CLF. First we have prepared the program for 3-axis pre-machining when the orientation of worktable \( B = 0 \) and \( C = 0 \). Afterwards pre-machining continues with the machining of each of the four sides of the pyramid. After the completion of pre-machining, tool orientation is achieved by using tilting fixture for the calculated angles B and C, for machining the first side of the pyramid (C0.B-21.801).
After the completion of machining of each side of the pyramid, machine stops with command M0 and takes up a new tool orientation using tilting fixture for the calculated angles B and C.

These tiltings for each side of pyramid are: (C0. B-21.801), (C90. B-21.801), (C180. B-21.801) and (C270. B-21801) and are presented as a frozen tool position and orientation according to the workpiece in Figure 12.

Machining of four-sided pyramid on the machine LOLA HMC500 is shown in Figure 13.

At the beginning, blank workpiece was pre-machined in the programmed 3-axis milling operation in z=const tool paths, leaving allowance for finishing, Figure 13a. Figure 13b shows milling of the first side
of the pyramid, with rotation of B-axis only (B-21.801), where C=0. Milling of the last side of the pyramid with orientation setting C=270, B=-21.801, is shown in Figure 13c. Final result of milling of all four sides of the pyramid is shown in Figure 13d and Figure 13e. In this way postprocessing calculations are verified through particular checking for four programmed orientations.

5. CONCLUSION

The main goals set out in this paper, were related to the development of one class of desktop reconfigurable machine tools, based on the concept of CNC open architecture control, and for machine tools with specific configurations.

The paper presents the initial concept for the development of desktop reconfigurable 5-axis machine tools. The system of assembly components is established in the form of configurator with the rules for using basic modules during synthesis of the machine structures in the building program for planned multifunctional reconfigurable desktop five axis machine tools.

Among all the structures of machine tools planned in the building program one class of reconfigurable desktop machine, types S3D, S4D, S5D and H5D was selected.

Formalism for postprocessing calculations for machines of WCBVXYZT type is shown in this paper, with checking of calculations on a virtual prototype and with machining test on an available machine equipped with two-axis fixture for setting orientation of the workpiece.

The application of these machines is important for further research in the field of multi-axis machining and reconfigurable 5-axis machine tools, as well as for education in programming, which is particularly important for educational institutions, in the acquisition of knowledge about the multifunctional reconfigurable machines tools.

Realization of the virtual five-axis machine which is integrated in a control system and system for programming will be considered in our future research. Also, the use of one kind of hybrid object programming of CNC machine tools, which is well known as STEP-NC, is planned, to the extent to which this method of programming will be applicable for future CNC units [7].

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REZIME

JEDNA STONA REKONFIGURABILNA MAŠINA ALATKA SA HIBRIDNOM KINEMATIKOM

U ovom radu je predstavljena jedna stona rekonfigurabilna mašina alatka sa hibridnom kinematikom, za četiri tipa mašina alatki, sa opisom primenjenog mehanizma i uspostavljenim modularnim sistemom za njihovo konfigurisanje. U radu je opisan i postprocesor za petoosnu obradu, primenjen na kinematičku strukturu mašine sa obrtno-nagibnim stolom, sa rotacijama (B,C). Takođe je pokazano izračunavanje pozicija aktuatora p1 i p2 kada mašina radi sa hibridnom kinematikom. Verifikacija postprocesora je ostavljena na virtualnom prototipu u CAD/CAM okruženju i eksperimentalno na jednoj raspoloživoj troosnoj mašini, sa dodatnim dvoosnim priborom. Eksperimentalni rezultati su potvrdili konfigurisani postprocesor, koji može da se koristi za programiranje mašina.

Ključne reči: konfigurisanje, rekonfigurabilna mašina alatka, postprocesor
Optimal Hardware Realization of Direct Subband Transformer

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State-of-the-art realizations of direct subband transformers require utilization of synchronization memory banks with significant capacity between different levels of image decomposition. This paper presents novel optimal hardware realization of direct subband transformer without synchronization memory banks between different levels of image decomposition. This solution also enables significant savings in memory and logic resources, as well as minimal delay which direct subband transformer introduces into image compression system.

**Key words:** Direct subband transformation, Direct two-dimensional image filtering, Digital image compression, Minimization of used resources

1. INTRODUCTION

State-of-the-art direct subband transformers for an input uncompressed image require synchronization memory banks between different levels of image decomposition. Significant efforts are devoted to reduce the amount of used synchronization memory.

Achieved results are memory efficient solutions presented in [1] - [9]. Generally, block diagram of state-of-the-art direct subband transformer for an input uncompressed image with synchronization memory banks and 3 levels of image decomposition, is shown in Figure 1.

Each block (Block 0, Block 1 and Block 2) performs two-dimensional direct filtering of coefficients fed to its input. The two-dimensional direct filtering comprises of separate applications of one-dimensional direct filtering, first horizontally along the rows and then vertically over columns. The output results of two-dimensional direct filtering within a single decomposition level are transformation coefficients in four subbands: LL, LH, HL and HH.

The LL subband is the result of direct low-pass (LP) filtering along the rows and direct LP filtering over columns, and contains simultaneously low frequency horizontal information and low frequency vertical information.

The LH subband is the result of direct LP filtering along the rows and direct high-pass (HP) filtering over columns, and contains simultaneously low frequency horizontal information and high frequency vertical information, i.e. horizontal edge information.

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The HL subband corresponds to direct HP filtering along the rows and direct LP filtering over columns, and contains simultaneously high frequency horizontal information and low frequency vertical information, i.e. vertical edge information.

The HH subband corresponds to direct HP filtering along the rows and direct HP filtering over columns, and contains simultaneously high frequency horizontal information and high frequency vertical information, i.e. diagonal edge information.

State-of-the-art multilevel two-dimensional direct filtering is performed by the application of single level two-dimensional direct filtering over the input uncompressed image at the decomposition level 0 or the subband LL\(_i\) at the next decomposition level \(i+1\), that is the result from previous filtering. The subbands of the decomposition level \(i\) (generated by Block \(i\)) are LL\(_i\), LH\(_i\), HL\(_i\) and HH\(_i\), \(i = 0,1,2\).

In order to have all transformation coefficients available for further processing in the image compression system (quantization, probability estimation, entropy encoding) in a timely manner, it is necessary to perform compensation of delays occurring during direct filtering. The synchronization memory banks \(z^{-D}\) and \(z^{-2D}\) from Fig. 1 are used for that purpose.

2. OPTIMAL DIRECT SUBBAND TRANSFORMER

Block diagram of the optimal direct subband transformer for an input uncompressed image without synchronization memory banks and with 3 levels of image decomposition, which shows the basic concept of optimal hardware realization described in next section, is shown in Fig. 2.

This system is able to process the input uncompressed image, as well as the coefficients generated by filtering at the decomposition level 0 and at the decomposition level 1, without using synchronization memory banks.

Each block (Block 0, Block 1 and Block 2) performs two-dimensional direct filtering of data fed to its input. The two-dimensional direct filtering comprises of separate applications of one-dimensional direct filtering, first horizontally along the rows and then vertically over columns.

Subbands of the decomposition level 0, LL\(_0\), LH\(_0\), HL\(_0\) and HH\(_0\), are generated by Block 0 by applying single level two-dimensional direct filtering over the input uncompressed image. Subbands of the decomposition level 1, LL\(_1\), LH\(_1\), HL\(_1\) and HH\(_1\), are generated by Block 1 by applying single level two-dimensional direct filtering over the subband LL\(_0\). Subbands of the decomposition level 2, LL\(_2\), LH\(_2\), HL\(_2\) and HH\(_2\), are generated by Block 2 by applying single level two-dimensional direct filtering over the subband LL\(_1\).

![Figure 2 — Block diagram of the optimal direct subband transformer for an input uncompressed image](image)

Within each block, filtering begins with one-dimensional horizontal filtering of input data, line by line, starting from the first line. The beginning of vertical filtering does not wait for the completion of horizontal filtering over all lines — it starts as soon as minimum number of coefficients required for vertical filtering is generated. As soon as horizontal filtering of the first two lines is over and the horizontal filtering of the third line has started, the first resulting coefficients of vertical filtering are generated on the basis of the input coefficients produced by horizontal filtering. Horizontal filtering of the consequent lines of input uncompressed image is performed next, with vertical filtering resuming as soon as the consequent coefficients are produced by horizontal filtering for the continuation of vertical filtering.

Also, the direct filtering of the subband LL\(_i\) (resulting from two-dimensional filtering within the Block \(i\)) by the Block \(i+1\), begins as soon as the coefficients from the first horizontal line of the subband LL\(_i\) are produced. In other words, the Block \(i+1\) „does not wait“ for the completion of two-dimensional filtering from the previous Block \(i\). It filters its input data as soon as minimum required number of (both horizontally and vertically) filtered lines is produced by the previous Block \(i\). In this manner, the final results of direct filtering from all
three levels of decomposition are available at the system output without any synchronization memory banks, thus saving memory resources.

Hardware realization of described concept is shown in next section of this paper.

3. OPTIMAL HARDWARE REALIZATION OF DIRECT SUBBAND TRANSFORMER

Schematic diagram of optimal hardware realization of direct subband transformer for an input uncompressed image is shown in Figure 3 (data processing section) and Figure 8 (control signal generation section).

Figure 3 – Schematic diagram of optimal hardware realization of direct subband transformer for an input uncompressed image - data processing section

Nonstationary direct filter described in [10] is used as horizontal and vertical filter from Fig. 3. This filter has been chosen since its hardware architecture requires less logic resources than any other state-of-the-art solution, as it is shown in [10]. The difference equations describing LP filtering and HP filtering are given in (1) and (2), respectively.

\[
y_0[n] = -\frac{1}{8}x[n] + \frac{1}{4}x[n-1] + \frac{3}{4}x[n-2] + \frac{1}{4}x[n-3] - \frac{1}{8}x[n-4] \tag{1}
\]

\[
y_1[n] = -\frac{1}{8}x[n-1] + x[n-2] - \frac{1}{8}x[n-3] \tag{2}
\]

The input data for the horizontal filter are routed through the multiplexer that provides direct filtering of either input pixels or the coefficients from decomposition level 1 or the coefficients from decomposition level 2, in appropriate time slots. The control signals \textit{ctrl_coeff} and \textit{ctrl_mux} are used in order to secure that, within each line of the input uncompressed image, the input of horizontal filter is fed firstly by input pixels, namely first three pixels from the respective line consecutively, which are necessary for the generation of the first results of horizontal filtering. Next, the control signals secure that, at the horizontal filter input, the first coefficient from the appropriate line from the level 1 of the decomposition (meanwhile generated after horizontal and vertical filtering) is fed. Further, the control signals provide that, after every two new pixels of the input image, there is one coefficient of the appropriate line of the decomposition level 1 (meanwhile generated after horizontal and vertical filtering) at the input of the horizontal filter. The first coefficient of the appropriate line from the decomposition level 2 (meanwhile generated after horizontal and vertical filtering) is fed to the input of horizontal filter after horizontal and vertical filtering of the first three coefficients from the appropriate line from the decomposition level 1. Each following coefficient from the appropriate line from the decomposition level 2 is routed to the horizontal filter input after every two new coefficients from the appropriate line from the decomposition level 1, have been horizontally and vertically filtered.

The described dynamics of direct filtering of the pixels and the coefficients from the beginning of the lines that are directly filtered is presented in time diagrams in Fig. 4. The rectangles denote time instants when horizontal filtering of appropriate pixel or coefficient is performed, whereas the eclipses denote time instants when vertical filtering of appropriate coefficients is performed. This kind of dynamics provides minimization of delay which the direct subband transformer introduces into an image compression system, since the coefficients from the decomposition levels 1 and 2 are filtered right after they are generated by filtering at the previous decomposition level.

Figure 4 – Filtering of pixels at the beginning of line

The end of filtering of a single line is done in such a manner that the multiplexer, after all pixels of the input image have been directly filtered, routes all remaining coefficients of the appropriate line from the decomposition level 1 (which have been already generated by horizontal and vertical filtering of the input pixels) to the input of the horizontal filter. This
way, the process of generation of input coefficients for the filtering at the decomposition level 2 is over, and the multiplexer routes these coefficients to the input of the filter.

Filtering of the appropriate line at the level 2 of the decomposition is finished by horizontal and consecutively vertical filtering of remaining coefficients from the decomposition level 1. The dynamics of the filtering of the pixels and coefficients at the end of lines being filtered is shown in Figure 5.

![Figure 5 – Filtering of pixels at the end of line](image)

Vertical filtering of each coefficient is performed in the following time instant after horizontal filtering, provided by cascade connection of the horizontal and the vertical filter. Horizontal filtering is activated by means of an appropriate control signal from the signal group ctrl_h_filter, whereas vertical filtering is activated by means of an appropriate control signal from the signal group ctrl_v_filter.

The output coefficients from the vertical filter are fed back to the multiplexer input (if the coefficients are result of level 0 or level 1 of the decomposition), or forwarded to the output of the direct subband transformer (if the coefficients are result of level 2 of the decomposition).

The results of vertical filtering of the first line of coefficients at each consecutive decomposition level are generated after the first three lines of input pixels (for the level 0 of the decomposition) or coefficients (for the levels 1 and 2 of the decomposition) have been filtered.

Further, the results of the vertical filtering of every line of coefficients at every succeeding decomposition level are generated after two succeeding lines of pixels (for the level 0 of the decomposition) or coefficients (for the levels 1 and 2 of the decomposition) from the preceding decomposition level have been filtered.

The block Temp buffer is used for temporary storage of interim results, wherein writing to and reading from are controlled by the control signals ctrl_buffer. The time diagrams depicting the beginning of two-dimensional direct line-wise filtering are given in Figure 6.

![Figure 6 – The beginning of line-wise filtering](image)

After vertical filtering of the input uncompressed image has been finished, there is vertical filtering of all remaining lines of coefficients at the decomposition level 1. After vertical filtering of the last line of coefficients at the decomposition level 1 has been finished, vertical filtering of all remaining lines of coefficients at the decomposition level 2 is performed, finishing the process of direct filtering and the decomposition of input image by means of the disclosed direct subband transformer. The time diagrams depicting the end of two-dimensional direct line-wise filtering are given in Figure 7.

![Figure 7 – The end of line-wise filtering](image)

When odd lines are directly filtered, the generated coefficients belong to LL and LH subbands of respective decomposition level. When even lines are directly filtered, the generated coefficients belong to HL and HH subbands of respective decomposition level.

**HFSM** state machines in Fig. 8 have key role for the generation of control signals ctrl_coeff, ctrl_mux, ctrl_h_filter and ctrl_buffer for the decomposition levels 0, 1, and 2. Each state machine is responsible for a respective decomposition level. The state machines forward requests for use of the horizontal filter to the block Arbiter, which selects the decomposition level to which the access to the filter will be granted, that is from which level the coefficients will be filtered in the given time instant. If only a single **HFSM** requests the use of the horizontal filter at a given time instant, the
block Arbiter grants the access to the filter to the given HFSM.

Figure 8 – Schematic diagram of optimal hardware realization of direct subband transformer for an input uncompressed image - control signal generation section

If more than one HFSM simultaneously request to use the horizontal filter, the block Arbiter grants the access to the filter to the HFSM which corresponds to the lowest decomposition level. The HFSM whose request has been serviced is informed about the acceptance by means of corresponding feedback signal. The HFSM state machines with the block Arbiter provide the dynamics of control signals generation to be in accordance with the previously described dynamics of the filtering of coefficients that secures minimization of delay which the direct subband transformer introduces into the image compression system. Besides the signal that provides use of the horizontal filter, there are signals in the control signal group ctrl_h_filter, denoting a coefficient’s position within a line and the decomposition level the filter is at the moment assigned to.

The state machines VFSM have key role for the generation of control signals ctrl_v_filter for decomposition levels 0, 1 and 2. Each state machine is responsible for the generation of flags denoting the position of a line within the image for a given decomposition level. The multiplexer, controlled by signal that represents the decomposition level to which the horizontal filter has been granted in the previous cycle, forwards an appropriate level flags to the vertical filter.

The Initialization block provides a regular initialization of all HFSM and VFSM state machines.

Given that, in the described realization, the horizontal direct filtering of a coefficient is done first, followed by vertical direct filtering in the next cycle, it is possible to perform simultaneous horizontal and vertical filtering of coefficients from different levels of the decomposition. Moreover, this realization makes possible simultaneous horizontal and vertical filtering of neighboring coefficients from the same decomposition level, when it is needed. This way, savings in time resources and minimization of delay is accomplished.

Table 1 shows the comparison between the latency introduced into image compression system by optimal hardware realization of direct subband transformer and latency introduced into image compression system by state-of-the-art direct subband transformer presented in [1] - [5]. Presented latency corresponds to direct subband transformer with 3 levels of decomposition. It is clearly shown that optimal hardware realization presented in this paper introduces several times lower latency.

Table 1. Latency comparison of direct subband transformer hardware realizations (for 3 levels of decomposition)

<table>
<thead>
<tr>
<th>Latency (number of lines)</th>
<th>[1]-[5]</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

The described concept for optimal hardware realization of direct subband transformer can also be used for systems with an arbitrary number of decomposition levels.

Table 2 shows the comparison between the hardware resources of optimal hardware realization of direct subband transformer and hardware resources of state-of-the-art direct subband transformer presented in [1] - [5]. Presented results correspond to direct subband transformer with N levels of filtering and decomposition of digital image with W pixels width, wherein in hardware realizations [1] - [5] finite impulse response filters of 2D+1 length are used.

Table 2. Hardware resources comparison of direct subband transformer hardware realizations (for N levels of decomposition)

<table>
<thead>
<tr>
<th>Resources</th>
<th>[1]-[5]</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of horizontal filters</td>
<td>N</td>
<td>1</td>
</tr>
<tr>
<td>Number of vertical filters</td>
<td>N</td>
<td>1</td>
</tr>
<tr>
<td>Capacity of synchronization memory</td>
<td>[2W \left( 2^N - 3 + \frac{1}{2^{N-1}} \right)]</td>
<td>0</td>
</tr>
</tbody>
</table>
Unlike the state-of-the-art solutions, proposed optimal hardware realization of direct subband transformer uses a single horizontal and a single vertical filter for all decomposition levels, thus providing significant savings in logic resources. The proposed realization achieves significant savings in memory resources as well, since it does not require synchronization memory banks between different levels of decomposition. Also, it has to be noticed that amount of used hardware and memory resources in state-of-the-art direct subband transformers is being increased when number of decomposition levels is increased, while increasing the number of decomposition levels in proposed optimal hardware realization of direct subband transformer does not affect the amount of used hardware and memory resources.

Functional correctness of proposed optimal hardware realization of direct subband transformer has been experimentally verified by implementing the proposed realization with 7 levels of decomposition in FPGA integrated circuit. The exact number of decomposition levels for experimental verification has been chosen based on the fact that good quality of full HD (1920x1080 pixels) image compression requires 7 levels of decomposition.

Table 3 presents used hardware resources and maximum operating frequency of optimal direct subband transformer implementation in Altera FPGA EP4CE115F29C7

<table>
<thead>
<tr>
<th>Used resources</th>
<th>Memory usage</th>
<th>Operating frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logic elements</td>
<td>6415/114480 (6%)</td>
<td>138.27MHz</td>
</tr>
<tr>
<td>Registers</td>
<td>3296</td>
<td></td>
</tr>
<tr>
<td>Memory (bits)</td>
<td>192512/3981312 (5%)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 presents used hardware resources and maximum operating frequency for optimal hardware realization of direct subband transformer for an input uncompressed image for seven decomposition levels in Altera FPGA device EP4CE115F29C7 using Altera software suite Quartus II 12.1.

4. CONCLUSION

Optimal hardware realization of direct subband transformer for an input uncompressed image, presented in this paper, eliminates synchronization memory banks between different levels of decomposition, thus providing significantly savings in memory resources. The proposed realization achieves savings in logic resources as well, since it does not require simultaneous horizontal and vertical filtering of coefficients from different levels of decomposition. The proposed solution also achieves minimum delay which the direct subband transformer introduces into the image compression system, providing significant savings in time resources.

5. ACKNOWLEDGEMENT

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REFERENCES

REZIME

OPTIMALNA HARDVERSKA REALIZACIJA DIREKTNOG PODOPSEŽNOG TRANSFORMATORA

Realizacije direktnog podopsežnog transformatora prema postojećem stanju tehnike zahtevaju korišćenje sinhronizacionih memorija značajnog kapaciteta između različitih nivoa dekompozicije slike. U ovom radu je prezentovana optimalna hardverska realizacija direktnog podopsežnog transformatora bez korišćenja sinhronizacionih memorija između različitih nivoa dekompozicije. Ovo rešenje takođe omogućava značajnu uštedu u memorijskim i logičkim resursima, kao i minimalno kašnjenje koje u sistem za kompresiju slike unosi direktni podopsežni transformator.

Ključne reči: direktna podopsežna transformacija, dvodimenzionalno filtriranje slike, kompresija slike, minimizacija utrošenih resursa
Realization and Operation of Roof-top Photovoltaic Power Plant at the Faculty of Technical Sciences in Novi Sad

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The paper presents a process of realization and operation of roof-top photovoltaic power plants at the Faculty of Technical Sciences in Novi Sad. A procedure for location selection, designing process and optimization of equipment of the power plants is presented. The realization is given through overview the plant assembling, checking of the equipment and final testing. At the end, the plant operation is analyzed based on the results of the three years period.

Key words: Renewable Energy Sources, PV panels testing, PV plant design and operation

1. INTRODUCTION

Excluding the hydro power sector, where there is a significant capacity, other forms of renewable energy sources (RES) in Serbia are still under-utilized. It is estimated that the total technically usable potential of renewable sources is about 5.06 Mtoe (tonnes of oil equivalent, toe), which is 32.5% of total primary energy consumption in Serbia (15.531 Mtoe). The target set for 2020 is that 27% of total primary energy consumption should be covered by RES [1]. To achieve this objective at least 1092 MW of new RES capacity should be built. Among others, solar energy is a realistic option to participate in fulfilling of this task.

The average intensity of solar irradiation on a horizontal surface in the territory of the Serbia ranges from 1.1 - 1.7 kWh/m²/day in January, up to 5.9 - 6.6 kWh/m²/day in July [1,2,3]. These data indicate that it can be expected from 1200 kWh/m² to 1550 kWh/m² annually. The level of irradiation can be much higher (about 20% - 30%) if one considers angled surfaces or rotating panels (which follows the movement of the Sun). In that cases, from 1560 kWh/m² to 2000 kWh/m² can be expected. Based on these data it can be concluded that the potential of solar energy in Serbia is very favorable.

This type of energy may be used as thermal energy or for the conversion into electrical one using photovoltaic (PV) panels [2,3]. Based on official infor, Serbia has 8.1 MWp of solar PV power plants in operation, and further 1.84 MWp in built [1] (Sep. 2015).

This paper presents the process of designing, building, commissioning and operation analysis of one of the first photovoltaic (PV) power plants in Serbia, “FTN Novi Sad”, placed on the flat roof of the Faculty of Technical Sciences (FTS) in Novi Sad. The task was to build a PV power plant with installed power of 8 kW (9.6 kWp). The project was implemented in 2011. The aim of the project was to obtain a sort of training ground - open laboratory for students of FTS and thus provide conditions for practical training and research. The investor and implementer was FTS through its Centre for Renewable Energy and Power Quality (CRESPQ) with support of the Provincial Secretariat.
for Education, Administration and National Communities and various commercial companies (SMA Solar Technology, Hilty, Gran Solar, Evrothenerika, Eaton Moeler, Elektrokoil, Elektrovojvodina and Banca Intesa).

2. POSITIONING OF A PV PLANT

The first step in process of designing the roof-top PV plant was to determine location, i.e. the suitable roof and exact location of the PV plant on it. In that process available flat roof of the FTS buildings within the campus of the University of Novi Sad were considered. Figure 1 shows that two flat roofs (the roof of the tower and the roof amphitheatres) were available. Additional request was that connecting point to the public grid should be as close as possible, to avoid additional cable costs and losses.

Selected location for PV panels is shown in Figure 2. This is a flat roof of FTS building covering four amphitheatres, a library, a reading hall and corridors. The surface of the flat roof is approximately 1,100 m², it is without significant obstacles for PV panels mounting and very close to the public electricity grid connection point. However, during the morning hours, part of the roof enters into surrounding buildings shadow, so entire surface is not suitable for setting up the PV panels. After a detailed analysis a proposal was that the PV panels should be placed on the northern side of the roof and placed on fixed support structure, under optimum angle.

3. DESIGNING PROCEDURE

Designing a roof-top PV plant requires following steps:
- assessment of energy energy potential,
- selection PV power plant concept,
- determination of the panels optimum position, i.e. panels micro-location,
- optimization and harmonization of the PV power plant’s components.

3.1. Assessment of solar energy potential

Before the beginning of the project, CRESPQ engineers made assessment of the solar energy potential (solar irradiation) and expected annual electricity generation of the selected location. For both evaluations, interactive software tools PVsyst [4] and PVGIS [5] were used.

The results showed that the average annual value of solar irradiation is 1,537 kWh/m². Assuming that the efficiency of PV panels is around 14.3% (for polycrystalline panels) and that total losses in the PV power plant is about 23% (12% electrical losses, and 11% losses due to temperature characteristics of the panels) [5,6,7], estimated average annual electricity generation is 169.2 kWh/m².

For desired PV plant, with installed PV capacity of 9.6 kWp (40 panels of 240 Wp), an estimate of average monthly electricity generation is shown in Figure 3. Based on that estimate, annual production of such a PV power plant would be around 11.2 MWh of electricity.
3.3. Optimal positioning of PV panels

For purposes of determining the optimal position of the PV panels, a geodetic survey of the position and height of the roof, as well as the surrounding buildings (shading effect) was performed. To find optimal positioning of PV panels on the roof, which enables optimization of electricity generation, the PVsyst software package was used [4]. An additional problem for positioning the PV panels were restrictions of available roof surface due to existence of various low height obstacles on the roof. A special request was that structure should be mounted on the roof without drilling holes or making any other damages on the roof surface, during assembly and in the course of exploitation of PV system. The construction itself had to meet usual requirements related to robustness, temperature change, climate, humidity, wind blowes and similar.

After careful consideration of all factors, it was determined that the panels should be placed on the northern side of the roof, so that the structure is set up facing south with an inclination of 30° (Figure 5). Selected position is determined after optimization using shading yearly diagram, as shown in Figure 6. The diagram shows that shading can not be avoided and that the largest losses occur (on average) until 9:00h a.m. An example of the shade, coming from the surrounding building is shown in Figure 2.

3.4. PV plant optimization and components harmonization

Selection of PV system components starts with PV panels and inverter. Generally, there are three types of PV panels: mono-crystalline, poly-cristalline and thin-film. They have different characteristics and efficiency [2]. Taking into consideration their efficiency, economic effects and market availability, poly-crystalline PV panels were chosen.

When choosing a value of installed power of PV panel and inverter, the factor of inverter dimensioning, $k_{inv}$ should be taken into account [8]. This factor represents the ratio of rated (nominal) power of PV panel ($P_{inv}$) and output power of inverter ($P_{inv}$):

$$k_{inv} = \frac{P_{inv}}{P_{inv}}$$

Factor of inverter dimensioning typically ranges between 0.8 < $k_{inv}$ < 1.25. The exact value of $k_{inv}$ depends on geographic location, level of solar irradiation, type of supporting structure and inverter characteristics. Analysis of these factors indicated that the $k_{inv}$ may be greater than 1, and the designers have opted for $k_{inv}=1.2$.

For desired PV plant, a three-phase grid inverter Sunny Tripower 8000 TL (manufacturer SMA Solar
Technology), with rated output power of 8 kW was selected [6].

As it was decided that $k_{inv}=1.2$, it was determined that the total PV rated power should be 9.6 kWp. After considering different technical and economical factors, polycrystalline silicon type PV panels type JKM 240P were selected (manufacturer Jinko Solar), with rated power of 240 Wp [7]. They are arranged in two strings (series A and series B) with 20 serially connected panels in each string (Figure 4).

When calculating the electrical installation in a PV power plant, particular attention was paid to minimizing power losses in the conductors, which are limited to 1% [10]. The most significant losses are on the AC side in the supply line, which connects the inverter and cable connection box (CCB). A cable with cross section of 4x6 mm$^2$ was selected, thus limiting the maximum losses in the supply line to the value of 0.2%. The average value of the losses in the DC cables, with cross-section of 6 mm$^2$, for both PV strings, is up to 0.5%.

A further requirement is to check the conformity of the voltage and current levels of inverter and PV panel arrays (it determines the number of panels in series and, if necessary, in parallel connection). Since the output voltage of the PV panels significantly changes with temperature, checking of the voltage level was carried out as a function of temperature. Standard checking for regions with moderate continental climate includes panel (cell) temperature of 70$^\circ$ C, which relates to summer months conditions and panel temperature of -10$^\circ$ C, which relates to winter months conditions [10]. It is recommended to check voltage levels for even lower temperatures if they may occur in the PV plant operating area. These checks have confirmed the choice of 2 x 20 panels with total installed power of 9.6 kWp.

4. THE PROJECT REALIZATION

After the designing phase (spring 2011), in which CRESPO's experts made final detailed design, received appropriate permits and approvals and fulfilled technical requirements, building (realization) of the plant have started (summer 2011).

Works on the site began by mounting metal support structure on the flat roof. The structure is fixed on concrete feet, which are mounted on rubber surfaces in order not to damage the roof, and then placed in an array. One set of the galvanized metal structures, shown during installation phase can be seen in Figure 7.

PV panels were mounted in such a way that the long edge was parallel to the roof (landscape) with an angle of 30$^\circ$, as specified during optimization. Two such strings were placed. The string “A” panels after installation are shown in Figure 8.

![Figure 7 – Metal construction uduring assembly.](image)

Next, it was necessary to install inverter, switching and protection equipment as well as communications and monitoring equipment. All these devices are housed in a standard electrical cabinet, which is mounted inside the FTS building. Attached to it is an external monitor for displaying characteristic parameters of the PV plant and environmental conditions.

![Figure 8 – String A with PV panels.](image)

Inverter, which is shown in Figure 9, is located in the upper part of the cabinet, for safety reasons in order to prevent personal injury due to high operating temperatures. Still, it is visible through a glass window and students and other interested persons may follow its operation on small front display.

![Figure 9 – Three-phase inverter](image)
Below the inverter necessary switchgear and protective equipment is located, which consists of manual DC and AC circuit breakers, motor switch, time relay and relay intended for small PV plants to prevent the island mode of operation.

In addition to the power part there are following communication, monitoring and measuring devices: integrated communication device in the inverter, a device for communication over the Internet (Webbox), a measuring and monitoring device (Sensorbox) and a computer. Webbox with integrated webserver, enable recording most of the important system parameters in the internal memory and on the computer. Sensorbox is actually a mini weather station that measures the solar radiation, wind speed, temperature PV panels and air temperature. These devices enable monitoring of the plant operation parameters on-site, or remotely via the Internet.

On the attached computer, special software delivered by SMA is installed, whose task is to process information from sensorbox and displays them on the connected monitor. In addition to the above-mentioned measured data, the monitor displays the value of the instantaneous power, produced energy (during this day and total generated energy from commissioning day), equivalent CO₂ emission reduction, and a couple of other interesting data. Complete PV plant operation can be monitored via the web site https://www.sunnyportal.com.

5. PV PANELS TESTING

Installed PV panels are accompanied with ten different certificates, as acknowledgement of their quality and functionality. These certificates were supplied by the manufacturer and they are results of testing in the factory or accredited laboratory.

However, to verify the functionality of the PV panels, experts of the CRESPQ have to conducted appropriate tests on site. Firstly, measurement of I-U and P-U characteristics of one, randomly selected PV panel was performed, and then validity of all installed PV panels was tested. The purpose of these on-site tests was to check the characteristics of all PV panels and exclude any possibility of damage which may occur during transport or installation.

5.1. Determination of PV panels’ characteristics before connection

Current-voltage (I-U) characteristic is a fundamental indicator of a PV panel performance. One of the delivered JKM-240P PV panels was tested.

At the beginning and at the end of the measurement, intensity of solar irradiation and PV panels’ temperatures were recorded. The mean value of the irradiation during the measurements was 612 W/m², while the average value of the panel temperature was 22° C. For the above mentioned conditions following characteristic data are obtained: short circuit current \( I_{sc} = 5.3 \text{ A} \), open circuit voltage \( U_{oc} = 35.3 \text{ V} \), maximum power \( P_{max} = 147 \text{ W} \), voltage at the point of maximum power \( U_{mp} = 28 \text{ V} \), current at the point of maximum power \( I_{mp} = 5.25 \text{ A} \). Further measurement was performed at several characteristic points [12]. Figure 10 shows the I-U and P-U curve of the PV panel JKM-240P.

![Figure 10 - I-U and P-U characteristics obtained by measurements](image)

Recorded I-U and P-U curves of the PV panels in these conditions closely match the I-U and P-U characteristics given in the data-sheet for 600 W/m² and 25° C [7]. By comparison of these characteristics, it can be concluded that PV panels fully operate in accordance with the data-sheets obtained from the manufacturer.

5.2. Individual PV panel testing

In addition to the mentioned characteristics determination, two set of tests were performed on each of the PV panels, individually. The first set was a visual overview of all PV panels in order to determine possible visible mechanical damage. The second set of tests was measurement of short circuit current and open circuit voltage of each PV panel using a digital multimeter. After comparison of the measured and catalog values validity of the PV panels was confirmed [12].

6. PV PLANR OPERATION START

The roof-top PV plant was named “FTN Novi Sad” and prepared for operation start at the end of October 2011.

However, before beginning, in order to analyze proper operation of the plant, a simulation model of the complete plant have been developed. The model uses the data from the installed components manufacturers’ data sheets (PV panels, DC/AC inverters, DC and AC switches, etc.). The complete model is described and application results are shown in [13].
Comparison of simulation results with actual results of plant operation has demonstrated the validity of the concept. The analysis confirmed that implemented system and structure were well designed and it was concluded that the plant can be put into operation.

Photovoltaic power plant “FTN Novi Sad” was put into operation on October 25, 2011, after due verification and testing of protection and grid connection by experts and officials of power supply company “DP Elektrovojvodina” from Novi Sad.

After a test regime operation, which lasted for 2 months, the plant officially started with delivering electrical energy to the power system of Serbia on January 1, 2012.

7. ANALYSIS AFTER THE FIRST YEAR OF OPERATION

7.1. Analysis of energy generation results

To illustrate the work PV power plant two typical cases were selected. Figure 11 shows the daily variation of the PV plant (inverter) output power on July 13, 2012, when it was sunny and mostly a clear day. On that day the plant has achieved the highest daily production since beginning of the operation, 60.9 kWh. During highest solar irradiation inverter operated with maximum power of 8 kW, although the temperature of the PV panels was high (Figure 11).

![Fig. 11 – Variation of inverter output power for July 13, 2012](image)

Effects of shading reduced generation results, as it was expected, especially in the morning hours. This effect can be seen in Figure 11 as low power period in the morning from 6:30h to 8:35h. After that (at 8:35h) a sharp rise in power can be observed - from 0.5 kW to 4 kW. This is a result sudden insolation of the panels as they exit from the shadow. How to overcome this problem will be specifically investigated in future research.

Figure 12 shows the daily change of output power for Dec. 22, 2012, when in the course of the whole day was present fog. This day has been the day with the smallest energy generation since the beginning of the plant operation, only 1.1 kWh. Output inverter power throughout the day has not reached even 300 W. Irradiation throughout the day was less than 100 W/m². These results are in accordance with expected ones and fit into estimated values presented in the Figure 3.

![Fig. 12 – Variation of inverter output power for Dec. 22, 2012.](image)

7.2. Performance ratio

To determine the efficiency of available solar power the Performance Ratio (PR) is used. It does not depend on the location and represents a unique operating factor. It is defined as the ratio of actual energy generated and theoretically predicted for a particular PV power plant. For this plant the PR is very high due to good design, optimization and compliance components. During winter is higher, and in the summer a little smaller, so that the average value per annum is 0.85 (otherwise, the practical limits are 0.75 to 0.85). More detailed analysis and achieved PR values are given in [14].

7.3. Harmonic distortion

Testing of permitted current harmonics is a standard procedure that is required during the trial run of the plant. At the time of commissioning the plant “FTN Novi Sad” this criterion has not been checked. The plant has been one of the first PV power plants in Serbia that have been officially connected to the distribution network, and there were not enough experiences in this field. Since CRESPPQ has a device for power quality monitoring, such measurements were subsequently carried out.

In the existing „Rules on Distribution System Operation“ values of individual harmonics are given in relation to short circuit power at the point of common coupling (PCC) of the PV plant [8]. These values are named “Normalized current harmonic values”, and presented in A/MVA for each harmonic (Table 1).

These limit values are multiplied with actual short-circuit power at the PCC of the “FTN Novi Sad” and permitted individual harmonic currents value are calculated \( I_{S\text{perm}} \) (Table 1). The values of \( I_{S\text{perm}} \) are in fact the maximum permissible current harmonics values at the plant output.
Table 1. Current harmonic values

<table>
<thead>
<tr>
<th>Harmonic order - ν</th>
<th>5</th>
<th>7</th>
<th>11</th>
<th>13</th>
<th>17</th>
<th>19</th>
<th>23</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>1.0</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>0.25</td>
<td>0.3</td>
<td>0.25</td>
</tr>
<tr>
<td>I_h-perm [A]</td>
<td>4.85</td>
<td>3.23</td>
<td>1.62</td>
<td>1.29</td>
<td>0.97</td>
<td>0.81</td>
<td>0.97</td>
<td>0.81</td>
</tr>
<tr>
<td>I_h-meas.max [A]</td>
<td>0.64</td>
<td>0.50</td>
<td>0.12</td>
<td>0.17</td>
<td>0.12</td>
<td>0.03</td>
<td>0.01</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Results of harmonics measurements, i.e. the measured values of the maximum individual current harmonics (I_h-meas.max) are noted in the Table 1, also. As it can be seen, the measured values of individual current harmonics at the PV power plant are far below the permissible values. The measurements have confirmed that the plant is in full compliance with the criteria of the grid operator.

However, it should be noted that the manufacturer's specification defines that the inverter works with low current harmonic distortion (~2%) only if operating power is above 50% of the rated (nominal) [6]. This indicates that there is a potential for significant current distortion, especially in morning and evening hours. Some results are shown in [15]. Still, this phenomenon requires further study and explanations, so it will be the subject of separate research work.

8. ANALYSIS AFTER THREE YEARS OF OPERATION

8.1 Power generation results

Photovoltaic power plants FTN Novi Sad in the period 2012-2014 generated in total of 33,410 kWh of "green" energy and deliver it to the electric power system of Serbia. This is a very good result, about 2.9% higher than expected. Figure 13 provides a comparative overview of the estimated (line) and actual monthly production of electricity (columns) in period 2012-2014.

![Figure 13 – Comparative display of actual and estimated production](image)

It can be seen that the highest production have been achieved during summer months (June, July and August) in range from 1,285 kWh/month to 1,543 kWh/month, while the minimum monthly production were in December and January - from 292.2 kWh/month up to 500 kWh/month.

8.2 PV array characteristics

Power characteristics of PV panels array has been recorded before the start of commissioning the plant in operation, and again after three years with new professional equipment. The aim was to determine the amount of power reduction during this period. According to the terms of the manufacturer’s warranty, weakening of the PV panels’ power should not exceed 0.83% per year for the first 12 years of operation.

According to manufacturer’s data, PV array of 20 panels has rated power of 4,800 Wp (20x240Wp) [7]. It is necessary to take into account the tolerance of ±3%, so the actual PV array power, with new panels should be in the range of 4,656 Wp to 4,944 Wp. After three years in operation, PV arrays’ power should be between 4,359.6 Wp to 4,820.4 Wp.

Figure 14 shows the P-U characteristics of the tested PV array with solar radiation at 480 W/m² and the panel temperature of 40.4° C. The point of maximum power (PMP) of the PV array will be further observed, only. The measured value of the PMP is 2,016 Wp. Reduced to standard test conditions (STC), the full array power is 4,535.6 Wp.

It can be seen that the measured PV arrays’ power is reduced, and it practically coincides with the lower limit of the predicted power range.

![Figure 14 – Output power characteristics of PV array after three years](image)
9. CONCLUSION

Team of experts from the Center of Renewable Energy Sources and Power Quality (CRESPOQ) of the Faculty of Technical Sciences (FTS) in Novi Sad, completed feasibility studies and major construction projects, made the PV plant’s design, obtain all the necessary permits, and commissioned a solar PV power plant 8 kW on the flat roof of the FTS.

Significant assistance in the implementation of the project was provided by the students of the study program Electrical Power Engineering - Renewable Energy Sources. For them this project was part of their education and has the character of practical work in an open laboratory or at an experimental polygon. The PV plant will maintain its role and will be used for further training of students, in order to gain practical knowledge and skills. It will be employed also for further research in the current field, and for popularizing the use of renewable energy sources.

After three years of experience it can be concluded that the roof-top PV plant of the Faculty of Technical Sciences works seamlessly and that in period 2012-2014 it has delivered around of 33,410 kWh of “green” electrical energy to the power system of Serbia.

REFERENCES


SUMMARY

REALIZACIJA KROVNE FOTONAPONSKIE ELEKTRANE NA FAKULTETU TEHNIČKIH NAUKA U NOVOM SADU

Opisana je realizacija i rad krovne fotovoltačke elektrane na Fakultetu tehničkih nauka u Novom Sadu. Prvo je predstavljen metod izbora lokacije elektrane. Proces projektovanja je uključio procenu proizvodnje, izbor koncepta elektrane i optimizaciju opreme. Sama realizacija je data kroz prijek izgradnje, ispitivanja opreme i završnih testiranja. Na kraju je analiziran rad elektrane na bazi rezultata u trogodišnjem periodu.

Ključne reči: fotovoltačka elektrana, fotovoltački paneli, proizvodnja energije
Entrance Control Eliminates a Conflict of Vehicles at the Exit of the Two-lane Roundabout

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Within a roundabout traffic streams merge, weave and diverge, thus creating conflict points and conflict areas. The number of conflict points and the size of the conflict area on roundabouts depend on the type of the roundabout and the number of entry and exit roadways. The frequency of accidents on roundabouts shows a significantly higher number of accidents on two-lane roundabouts, compared to single-lane roundabouts. The number of accidents at the entry of the two-lane roundabout is two times higher than the number of accidents at the single-lane roundabout entry, which is proportional to almost twice the volume of inbound traffic. However, the number of accidents at the exit of the two-lane roundabout is seven times higher than the number of accidents at the exit of the single-lane roundabout and could not be explained by the higher volume of traffic. The following analysis of accidents indicates that two-lane roundabout exits are a safety issue to be resolved. Starting from the premise that the roundabout, in its general performance aspect, can be viewed as an input output system, and setting the goal of traffic safety in the two-lane roundabout beyond compare, we created a model of traffic control at entry of the two-lane roundabout that eliminates the dominant vehicular conflict at the exit, caused by exiting traffic crossing the path of the traffic that entered the circulating lane of the roundabout.

Key words: two-lane roundabout, entrance, exit, control, vehicles' conflict, crossing, road safety

1. INTRODUCTION

A roundabout intersection is a circular traffic area where two or more roads merge and diverge.

Roundabouts have been in application since the beginning of the twentieth century [1]. The first roundabouts had been designed to provide high speed and were regulated by the rule that vehicles entering the roundabout have the right-of-way (yield at entry). Due to frequent vehicle collisions resulting in severe casualties, traditional roundabouts ceased to be applied.

Construction of modern roundabouts began in Great Britain in 1966, adopting two basic principles: right-of-way is yielded to vehicles circulating around the central island in one direction, and speed limit is reduced to approximately 50 km/h, subject to limited island radius [2].

Modern roundabouts are junctions with specific traffic control and special design to induce the speed limit and control vehicles on entry onto the roundabout [2].

Roundabouts are channeled intersections in which two or more pathways overlap as traffic circulates counterclockwise around the central island. [3].

Roundabout, as a junction with circulatory traffic flow, has been defined as a set of several individual junctions formed by the circulatory single-direction path around the central island, where traffic flows counterclockwise, together with entry and exit roadways. [4].

Improvement of traffic safety effects by converting conventional into modern roundabouts, have encouraged intensive installation of modern roundabouts in the last two decades. In the Netherlands, the conversion of conventional intersections into modern roundabouts led to a reduction of about 46% in the number of severe casualties. [5] According to Dutch National Road Register (NVB) there were around 3,900 roundabouts in the Netherlands in 2010 [5].

Roundabouts have become the most attractive type of junctions in Germany. This can be attributed to
higher level of traffic safety, lower losses of time and popularity among politicians and the public [6]. Construction of modern roundabouts is noticeable in Montenegro as well, where more than 20 roundabouts have been installed in the last five years, most of which in Podgorica [4]. It is estimated that over forty thousand roundabouts have been installed worldwide [8].

Modern roundabouts have been categorized according to size, environment and number of lanes, into three groups [2]:
- mini-roundabouts,
- single-lane roundabouts, and
- multi-lane roundabouts.

These groups of roundabouts are further divided into urban, suburban and rural.

According to the inscribed circle diameter and maximum capacity in terms of average daily traffic, they have been categorized into four groups, Figure 1.[6]:
- mini-roundabouts,
- single-lane roundabouts (urban and rural),
- two-lane roundabouts, and
- multi-lane roundabouts.

![Figure 1 - Defining roundabout types. Source: Brilon, 2011[6]](Image)

In comparison to conventional intersections, the vital advantages of roundabouts are fewer collisions with less severe injuries and fewer casualties in vehicle collisions, particularly among vehicle occupants. [1]. Studies carried out in the USA, Europe and Australia found that the single-lane roundabouts are the safest ones. Traffic safety on small and medium-size roundabouts is better than on large and multiline roundabouts [2].

Presently, as the strategies and action plans have been developed to enhance traffic safety, the roundabout has become a paradigm in deciding on the approaches aimed at reduction of vehicular conflicts at intersections, as it leads to the reduced manifestation of two predominant causes of collisions: by simplifying yield control, and implicit speed reduction. [7].

Choice of the roundabout design from a wide range of optional categories and groups is determined by the balancing of competing objectives. In doing so, except for the primary traffic goals: safety, throughput, flow rate, accessibility, secondary objectives are evaluated as well: economy, land use, aesthetics, and ecology.

By setting the goal of traffic safety in the two-lane roundabout beyond compare, we stated the hypothesis: "entry control eliminates the conflict of vehicles diverging at the exit of the two-lane roundabout."

This paper presents a model of controlling the entry of vehicles in the two-lane roundabout, which confirms the hypothesis. The model is generated by the requirement to eliminate the dominant type of vehicle collision at the exit of the two-lane roundabout, which is caused by overlap of traffic exiting the roundabout with the one circulating after the entering the roundabout.

2. ROUNDABOUT

The roundabout intersection, in its general functional aspect, can be viewed as an input output system (Figure 2.)

![Figure 2 - Roundabout: input output system.](Image)

2.1. Functional elements of the roundabout

2.1.1. Traffic operation elements of the roundabout

Inbound traffic stream, which implies driving in one direction from channelized approaches, and flowing into one-way inner lane that circulates around the central island.

Circular traffic stream, which implies counterclockwise circulation of vehicles around the central island.

Outbound traffic stream, which implies one-way movement of vehicles, channelized out of the inner lane that circulates around the central island towards exit roads.

2.1.2. Physical functional elements of roundabout

2.1.2.1. Circulatory roadway around the central island

The circulatory roadway around the central island enables vehicles to travel around the island, and can consist of one, two or more traffic lanes (Figure 3).
2.1.2.2. Central island

The central island of a roundabout is the raised, non-traversable area, installed in the center of the roundabout, which conditions the vehicles to travel circulating in one direction and enables approaching drivers to recognize the roundabout within the traffic network.

2.1.2.3. Entry roadways that join the circulatory roadway around the central island and the exit roadways that separate from it

Entry roadways that join the circulatory roadway around the central island and the exit roadways separating from it, should enable one-way vehicle movement, should enable one-way running of vehicles, by flowing into the circulating roadway around the island, from the roads that join it, and continue out of the circulating lane to the roads that separate from it (Figure 3).

Entry and exit roadways are shaped by the splitter island, a raised obstacle, or outlined area, which is placed in-between the lanes joining the circulatory roadway around the central island or separating from it, and is used to separate the entering and exiting traffic streams. Entry and exit roadways can have one, two or more traffic lanes.

3. CONFLICTS ON THE ROUNDABOUT

Roundabout is a round-shape traffic facility at which traffic streams merge, weave and diverge, thus creating conflict points and conflict areas. The number of conflict points and the size of the conflict area on roundabouts depend on the type of the roundabout and the number of entry and exit roadways.

The larger the number of conflict points and the greater conflict area affect the traffic safety on the roundabout. A four-leg roundabout with single two-way roads has 8 potentially conflicting points (0 crossing, 4 merging and 4 diverging), (Figure 4). A four-leg roundabout with two-way double-lane roads (a typical two-lane roundabout) has 24 potential conflict points (4 crossing, 12 merging and 8 diverging) and 4 weaving conflict areas. (Figure 5).

The frequency of accidents at roundabouts shows a significantly higher number of accidents at two-lane roundabouts, compared to single-lane roundabouts. The number of accidents at the two-lane roundabout entry is two times higher than the number of accidents at the entry of a single-lane roundabout [9].

If we assume that the traffic volume at two-lane entry roundabout was two times higher than the volume at one-lane roundabout, the accidents rate would be at similar level on both one- and two-lane roundabout. However, the number of accidents at the exit of the two-lane roundabout is seven times higher than the number of accidents at the exit of the single-lane roundabout [9].

This difference could not be explained by the higher volume of traffic. That is why this accidents analysis indicates that the two-lane roundabout exits should be addressed as a safety issue to be resolved.

Table 1. Distribution of accidents in one-lane and two-lane entries/exits. Source: Leemann, 2009 [9]

<table>
<thead>
<tr>
<th>Type of Roundabout</th>
<th>Number of conflicts/exit</th>
<th># accidents/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-lane entry</td>
<td>10</td>
<td>0.26</td>
</tr>
<tr>
<td>Two-lane entry</td>
<td>19</td>
<td>0.67</td>
</tr>
<tr>
<td>One-lane exit</td>
<td>47</td>
<td>0.10</td>
</tr>
<tr>
<td>Two-lane exit</td>
<td>5</td>
<td>0.12</td>
</tr>
</tbody>
</table>
4. VEHICULAR CROSSING CONFLICTS AT THE TWO-LANE ROUNDABOUT EXIT

Vehicular crossing conflicts at the exit account for the most common type of conflicts at the two-lane roundabout and are caused by the intersection of traffic streams as the vehicle exiting the roundabout crosses the path of the vehicle circulating after entering the roundabout.

The typical two-lane roundabout has an inbound traffic stream whose right lane is intended for running directions: right and straight, and left lane is intended for running directions: straight and left (Figure 6a). Such a regulation of approaching traffic may induce not only conflicts at the entry and cross-intersections, but also conflicts at the exit (Figure 6b).

Starting from the premise that the roundabout, in its general performance aspect, can be viewed as an input output system, and setting the goal of traffic safety in the two-lane roundabout beyond compare, we stated the hypothesis: "entry control eliminates the conflict of vehicles diverging at the exit of the two-lane roundabout."

In testing the hypothesis we set the control of the inbound traffic stream whose right lane is intended for running directions: right and straight, and left lane is intended for running directions: straight and left (Figure 8). When the same principle of entry control is applied at all approaches that join the circulating roadway around the central island, and shaping the splitter island envelope by extending it to the one-way circulating road around the island providing the same width as the external lane, thus obtaining a model of entry control into the two-lane roundabout which verifies the set hypothesis (Figure 9.).

**Figure 6** - The typical two-lane roundabout.

**Figure 7** - The typical two-lane roundabout: input output system.

**Figure 8** - Entry control into two-lane roundabout: input output system.

**Figure 9** - Entry control at two-lane roundabout.

a) allowed driving directions at entry

b) eliminating circulation-exit conflict
The above accounts for the reduction of conflict points in the two-lane roundabout to 8 (0 crossing, 4 merging and 4 diverging) while the 4 weaving conflict areas are eliminated, and equalized to the number of conflict points in one-lane roundabout (Figure 10).

5. CONCLUSION

The frequency of accidents on roundabouts indicates that the exits from two-way roundabouts are a safety issue to be resolved. Since neither solution is absolutely optimal, this paper analyzes the principles and techniques of looking for solutions as traffic safety of two-lane roundabout is the goal beyond compare, as we start with the premise that the roundabout, in its general performance aspect, can be viewed as an input output system, and that the entry control eliminates the conflict of vehicles diverging at the exit of the two-lane roundabout.

The application of this principle and technique of looking for solutions, has resulted with a model of entry control at two-lane roundabout that eliminates the most common vehicular conflict at the exit of the roundabout, caused by the intersection of traffic streams as the vehicle exiting the roundabout crosses the path of the vehicle circulating after entering the roundabout.

This type of control reduces the number of conflict points at two-lane roundabout from 24 (4 crossing, 12 merging and 8 diverging) to 8 potential conflict points (4 merging and 4 diverging), while the 4 weaving conflict areas are eliminated, and thus equalized to the number of conflict points in one-lane roundabout (Figure 10.).

REFERENCES


REZIME

KONTROLA ULAZA ELIMINISE KONFLIKT VOZILA NA IZLAZU IZ DVOTRAČNE KRUŽNE RASKRSNICE

U kružnoj raskrsnici se saobraćajni tokovi spajaju, prepliću i razdvajaju i na taj način stvaraju se konfliktne tačke i konfliktne područja. Broj konfliktnih tačaka i veličina konfliktnog područja kružne raskrsnice zavisi od tipa kružne raskrsnice i broja ulaznih i izlaznih saobraćajnih tokova. Distribucija nezgoda u kružnim raskrsnicama pokazuje znatno veći broj nezgoda kod dvotračnih kružnih raskrsnica, u odnosu na jednotračne kružne raskrsnice. Broj nezgoda na ulazu u dvotračnu kružnu raskrsnicu oko dva puta je veći od broja nezgoda na ulazu u jednotračnu kružnu raskrsnicu, što je proporcionalno sa skoro dva puta većim obimom ulaznog saobraćaja. Međutim, broj nezgoda u izlazu iz dvotračne kružne raskrsnice je sedam puta veći od broja nezgoda u izlazu iz jednotračne kružne raskrsnice i ne može se objasniti većim obimom saobraćaja. Ova analiza nezgoda pokazuje da su izlazi iz dvotračne kružne raskrsnice problem bezbjednosti saobraćaja, koji traži rješenje. Tako se, polazeći od stava da se kružna raskrsnica, u opštem funkcionalnom aspektu, može posmatrati kao input output system i postavljanjem bezbjednosti saobraćaja ciljem bez konkurencije u dvotračnoj kružnoj raskrsnici, generiran je model kontrole ulaza vozila u dvotračnu kružnu raskrsnicu koji eliminiše dominantni konflikt vozila na izlazu iz dvotračne kružne raskrsnice, izazvan presijecanjem putanje vozila koje izlazi iz kružne raskrsnice, sa putanjom drugog vozila koje cirkuliše nakon ulaza u kružnu raskrsnicu.

Ključne riječi: dvotračna kružna raskrsnica, ulaz, izlaz, kontrola, konflikt vozila, ukrštanje, bezbjednost saobraćaja
Possibilities of FCD system implementation in Belgrade

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Floating car data system is relative new way for forecasting travel time value on links. This system is using data gathered by vehicles equipped with GPS devices and devices for wireless communication. The pilot study presented in this paper, includes data obtained by postal vehicles equipped with GPS devices. As a result of this research, we obtained the value of relevant parameters such as: coverage of primary and secondary street network, spatial and time distribution of data, total number of recorded GPS data during defined time intervals and required number of vehicles necessary to include in FCD system. Examined literature and obtained results showed that the value of these parameters is below recommended values for the street network in Belgrade. The current number of postal vehicles is not sufficient to establish a reliable system for estimation and forecasting travel times in real time application.

Key words: travel time estimation, dynamic detectors, float car data, GPS data, postal vehicle

1. INTRODUCTION

Population growth, increase of purchasing power and an increasing number of various activities, caused the constant growth of the population's needs for mobility. Major cities are faced with a lack of the street network capacity, because transport demands are not distributed evenly over time.

Capacity expansion of street segments is limited due to the location of existing urban facilities and usually this kind of measures are not economically justified. Also it can cause unwanted effects in the form of rising delays and "relocation" of the problem (generate new transport demands).

In bigger cities, experts are rapidly implementing strategies that use existing resources in order to influence on transport demands. Before choosing any strategies, it is necessary to provide input for the evaluation process of the current and future traffic conditions.

By the end of the nineties, loop and other detectors has been used for obtaining traffic data. Because these devices are mounted on fixed points, considerable financial investment are needed to cover most of the street network with them.

Traveler desire for fresh and reliable information, generate the need for cheaper and more dynamic way of collecting and processing traffic data. One of those methods is the floating car data system (FCD). The term FCD describes the method used for collecting data on the observed territory.

Vehicle equipped with navigation and wireless communications devices is recording and sending information at certain time intervals (current longitude and latitude, time, etc.) to the command center (server). These data are then used for the assessment of Q/K relationship (Q - traffic flow, K - capacity of street segments) and estimation of travel time on the street network.

Popularity of navigation devices is rising with the development of telecommunication and computer technology. Conditions have been created for the effective implementation of the FCD system in urban areas since operators (taxis, post office, mass passenger vehicles, etc.) nowadays often possess a fleet with vehicles equipped with GPS and wireless communication devices.
2. LITERATURE REVIEW

At the beginning of the last century, first efforts were made to measure the travel time using "probes" vehicle. This idea was considered again as an option for measuring travel time in the 1980s, but the implementation of this technology was expensive at that time [7]. In 1991, FCD technology was first implemented in project called ADVANCE (Advanced Driver and Vehicle Advisory Navigation Concept). In this project, vehicle equipped with navigation devices were used for estimating value of travel time on street network [1].

At the end of the last and at the beginning of the new century, navigation and wireless communications devices become more accessible to the public. Many researchers have conducted using the FCD system in cities around the world (Berlin, Munich, Nuremberg, Studgradu, Vienna, Ningbo, etc.).

One of the first studies with a larger number of vehicles were carried out by Ralf-Peter and Thiessenhusen in Germany [5]. In May 2001, they implemented the FCD system in Berlin using data collected from 300 taxi vehicles. The results of this study showed that FCD system is good substitution for conventional fixed detectors. In Hamburg (conducted in 2006/2007.) the results of similar research has shown that the data collected by the 700 taxi vehicles were accurate and can be used in dynamic models for estimating the average travel time value on links [6].

Research in the Ningbo, showed that the link coverage are rapidly increasing after five-minutes measurement period. Data obtained by the taxi vehicle were used in estimation of travel time on shorter segments (up to 3 kilometers). Estimated values of travel time were compared with data which are collected with test vehicles and results of this analysis have shown that the estimation error is lower than 10%. They show that data from shorter segments lead to higher errors and that segment length of 3 km is critical value for the accuracy of the results [2].

The second generation of FCD system includes vehicles equipped with sensors, devices and cameras. A wider range of data provide a higher level of detail information than earlier systems. In the literature this system is called Extended Float Car Data (XFCD) and refers to the amount and type of different data being monitored and recorded.

BMW Group has implemented XFCD system, which includes weather condition data. XFCD system predicts traffic condition by vehicle speed data, data of current wiper/washer and brakes activitie status, data generated by the system for stability control and navigation system. The system informs other drivers about the possible congestion and hazards in case of incident situation.

In Trento (Italy), groups of experts develop special Data Fusion system, which include images obtain from the cameras installed on the vehicles [3]. Level of service for urban streets was calculated using cameras and sensors, which were reliably detected recognizable forms (warning signs), headway distance and speed of vehicle in front of the car.

3. PROBE VEHICLES

Floating car data is a method based on the system for collecting of data from vehicles equipped with GPS devices or "smart" mobile phones. Vehicles equipped with GPS devices provide very accurate data, but there are fewer opportunities for formation of a fleet with these devices than with “smart” mobile phones. Fleets are usually composed from commercial vehicles and many researches shown that taxi vehicles were most suitable for this purpose.

Due to the fact that these drivers are more capable to avoid congestion then most popular users and that in some situations these vehicles are allowed to use yellow and HOV (high occupied vehicle) lanes, it is necessary to be careful when using data obtained by taxi fleet.

Floating cellular data represents a new form of FCD method that uses mobile phone networks (CDMA, GSM, UMTS and GPRS) for collecting travel time data. The main advantage of this system is the possibility of creating a fleet with a large number of vehicles. Because this technology is not capable to provide accurate data like GPS devices, when processing raw data there is a need for complex algorithms. Position of the vehicle is determined using different signal strength received by the antennas of various mobile operators in the process known as triangulation.

FCD system can be divided into six phases: collecting data, decoding and filtering data, processing data, analysing and interpreting data, storing data and distributing relevant information to users.

Information obtained by these probe are distributed to users via digital traffic signs, service information, GPS devices, mobile phones, etc.

The advantages of FCD system are detailed level of information, coverage of a large part of the street network, compatibility with many sources of information, cost-effectiveness, origin-destination trip matrices, etc. It is necessary to point out the weaknesses of these systems, which are the inability to obtain direct information on fundamental traffic parameters and the fact that the results depend mainly on the characteristics of the fleet. We are come to the conclusion that the most accurate resultates would be obtained
with strategy that combines dynamic and static detectors, which cover disadvantages of each other.

4. DATA PROCESSING

Data obtained by GPS devices must be filtered in order to eliminate incorrect and unrealistic data, caused by the impact of the environment and errors in navigation system. Non valid records which do not reflect the usual movement of the car must be removed from remaining data too. Experience has shown that about 10-20% of the data are rejected. This percentage represents illustrative value and they mostly depends on the methodology used for the recording and processing of data [4].

In the next step, map matching algorithms is used for the reconstruction of actual vehicles positions and their trajectories on the urban streets. According to the type of methodology, algorithms used for getting the actual trajectories of probes is being divided into geometry, topology and probability algorithm. Geometry algorithms are the simplest and quickest. They taking into account shape and spatial position of links on the street network. However, it is necessary to pay attention while a vehicle passing along a street that is parallel with a nearby link on a map and through intersections, because relatively inaccurate results could be provided with geometric algorithms in this situation.

Travel time for links that are not covered with a enough amount of data are estimated with historical data by using records for same traffic condition, time of day and day of the week. Only high quality and reliable data collected from GPS devices are being stored in historical database. Estimatoins of travel time can be expressed as

\[
\hat{t}(i, j) = \sum_{t_{ij}} \frac{l_{ij}}{v(t)},
\]

\(l_{ij}\) – distance between two successive GPS records, on link \(j\) for \(i\) hour in week
\(\hat{v}(i, j)\) – estimated speed on node \(j\) for \(i\) hour
\(t_{ij}\) – time interval between two successive GPS records, on link \(j\) for \(i\) hour in week

This method assume that we already have historical data of travel time on links. If we dont have this data, travel times are estiamated with data from other measurements and pilot studies. With each measurement period a new data is stored in database, which affects the accuracy of future evaluations.

5. PILOT STUDY

The fleet in this research is consisted of 220 probe vehicles equipped with GPS devices and sensors, which are owned by the Belgrade Post Office. From total number of vehicles, 168 vehicle is used for the delivery and receive of shipments. These vehicles are moving within the boundaries of predefined zone. Other 52 vehicles transport parcels and mails between postal facilities, according to predefined routes and time of their arrival/departure.

The average time gap between two GPS records is 15 seconds. Six different types of data are captured by installed devices: the position of vehicle, time stamp, vehicle speed, changes in fuel level, status of engin (turn on/off) and doors (open / close).

Data is stored in the command center via a data storage server. Access to data is enabled with the web application, which generates various reports like: break of speed limit, time of parking, changes in level of fuel and traveled distances. Application include vector map of Serbia as basemap on which user can displayed vehicle trajectories. In this study, data were collected through this application, using reports on position of vehicle, time of parking and traveled distances.

Day of the research was selected by considering total transport work and sum of travel times of all vehicles for the five working days in selected week. Data collected over selected period helped us to better understand possible ways of using postal vehicles in FCD system.

Sum of travel time and transport work were approximated for observed work days over the period of one week. Values of the transport work were in the range from 9000 km up to 10300 km. The mean value of total transport work was 9772 km, while on average it was necessary 345 h per day to complete transport work. These values most closely describes parameter values achieved on 07th April 2014, when transport work reached 9734 km and 342 h of total vehicles travel time.

Considering that predefine zones and routes do not change on the working days, results obtained over one representative day are indications of general fleet characteristics. For regular day it was selected 07th april 2014, when the fleet reached values of parameters that best describe the values achieved over chosen calendar week.

Collected data include information on time stamp, vehicle position (latitude/longitude), current speed and the vehicle identification number. Processing of GPS data was performed using the Microsoft Excel, ExpertGPS and ArcGIS program. The GPS positions of the vehicle were projected on the links by using these applications, while the trajectories of the vehicles were constructed after this process.

Data was collected over 12-hours period (from 06:30h to 18:30h), which is divided into six equal
measurement periods. Analysis of the data is conducted for every measurement period separately and as one time period too.

6. REQUIRED NUMBER OF PROBES

When designing FCD system it is important to determine required number of probe vehicles. For FCD systems that required small number of vehicles, possibility for selecting an appropriate fleet (commercial fleet) is increased, while resources needed to collect and process data is reduced. Required number of vehicles is directly affected by length of measurement period, minimum number of passes per link and percentage of link coverage.

Accuracy of travel time estimation depends on required value of parameter \( n \), which representing a sample size of GPS data per link. Borisavljevic (2000) shows several methods to define the required sample size and according to the author the most commonly used method in practice is by using empirical dispersion

\[
S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{X})^2. \tag{2}
\]

\( S \) – measure of central dispersion
\( n \) – sample size
\( x_i \) – measured values
\( \bar{X} \) – arithmetic mean of the measured values

Required sample size \( n \) is determined by desired confidence interval for the mean value (\( \mu \)) as

\[
P(\bar{X} - L < \mu < \bar{X} + L) = 1 - r. \tag{3}
\]

\( L \) – half-length of the confidence interval
\( (1-r) \) – confidence coefficient

Expression for calculating the parameter \( n \) can be formulated as follows

\[
n = \left( \frac{t_{(k)}^2}{L^2} \right) S^2. \tag{4}
\]

\( t_{(k)} \) – value that fit the student’s distribution with \( k \) degrees of freedom

Karthik and Paul (2007) stated that value of \( n \) cannot be obtained with the assumption that travel time fits normal distribution [4]. If above assumptions is correct, with maximum error (\( \epsilon_{\text{max}} \)) and statistical significance (\( r \)) we can express \( n \) as

\[
n = \left( \Phi^{-1} \left( \frac{1 - r}{2} \right) \right) \left( \frac{\epsilon_{\text{max}}}{\mu} \right). \tag{5}
\]

\( \Phi^{-1} \) – cumulative distribution function
\( \mu \) – mean value of travel time
\( \sigma \) – dispersion of travel time

May (1990) states that the coefficient of variation is in the range 0.08 - 0.17 and that \( \eta \) is in the ranges from 2 to 11 passes per link, for \( r = 95\% \) and \( \epsilon_{\text{max}} = 10\% \) [8].

It is necessary to define the required number of vehicles \( N \) after defining the value of parameter \( n \). This parameter depends on value of measurement period \( t \), percent of link coverage \( p \) and sample size \( n \). Karthik and Paul [4] suggest a model for determining the value of required number of vehicle as

\[
\log N = a + b \log n + c \log p + d \log t + e \tag{6}
\]

where \( e \) is value of error and \( a, b, c, d \) are calibrated coefficients with origin-destination trip matrix inside simulation. The percentage of link coverage depends on the values of relevant parameters \( (n, N \) and \( t \)), characteristics of the street network and trip purpose.

Many authors are recommending that required number of vehicles should be determined for ten-minute measurement period and for link coverage of 60%-80% with at least two samples of data per link. Borisavljevic (2000) states that the sample size is determined by rough estimation. This estimation is created with assumptions based on others experiences and pilot researches [13].

Since that is necessary to conduct large-scale pilot study in order to estimate required number of vehicle for urban street network, rough estimate was made by using GPS data collected with postal vehicles (Figure 1). By using the relationship between the number of recorded GPS data and the percentage of covered links, parameter \( N \) was determined for at least two samples of data per link. Goal is to define required number of GPS records in order to cover 60% of links on the urban street network.

![Figure 1](image_url)

**Figure 1** – The linear dependence between the number of GPS readings and link coverage.

In equation (7), required number of recorded GPS data to achieve 60% of link coverage \( (y) \) is obtained by regression analysis. Since average time gap between two GPS records is 15 seconds, single vehicle in average generated \( y_0 = 40 \) packets of GPS data over the ten-minutes measurement period. We were able to calculate that the fleet must be made of at least \( N = 390 \).
vehicle to cover 60% of the streets with two samples of data per link after ten minutes of recording. This result is obtained by dividing the total number of required data \( y \) with the average packets of GPS data per probe \( (y) \)

\[
j = 17000 \quad x + 5364. \tag{7}
\]

\( j \) – total number of readings
\( x \) – percent of link coverage \([0,1]\)

In order to establish a reliable system for real time estimation of travel times values, at least 400 probes must be active every ten minutes. Over the two-hour measurement periods, the highest number of active postal vehicles was \( N = 95 \) vehicle (Figure 2). This result indicates that the FCD systems in Belgrade need to include additional vehicles from other sources (e.g., taxis).

The highest number of activity was recorded over the period from 10:30h to 12:30h, when a total of 95 vehicles were active. The minimum number of active vehicles was 40 vehicles recorded during the morning peak period from 06:30 to 08:30 h (Figure 2). Average number of active vehicle was 73 vehicles recorded during studied time interval.

\[\text{Figure 2 – Number of active vehicle for every two-hour measurement period.}\]

When calculating the required number of probes, minimum values of parameters should be \( n \geq 2 \) passes/link, \( t = 10 \) min and \( p = 60\% \), which are recommended by other authors too (Karthik and Paul). Based on conducted simulations by Karthik and Paul, required number of probes for above values is \( N = 1100 \) vehicles. Since that covered area in this simulation (44,000 ha) is greater than the inner city areas of Belgrade (35.996 ha), during each ten-minutes measurement period the required number of vehicles in Belgrade should be less than the specified value.

Experiences of other cities indicates that the current number of vehicles in the fleet is not sufficient to meet the requirements. Reviewing experiences from other researches, we can conclude that required number of probes in FCD fleet is ranging between 2000 and 5000 vehicles (for some specific situation this number should be higher). Also, Chen (2001) states that 1% of all active vehicles on streets over the measurement period should be part of the FCD fleet [15].

Accurate travel time estimation is calculated when links are covered with at least two passes of vehicles for every ten-minutes measurement period (time interval that relates to the last 10 minutes of recording). The fleet of postal vehicles can not meet this requirements, because it is necessary to have large number of vehicles in order to increase the likelihood of obtaining enough sample size per link over measurement period. The advantages of this fleet is related to relatively small time gap between two successive GPS records (high frequency) and accurate positioning of the vehicle on a street network (accurate data).

7. RESEARCH RESULTS

Real-time estimation of the travel time values requires large numbers of vehicles in order to reach 60% to 80% of link coverage with at least two passes of vehicles per measurement period. From 06:30h to 18:30h, postal vehicles (220 vehicles) have traveled 5350 km of total length.

The percentage of link coverage for the street network was calculated by using estimated value of total street network length in the target year (year of this research). Value of estimated total length is 970 km and it was made by using linear regression and data from the General Plan of Belgrade [9]. The longest traveled distance was reached over the measurement period from 14:30h to 16:30h, when vehicles covered the largest part of the urban street network. Vehicles covered 565.5 km (Figure 3) or 60% of the urban street network over this period. Total average vehicle distance traveled was 892 km, while the average link coverage was 390 km or 40% of the urban street network.

\[\text{Figure 3 – Comparison between total traveled distance and total length of covered links [km].}\]

Approximately 60% of the primary urban street network (urban highway and motorway) was covered with GPS data over the morning peak hours, from 06:30h to 08:30h. In this period, link coverage of primary urban street network was 189 km long (the
total length of the primary street network was 300 km long) and for secondary urban street network (first and second priority streets) it was 53.5 km long. The highest coverage of primary urban street network has been detected over the period from 10:30h to 12:30h, when the GPS data covered around 90% of the primary street network. The highest number of activities on the secondary street network (first and second priority streets) is detected in measurement period from 14:30h to 16:30h, when the link coverage reached 54% of total secondary urban streets length.

Table 1. Link coverage of primary and secondary street network

<table>
<thead>
<tr>
<th>Measurem. period</th>
<th>Total</th>
<th>Prim. (H+M)</th>
<th>%</th>
<th>Second. (I &amp; II)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>06:30-08:30</td>
<td>242.5</td>
<td>189</td>
<td>63</td>
<td>53.5</td>
<td>10</td>
</tr>
<tr>
<td>08:30-10:30</td>
<td>471</td>
<td>254</td>
<td>85</td>
<td>217</td>
<td>42</td>
</tr>
<tr>
<td>10:30-12:30</td>
<td>526.9</td>
<td>271</td>
<td>90</td>
<td>255.9</td>
<td>49</td>
</tr>
<tr>
<td>12:30-14:30</td>
<td>408.1</td>
<td>263</td>
<td>88</td>
<td>145.1</td>
<td>28</td>
</tr>
<tr>
<td>14:30-16:30</td>
<td>565.5</td>
<td>285</td>
<td>95</td>
<td>280.5</td>
<td>54</td>
</tr>
<tr>
<td>16:30-18:30</td>
<td>326.1</td>
<td>212</td>
<td>71</td>
<td>114.1</td>
<td>22</td>
</tr>
</tbody>
</table>

From 08:30h to 16:30h, the value of link coverage constantly exceeded 50% of total primary urban streets length. Value of link coverage of the secondary urban street network was lower than primary, with relatively higher values reached over the fourth and fifth measurement periods.

Low values of link coverage over the morning peak hours from 06:30h to 08:30h is a consequence of reduced activity of courier services, considering that the most vehicles in the fleet are being used to carry out this tasks. After this analysis, it was necessary to calculate the link coverage for ten-minute measurement periods to determine whether the system based on data provided by the postal vehicles can meet the standards that FCD system should reach.

The number of collected data per ten-minute measurement periods, provide better insight into the distribution of vehicles activities over the day. It should be noted that the ten-minutes measurement period is chosen by recommendations from Karthik and Paul [4]. The highest number of data were recorded over the time period from 10:40h to 10:50h, when the value of vehicles traveled distance was 108.2 km long and street urban network coverage distance was 102.9 km long. This results indicate that only 10% of the urban street network was covered over the most active ten-minute measurement period.

The highest number of data (1229 records, Figure 4) is collected in morning period from 10:40h to 10:50h. Also, the increased activity of the fleet is detected over afternoon ten-minutes periods for following time intervals: 14:10-14:20h, 14:20-14:30h, 14:30-14:40h, 14:40-14:50h, 14:50-15:00h. Selected period of study was divided into three separate time periods by using the total amount of data transmitted with active vehicles per ten-minutes period.

The volume of broadcast GPS data was increasing constantly from 313 to 791 data packets per ten-minutes period (Figure 4) over the first measurement period, which last from 06:30h to 09:40h. In the second time period from 09:40h to 16:00h, constant variations in the range between 800 and 1200 volumes of data is detected (with occasional extremes), with an average amount of 984 packets of data collected per ten-minute period (Figure 4). The third time period from 16:00h to 18:30h is characterized by decline in the number of collected GPS data and this number is falling below 400 transmitted packets of data per ten-minute period.

Data recorded by the GPS devices are very precise and they can be used for creating the database of historical travel time values. Database helps during the estimation process of travel time values for link which are not covered by sufficient amount of data. Also, reconstructed vehicle trajectories obtained by this fleet, can be used for creating and updating vector maps (Figure 5).

![Figure 4](image1.png)  
*Figure 4 – Total number of transmitted GPS data per ten-minutes measurement periods.*

![Figure 5](image2.png)  
*Figure 5 – Path of all active vehicles on urban street network recorded over time period of study.*
Total length of covered links with at least two samples of data (n ≥ 2) is the lowest at morning hours, with only 72.6 km of covered street segments. The highest length of covered links with at least two samples of data (n ≥ 2) has been observed over measurement period from 12:30h to 14:30h and from 14:30h to 16:30h. In these periods vehicles covered in total 693.4 km and 678.6 km of street network, respectively.

Analysing the spatial distribution of GPS data helped us to determine the most active region over selected period of study. The highest number of activities was recorded in urban municipalities Vozdovac and Savski Venac. Also, high number of activities was recorded in the municipalities Stari Grad, Novi Beograd, Vracar, within urban zones in municipalities Zvezdara, Palilula, Zemun and around the area of the urban highway. The highest number of GPS response from vehicles, 2026 GPS readings, was recorded over the period from 14:30h to 16:30h in the area which includes Stari Grad and the northern part of the Savski Venac. Within this measurement period the highest value of link coverage on the central city area was recorded too.

Value of travel time is estimated by using current and historical travel speed data. In FCD system, the historical mean speed per link is calculated with previously determined values. This method is used in predicting value of travel time for the links which does not have enough real-time data. In this study, the mean speed of the fleet was 32 km/h and it is determined by using the total traveled distance and total travel time.

Value of link mean speed for all zones was determined in the municipalities Stari Grad, Savski Venac, Vracar, Palilula and Zvezdara. Since obtained values are not localized at the level of street segments, they are only used for illustrative purpose (approximation of mean speed values within the defined zones) and they should not be used for estimation of travel time on individual routes.

The lowest values of mean speed were recorded over the time periods from 10:10-13:30h and 17:00-17:50h, while fleet mean speed reached value above 40 km/h for time intervals: 07:30-07:40h, 10:00 -10:10h, 14:00-14:10h and 16:00-16:10h (Figure 6). In most cases, for 47 ten-minute intervals the value of mean speed for all zones was within 30-40 km/h range, while for 21 ten-minutes intervals the mean speed was within 20-30 km/h range. Since the lowest value of mean speed was obtained over the period of the highest vehicles activity (period of the day with the highest number of received and delivered shipments), resultate of research shown that the values of mean speed are dependent on the number of active vehicles and amount of activity within urban area of the city.

To get a relatively accurate estimation of travel time, it is necessary to define the average travel time along the individual links for specific time periods of the day, as well as for certain days of the week at different traffic conditions (pavement condition, weather conditions, etc.).

These requirements create the need for large database with information on speeds of vehicles, classified by time periods and weather/traffic conditions. It is also necessary to daily update database with new records, in order to calibrate existing data and to raise level of accuracy of future estimation.

Spatial and time distribution, as well as number of transmitted GPS data are dictated by type of service and time schedule of the transport activities. These conclusions indicate that the maximum amount of data can be collected in the central area of city (municipality of Savski venac, Stari grad, Vracar and Novi Beograd) over the working days within time periods from 10:00h to 16:00h.

8. CONCLUSION

Comprehensive review of the strengths and weaknesses of the observed FCD system, summed up the results and conclusions of this pilot study. Although it is a qualitative approach, it is able to provide better understanding of the system potential according to the objectives and fleet/environmental restrictions. The main advantages of the system are: high precision devices, the possibility of creating a database, the coverage of the street network in suburban municipalities, data on the current vehicle speed and fuel consumption, good coverage of the central part of the city.
urban areas over the two-hour measurement period. Besides these benefits, shortcomings that prevent independent use of this system are: lower network coverage over the morning peak hours, the relatively small number of vehicles, as well as the low coverage of street segments with two samples of data per link over the ten-minute measurement period.

Main advantage of the postal fleet is the high quality of the data obtained from the GPS devices. These data can be used to create database for travel times estimates in situations where the real-time data is not available. This fleet provide constant amount of data every work day, because operation time and number of active vehicle are determined by customer demands and not by other external conditions. Since large part of the urban street network was well covered by the GPS data, particularly the area of city center, obtained trajectory of vehicles can be used for monitoring and updating the existing vector maps or for creating map from scratch. Also, fleet can provide additional information on traffic conditions in the peripheral municipalities around the city center.

Over the most active ten-minute period the value of link coverage was about 10% when fleet collected the highest number of GPS data. According to the recomendations from Karthik and Paul [4], which suggested that at least 60% of the street network over the ten-minute interval should be covered with at minimum two samples of GPS data, results have shown that these requirements can not be met. It should be mentioned that the type of service does not require constant movement of vehicles, and the number of active vehicles on the street network is always less than the total number of available vehicles.

This paper describes the methodology for analyzing the possibilities for implementing postal fleet in FCD system. The methodology can be divided into seven steps: determining equal measurement period, number of active probes per measurement period, total length of the traveled distance from all active probes per measurement period, percentage of coverage of primary and secondary street network per measurement period, total length of covered street segments with minimum two samples of GPS data (n ≥ 2) per measurement period, the spatial distribution of the GPS data, space and time mean speed of all active probes per measurement period.

The results indicated that the postal vehicles can not be used as the only source of information and that is necessary to include vehicles from other fleets. Establishing and maintaining such systems requires financial and regulative support of the governments and public. For the system to function properly it is necessary to educate population and to include important stakeholders in the project. These goals can be achieved by presenting the benefits of this system to the different target audiences. FCD system can improve quality of life and utilization of existing streets capacity, as well as to reduce global travel time, pollution, noise and total travel costs.

FCD system has great potential and it can be used as a good support during the implementation of other projects, such as travel demand management strategies. In future research, it is necessary to further explored all options that can be considered for implementation of potential FCD system in Belgrade.

REFERENCES


REZIME

ISTRAŽivanja mogućnosti primene FCD sistema u Beogradu

Float Car Data sistem (FCD) predstavlja relativno novu metodologiju utvrđivanja i prognoziranja vremena putovanja vozila duž linkova, pomoću podataka prikupljenih od strane vozila opremljenih uređajima za lociranje pozicije vozila. Pilot istraživanje, koje je u ovom radu predstavljeno, obuhvata podatke dobijene poštanskim vozilima opremljenim GPS uređajima. Kao rezultat analize, dobijene su veličine parametara pokrivenosti primarne i sekundarne puteve mreže, prostorna raspodela, ukupan broj očitavanja tokom definisanih vremenskih intervala i minimalni broj vozila koji je neophodno uključiti u sistem Float Car Data u Beogradu. Dobijeni rezultati istraživanja su pokazali da je vrednost ovih parametara ispod granica preporučenih vrednosti, ustanovljenih na osnovu uvida u literaturu, kao i da trenutni broj poštinskih vozila nije dovoljan da bi se uspostavio pouzdan sistem procene vremena putovanja u realnom vremenu, na uličnoj mreži Beograda.

Ključne reči: procena vremena putovanja, pokretni detektori, float car data, GPS podaci, poštanska vozila
ENGINEERING CARD

28 percent of the European working force considers tapping into foreign labour markets. In the light of the current shortage of skilled workers, this group of professionally mobile and well educated employers needs to be addressed properly.

However, despite the rising need of skilled workers from foreign countries and despite the willingness of many Europeans to actually work in a different country, many barriers are in place impeding job changes within the EU. To overcome these barriers in the long run, the EU commission filed a bill at the end of the year 2011 to modernise the recognition of professional qualifications Directive 2005/36/EG. Through transparent, quick, and reliable mechanisms of recognizing professional qualifications, professional mobility is supposed to be enhanced and the collaboration between member states on the realization of a single EU market is supposed to be strengthened.

At the heart of the proposal is the introduction of a European professional card. This professional card, which will be issued by the native country, will attest professional qualifications and the right to pursue a profession EU-wide. According to the commission, the introduction of the professional card will also lower processing times and costs for the recognition of professional qualifications. Moving professionals such as four million engineers will benefit from these developments. At this time, the European Parliament and the Council of Ministers deliberate on the EU commission’s bill to modernize the professional qualifications Directive.

In 2010, the Association of German Engineers (VDI) took initiative and invited representatives of the German Federal Chamber of Engineers and of all other Engineering Associations to jointly work on the realization of a European Professional Card for engineers.

The Association of German Engineers (VDI), together with the European Federation of National Engineering Associations (FEANI), succeeded with its pioneering work: As the first European professional group, engineers can use a voluntary professional card: the engineerING card. All 32 FEANI member associations are convinced by the advantages of this card.

The engineerING card serves as a proof of professional qualifications, thus facilitating application processes, in the entire European Union.

The representatives of the Union of Engineers and Technicians of Serbia, a national member of FEANI from Serbia, in 2013 signed Cooperation agreement for the issuing of the Engineering card in Serbia.

As a result of this Agreement every Serbian engineering professional that holds an engineering degree from an officially recognised Serbia tertiary institution can apply for the engineerING card. An expert committee looks into certificates and, if desired, relevant professional experience, as well as further educational trainings and then decides whether these qualifications can be recognized. All results are compiled in a central database. All information is provided on an excerpt from the register of a cardholder and is available to the card owner at all times on the respective website. Card owners can prove all their engineering qualifications with the excerpt from the register in applications. Likewise, businesses benefit from the increased transparency and comparability amongst candidates for a vacant position.
Analysis of dispatching rules application on scheduling problem in flexible-flow shop production

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We analysed a group of simple heuristic methods which are used for solving scheduling problems in manufacturing and services. The analysis was performed on the scheduling problem in a flexible-flow shop production (FFS). The task was to determine the schedule of processing multiple products on multiple machines, where all the products have the same sequence of processing and for each process there are multiple available machines. We translated this FFS problem into the corresponding mathematical model of mixed integer programming. Among potential methods for solving the set task, we considered simple heuristics because the original scheduling problem is NP-hard and finding the exact optimal solution would require unacceptably long computing time. Heuristic methods are based on priority rules performed based on the relations of importance between products and their processing time on individual machines. Heuristic methods are widely used for solving practical problems, which was the motivation for the analysis performed in this paper. The aim of the analysis is to identify the priority rules, from a set of considered, which provide a good solution to a hypothetical scheduling problem, where the evaluation of solution is performed using different criterion functions. The analysis presented in the paper was obtained by the computer program LEKIN. The main results of the analysis indicate that priority rules give different solutions to the problem of FFS and that each of this solution is significantly good result in terms of some of the considered criterion functions.

**Key words:** scheduling, flow shop, flexible-flow shop (FFS), dispatching (priority) rules

1. INTRODUCTION

The problem of scheduling generally refers to determination of spatial and temporal scheduling of execution of production activities. It is part of planning process in everyday business of production companies. Finding the best solution, i.e. optimal schedule, is a very complex issue which provoke a great deal of attention in scientific and professional literature [1].

Scheduling problem in a broader sense includes: (1) the assignment problem - assignment of certain manufacturing and service activities to work centers machine and executors and their termination, i.e. defining the time terms for the beginning and end processing [2, 3, 4, 5].

The production systems are characterized by a nu-

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to the class of NP hard problems. Therefore, to solve practical problems in FFS, as a rule, simple heuristic methods, known as priority or dispatching rules, are used [8], [9], [10].

The next section describes a scheduling problem in flexible-flow shop and gives an appropriate mathematical programming model. The third section presents a distinctive hypothetical example of a problem and describes heuristic methods for its solution. We present the numerical experiment on the basis of which we make the comparison of problem solving groups, with the help of program LEKIN. Based on the result analysis (see section 4) we try to answer the research question: Which of the following methods of solving problems in FFS generate good solutions in terms of different performances i.e. evaluation criteria?

2. SCHEDULING PROBLEM IN FLEXIBLE-FLOW SHOP PRODUCTION

The flow shop is a problem of the scheduling $n$ products on $m$ machines where all products have the identical processing route to follow, and which consists of a pre-defined set of operations on the machines. If this production system encompasses more homogeneous machines in parallel links for individual stages of processing, then it refers to a form of flexible-flow shop. FFS is a problem in which out of $m$ machine there are $m$ homogeneous groups of machines designed for products with the same type of processing. In this way the scheduling of the products for processing becomes more flexible, as products can be processed on any machine within the group of the same processing features. This scheduling problem in FFS is also known by terms: Hybrid flow shop, compound flow shop, multi-processor flow-shop [1], [2].

The mathematical problem of FFS is described in [3]:

We consider the problem of scheduling $n$ products $J_j$, where $j = 1, 2, ..., n$, such that in the production system FFS the total length of scheduling time is minimal. FFS consists of $m \geq 2$ production phases or machine centers with $l$ phases which have $k_l \geq 1$ identical machines with the same kind of processing $P_{[k_l]}$. For each product $J_j$, vector $[p_{ij}, p_{j2}, ..., p_{jm}]^T$ of processing times are known in advance, where $p_{ij} \neq 0$ for each $(i,j)$. Processing operation $T_l$ of product $J_j$ may be carried out on each of $k_l$ machines.

Products have to visit all processing phases in the same sequence as of phase $l$ throughout next $m$ phases. The machine can process at the most one product at a given time, and each product can be processed by only one machine at a time. A priority right to processing is not allowed. Scheduling problem consists of the allocation of processing operations of products to machines at every stage of the process and of defining the sequence in which the products are processed on machines with the aim of minimizing the criterion function. It should be noted that the processing time $p_{ij}$ does not depend on a machine that is assigned to the product $J_j$ at phase $l$. End-processing time of $J_j$ products at the processing stage $l$ is marked with $C_{jl}$.

Mathematical model of mixed integer programming for problem $FFm[k_1, k_2, ..., k_m]C_{max}$ is further presented.

In the mathematical model decision variables define the sequence of processing products on machines at every stage of processing:

- $x_{ijkl} = 1$, if the product $J_j$ is processed in sequence immediately after $J_i$ product on the machine $P_k$ at the processing phase $l$, $x_{ijkl} = 0$, otherwise;
- $x_{ijkl} = 1$, if the product $J_j$ is the first product in the processing sequence on machine $P_k$ in the phase $l$, $x_{ijkl} = 0$, otherwise;
- and the point in time of processing completion of the product at each stage: $C_{jl}$ = completion time of processing products $J_j$ in the phase $l$;

\[
\begin{align*}
(\text{min}) \quad & C_{max} \\
\text{s.t.} \quad & \sum_{i=0}^{n} \sum_{j=1}^{k_l} x_{ijkl} = 1, \quad \forall j = 1, \ldots, n, l = 1, \ldots, m & (1.1) \\
& \sum_{j=0}^{n} x_{ijkl} = 1, \quad \forall i = 0, \ldots, n, k = 1, \ldots, k_j, l = 1, \ldots, m & (1.2) \\
& \sum_{i=0}^{n} x_{ijkl} - \sum_{j=0}^{n} x_{ijkl} = 0, \quad \forall h = 1, \ldots, n, k = 1, \ldots, k_l, \quad l = 1, \ldots, m & (1.3) \\
& C_{jl} = \sum_{k=1}^{k_l} x_{ijkl} \cdot p_{ijkl} \quad \text{(1.4)} \\
\end{align*}
\]

Objective function $C_{max}$ (1.1) is the end processing time of all products. This function should be minimized. Constraints (1.2), (1.3) and (1.4) ensure that each product is processed exactly once in each stage of processing. In particular, the constraint (1.2) guarantees that for each stage of processing $l$ for each product $J_j$ there is one machine so that either the $J_j$ is processed first or after any other product on that machine. Inequality (1.3) shows that at each stage of the process there is a machine on which the product to be processed has a product that follows it in the series, or the product is processed last. Constraint (1.4) says...
that at every stage for each product there is only one machine that satisfies the previous two conditions. Constraints (1.5) and (1.6) take into account the end time of the product processing. Inequation (1.5) provides that the end processing time \( C_i \) and \( C_j \) of products \( J_i \) and \( J_j \) schedules in succession on the same machine respecting the sequence. \( B \) is a very large number, i.e. a constant which is greater than the sum of all processing times of the product. On the other hand, inequation (1.6) defines that products go through phases in the same order from phase \( 1 \) to phase \( m \). The constraint indicating that the end processing time of all products is not less than the end time of processing any product is expressed by inequation (1.7). The last two constraints (1.8) and (1.9) define the domain of control variables.

Given that the problem of FFS is NP-hard [11], [12], approaches to solving it can be divided into groups [13]:

1. Exact methods are the methods which, for acceptable dimensions of problems, guarantee finding an optimal solution from the aspect of one criterion, or Pareto optimal solution in the case of multiple criteria.
2. Constraint Programming refers to an approach in which we search for a solution that meets all constraints but which may not be optimal [14].
3. Heuristic methods are effective solution methods based on some common-sense rules of logic. These methods do not guarantee finding the optimal solution, but they can find very effectively a solution good enough or a range of solutions that meet the constraints. Heuristics are typically divided into: constructive heuristics that generate only one solution and local search heuristics that generate a range of feasible solutions in each iteration.

The complexity of the algorithms of the first two approaches is the exponential function of problem dimensions and therefore they are often ineffective in solving real problems in practice. Hence, to solve complex models, almost exclusively, simple heuristic methods are used. Some of them will be presented in the following paragraphs.

3. HEURISTIC METHODS AND NUMERICAL EXPERIMENT

The effectiveness of heuristic methods will be analysed on the example of FFS which in the \( \alpha | \beta | \gamma \) notation denotes as: \( FF5|p_d,w_j|\gamma \) and the actual data is shown in Table 1. It refers to the allocation of 15 products (P1-P15) to five machine centers (C1-C5). For each product the following parameters are given: \( p_j \) - the duration of processing operations for the \( j \)-th product on \( i \) machine, \( r_i \) - point in time when the \( j \)-th product becomes available for processing, \( d_j \) - point in time in which it is necessary that the \( j \)-th product processing is finished and \( w_j \) - weight coefficient, i.e. priority of \( j \)-th product in relation to other products. The structure of machine centers is as follows: in the first processing phase within the first machine center there are two homogeneous machines, in the second and third processing phase three homogeneous machines in each, in the fourth processing phase two homogeneous machines, and in the fifth processing phase three homogeneous machines.

### Table 1. The matrix of the data used in the problem analysis

<table>
<thead>
<tr>
<th>( p_i )</th>
<th>( r_i )</th>
<th>( d_j )</th>
<th>( w_j )</th>
<th>( t_j )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>C2</td>
<td>C3</td>
<td>C4</td>
<td>C5</td>
</tr>
<tr>
<td>P1</td>
<td>0</td>
<td>25</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>P2</td>
<td>0</td>
<td>26</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>P3</td>
<td>0</td>
<td>30</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>P4</td>
<td>0</td>
<td>30</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>P5</td>
<td>0</td>
<td>32</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>P6</td>
<td>3</td>
<td>48</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>P7</td>
<td>5</td>
<td>40</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>P8</td>
<td>3</td>
<td>24</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>P9</td>
<td>0</td>
<td>40</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>P10</td>
<td>2</td>
<td>36</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>P11</td>
<td>2</td>
<td>40</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>P12</td>
<td>0</td>
<td>36</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>P13</td>
<td>2</td>
<td>80</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>P14</td>
<td>2</td>
<td>36</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>P15</td>
<td>2</td>
<td>34</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

To solve the above problem we use heuristics known as priority rules (dispatching rules). They are particularly suitable in complex, dynamic and unpredictable production and service environments to generate quick solutions. The application of these rules in the process of scheduling implies scheduling the product ready for processing on a free machine, which in the best way meets adopted scheduling rule.

There are a large number of priority rules [2], [3], [4]. The paper analyses the following:

1. **SPT** (Shortest Processing Time) – gives an unscheduled product with the shortest processing time first priority at scheduling.
2. **WSPT** (Weighted Shortest Processing Time) – first schedules the product with the highest quotient of weighting factor and processing time (\( w_j/p_j \)).
3. **LPT** (Longest Processing Time) – first schedules the product with the longest processing time normative i.e. the most demanding products.
4. **EDD** (Earliest Due Date) – schedules firstly the product with the earliest due date. This rule is also known as the Jackson’s rule [15].
5. **MS** (Minimum Slack) – first schedules the product with the smallest slack time. The slack time of a \( j \)-th
product is calculated using the formula:
\[
\max \left\{ d_j - \hat{p}_j - t.0 \right\}
\]

ERD (Earliest Release Date) – first schedules the product which becomes available for processing at the earliest. This policy is in fact the rule "first come, first served" (First Come First Served - FCFS).

CR (Critical Ratio) – first schedules operation of the j-th product with the lowest value of the critical coefficient (the ratio of the due time and the time expected to finish processing):
\[
CR = \frac{d_j - t}{\sum_{i \in m} \hat{p}_j}
\]

Products whose critical factor is: (CR <1), are the products that are late in relation to the plan; (CR = 1) are the products that will be finished on time; (CR > 1) are the products that end prematurely and have a time reserve.

ATCS (Apparent Tardiness Cost with Setups) – This scheduling rule refers to a combination of several other rules. According to this rule, in the point of time \( t \), a product with the highest objective function has the processing priority on the \( i \)-th machine that is free. Objective function is defined as:
\[
I_j(t, l) = \frac{w_j}{p_j} e^{-\frac{\left(\max(d_j - \hat{p}_j - t.0)\right)}{k_1 p}} e^{-\frac{s_j}{k_2 s}}
\]

In this function designations are as follows:
- \( t \) - current time period;
- \( l \) - index of products that have just been completed;
- \( w_j \) - weight coefficient for the \( j \)-th product;
- \( p_j \) - processing time of \( j \)-th product (for which the value of the function rule ATCS is calculated);
- \( d_j \) - due completion time of the \( j \)-th product;
- \( \bar{p} \) - average processing time of all products;
- \( \bar{s} \) - average preparation time of all products;
- \( s_j \) - preparatory time required when the product \( j \) comes to the processing after product \( l \);

\( k_1 \) and \( k_2 \) are parameters for scaling functions. Their value can be defined by decision-makers, but recommendations given in the literature can be also used [16]:
\[
\begin{align*}
  k_1 &= 4.5 + R, \quad \text{for } R \leq 0.5 \\
  k_1 &= 6 - 2R, \quad \text{for } R > 0.5 \\
  k_2 &= \frac{\tau}{2\sqrt{\eta}}
\end{align*}
\]

Where:
\[
R = \left( \frac{d_{\text{max}} - d_{\text{min}}}{C_{\text{max}}} \right) \quad \text{Due date range, where: } d_{\text{min}} \text{ is the lowest value of the due completion date of all the products; } d_{\text{max}} \text{ is the maximum value of the completion date of all the products;}
\]
\[
\tau = 1 - \frac{\bar{d}}{C_{\text{max}}} \quad \text{Due-Date Tightness, where } \bar{d} \text{ is: the average value of the completion date of all products;}
\]
\[
\eta = \frac{s}{p} \quad \text{- severity of the average preparation time compared to the average time of processing operations (Setup Time Severity).}
\]

As for the other, more complex heuristics, in the analysis we have used:

**Shifting Bottleneck Heuristics** [17]: This heuristics shares a scheduling problem of several products on \( m \) machines, on \( m \) scheduling problems on one machine. In the case of FFS it is \( s \) scheduling problems on the machine centres that have \( m \geq 2 \) machines in parallel links. In each iteration there are machines on which the scheduling was done in previous iterations. The scheduling is first done on a new machine which is the bottleneck according to the decision i.e. the sequence of products obtained by solving scheduling problem only on that machine in order to minimize certain criterion function. The bottleneck is the machine or machine centre which is the most critical in terms of values of that criteria function. After the deployment on the machine that is a bottleneck in the given moment, the heuristics tries to revise again already scheduled products in order to obtain a better schedule. In the hypothetical example which is analysed here, the shifting bottleneck heuristics is used with different criterion functions for determination of bottlenecks and scheduling on a single machine (Table 2 Shifting Bottleneck / \( \sum w_j T_j ; C_{\text{max}} ; T_{\text{max}} ; \sum C_j ; \sum T_j : \sum w_j C_j \)).

**Hybrid method of solving - SB-LS (Shifting Bottleneck & Local Search):** This heuristics is a combination of shifting bottlenecks heuristics that generates initial schedule by machines, and local search heuristics which tries to find better schedules in the surrounding of the previous initial schedule. With FFS problem, if the number of products to be scheduled is substantially greater than the number of machines, this algorithm is proven much better in comparison to other algorithms [18].

The experiment was conducted in order to get the answer which of the above methods of solving...
problems of FFS generates good solutions in terms of different performances i.e. the evaluation criteria. For the experiment we used computer program LEKIN, which implements the above mentioned methods [19].

4. ANALYSIS OF RESULTS

Implementation results are presented in Table 2. Solutions obtained by different rules of priority are compared with each other according to the selected performances i.e. criterion functions. Performances are related to products and are marked as follows:

\[ C_{\text{max}} \] — completion date of processing of the product, or the time the last product is finished, \( C_{\text{max}}=\max_j(C_j) \), where \( C_j \) is the time when the \( j \)-th product is finished;

\( T_{\text{max}} \) - maximum delay; delay is defined as the positive difference between the time of the actual completion of the processing of a particular product and the due time by which its completion is expected, i.e. \( T_j=(C_j-d_j)^+ \); \( T_{\text{max}}=\max_j(T_1, \ldots, T_n); \)

\[ \sum_{j=1}^{n} T_j \] - Total delay, the sum of delays of all products. This criterion function can be represented by weight coefficients for each product \( \sum_{j=1}^{n} w_j T_j \).

Weights can denote delay costs of \( j \)-th product per unit of time or quantify the importance of each product.

\[ \sum_{j=1}^{n} C_j \] - The sum of completion time for processing all the products. This criterion can be multiplied by weight coefficients of each product to obtain the following functions \( \sum_{j=1}^{n} w_j C_j \).

\[ \sum_{j=1}^{n} U_j \] - the total number of products that are in delay. If the \( j \)-th product is late \( C_j\geq d_j \), then \( U_j=1 \), otherwise \( U_j=0 \).

Based on the results (presented in Table 2) of the scheduling problem \( FFS_j r_j, d_j, w_j, | \gamma \) the following conclusions can be drawn:

Shifting bottleneck heuristics (SB) for the dimensions of the problem \( (n, m) = (15, 5) \) provides excellent results. This can be seen in "bold" values in Table 2 for the criterion functions: \( \left( C_{\text{max}}, T_{\text{max}}, \sum C_j, \sum T_j \right) \)

Hybrid heuristics (SB-LS) was very successful in the defined problem by generating a good solution in terms of criteria functions: \( \left( \sum U_j, \sum w_j C_j, \sum w_j T_j \right) \)

Table 2. The problem solution of \( FFS_j r_j, d_j, w_j, | \gamma \)

<table>
<thead>
<tr>
<th>Method</th>
<th>( \text{time} )</th>
<th>( C_{\text{max}} )</th>
<th>( T_{\text{max}} )</th>
<th>( \sum U_j )</th>
<th>( \sum C_j )</th>
<th>( \sum T_j )</th>
<th>( \sum w_j C_j )</th>
<th>( \sum w_j T_j )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shifting Bottleneck / ( \sum w_j T_j )</td>
<td>7</td>
<td>92</td>
<td>37</td>
<td>11</td>
<td>729</td>
<td>182</td>
<td>1396</td>
<td>256</td>
</tr>
<tr>
<td>Shifting Bottleneck / ( C_{\text{max}} )</td>
<td>6</td>
<td>76</td>
<td>49</td>
<td>12</td>
<td>885</td>
<td>346</td>
<td>1847</td>
<td>723</td>
</tr>
<tr>
<td>Shifting Bottleneck / ( T_{\text{max}} )</td>
<td>6</td>
<td>108</td>
<td>28</td>
<td>10</td>
<td>761</td>
<td>229</td>
<td>1686</td>
<td>574</td>
</tr>
<tr>
<td>Shifting Bottleneck / ( \sum C_j )</td>
<td>6</td>
<td>88</td>
<td>31</td>
<td>11</td>
<td>705</td>
<td>179</td>
<td>1482</td>
<td>376</td>
</tr>
<tr>
<td>Shifting Bottleneck / ( \sum T_j )</td>
<td>7</td>
<td>86</td>
<td>31</td>
<td>11</td>
<td>701</td>
<td>161</td>
<td>1430</td>
<td>300</td>
</tr>
<tr>
<td>Shifting Bottleneck / ( \sum w_j C_j )</td>
<td>6</td>
<td>90</td>
<td>38</td>
<td>11</td>
<td>728</td>
<td>203</td>
<td>1433</td>
<td>341</td>
</tr>
<tr>
<td>Hybrid method (SB-LS)</td>
<td>6</td>
<td>100</td>
<td>35</td>
<td>9</td>
<td>717</td>
<td>176</td>
<td>1385</td>
<td>254</td>
</tr>
<tr>
<td>Shortest processing time (SPT)</td>
<td>1</td>
<td>109</td>
<td>35</td>
<td>11</td>
<td>732</td>
<td>200</td>
<td>1533</td>
<td>421</td>
</tr>
<tr>
<td>Weighted SPT (WSPT)</td>
<td>1</td>
<td>106</td>
<td>38</td>
<td>11</td>
<td>776</td>
<td>227</td>
<td>1460</td>
<td>328</td>
</tr>
<tr>
<td>Longest processing time (LPT)</td>
<td>1</td>
<td>78</td>
<td>53</td>
<td>13</td>
<td>1006</td>
<td>461</td>
<td>2156</td>
<td>1020</td>
</tr>
<tr>
<td>Earliest due date (EDD)</td>
<td>1</td>
<td>113</td>
<td>34</td>
<td>13</td>
<td>759</td>
<td>202</td>
<td>1572</td>
<td>412</td>
</tr>
<tr>
<td>Minimum slack (S)</td>
<td>1</td>
<td>109</td>
<td>33</td>
<td>13</td>
<td>800</td>
<td>243</td>
<td>1674</td>
<td>487</td>
</tr>
<tr>
<td>Earliest release date (ERD)</td>
<td>1</td>
<td>95</td>
<td>36</td>
<td>11</td>
<td>753</td>
<td>203</td>
<td>1585</td>
<td>439</td>
</tr>
<tr>
<td>Critical Ratio (CR)</td>
<td>1</td>
<td>112</td>
<td>35</td>
<td>13</td>
<td>791</td>
<td>234</td>
<td>1637</td>
<td>477</td>
</tr>
<tr>
<td>Apparent Tardiness Cost with Setups (2,1/2)</td>
<td>1</td>
<td>106</td>
<td>37</td>
<td>12</td>
<td>771</td>
<td>220</td>
<td>1451</td>
<td>315</td>
</tr>
</tbody>
</table>

1 Time spent to arrive to the solution, in seconds, while working at computer (Intel Core i3- 2.30GHz, 4GB RAM)
2 The value of scaling parameters is given in brackets as the ordered pair (k1, k2)
Priority rules provided varied results for a given problem:

- Scheduling rule SPT generates a good solution for the criterion function: $\sum U_j, \sum C_j, \sum T_j$.
- Scheduling rule WSPT generates a good solution for the criterion function: $\sum U_j, \sum w_j C_j$.
- Scheduling rule LPT generates a good solution for the criterion function $T_{\text{max}}$.
- Scheduling rule EDD generates a good solution for the criterion function $\sum T_j$.
- Scheduling rule MS generates a good solution for the criterion function $T_{\text{max}}$.
- Scheduling rule ERD generates a good solution for the criterion function: $\sum U_j, \sum T_j$.
- Scheduling rule CR generates a good solution in terms of criterion function $T_{\text{max}}$.
- Scheduling rule ATCS generates a good solution for criterion functions $\sum w_j C_j, \sum w_j T_j$.

5. CONCLUSION

This paper presents the problem of scheduling in flexible-flow production. With the help of software LEKIN we have demonstrated the applicability of some simple heuristic methods of scheduling on the example of a hypothetical problem. The solutions are compared mutually according to different performances. Based on the results of the numerical experiment, by using simple priority rules the following can be concluded:

For criterion $C_{\text{max}}$, LPT rule can be used; for criterion $T_{\text{max}}$, $S$, $ED$, $CR$ and SPT rules can be used; for criterion $\sum U_j$, priority rules SPT, WSPT, ERD; for criterion $\sum T_j$, rules SPT, EDD, ERD; for criterion $\sum w_j C_j$, rules ATCS and WSPT; for criterion $\sum w_j T_j$, priority rule ATCS.

All above mentioned priority rules have an enormous advantage over the exact methods or more complex heuristic methods in terms of time efficiency. Although they do not guarantee optimal solutions, they quickly give relatively good solutions as opposed to the exact methods that can be practically completely inapplicable because of the required volume of computation i.e. unacceptably long computation time.

By observing the results of applying priority rules in the hypothetical case analysed in this paper, it can be concluded that there is no universal rule for scheduling. It is rather recommendable to apply several priority rules to generate scheduling and make selection of the “best” scheduling solution in line with desired performances of decision makers. Limitations of this study relate to the application of a given number of methods of solving problems implemented in computer program LEKIN. Defining new heuristic and exact methods for solving scheduling problems remains constant practical and research challenge.

REFERENCES

ANALYSIS OF DISPATCHING RULES APPLICATION...


REZIME

ANALIZA PRIMENE PRAVILA PRIORITETA NA PROBLEMU RASPOREDIVANJA U FLEKSIBILNO PROTOČNOJ PROIZVODNJI

U ovom radu analizirana je grupa jednostavnih heurističkih metoda koje se koriste u rešavanju problema raspoređivanja u proizvodnji i pružanju usluga. Analiza je izvršena na primjeru raspoređivanja u fleksibilno protočnoj proizvodnji koji je poznat po engleskom akronimu FFS (Flexible-Flow Shop). Zadatak je odrediti raspored obrade više proizvoda na više mašina, pri čemu svi proizvodi slede isti redosled obrade i za svaku obradu postoji na raspolaganju više mašina. Za opisani problem FFS dat je odgovarajući matematički model mešovitog celobrojnog programiranja. Od potencijalnih metoda za rešavanje postavljenog zadatka detaljnije se razmatraju jednostavne heuristike jer je originalni zadatak NP tvrd i nalaženje točnog optimalnog rešenja zahtevalo bi neprihvatljivo dugo računarsko vreme. Heurističke metode počivaju na pravilima prioriteta koja se izvode na osnovu relacija važnosti između proizvoda i trajanja njihovih obrada na pojedinačnim mašinama. Heurističke metode imaju široku primenu u rešavanju praktičnih problema i to je bila motivacija da se analizu uspostavi sazvukaju u ovom radu. Cilj analize je da se na jednom hipotetičkom primeru problema raspoređivanja odrede ona pravila prioriteta koja daju dobra rešenja pri čemu se ocjenjuje korišćenjem različitih kriterijumskih funkcija. Analiza je obavljena pomoću računarskog programa LEKIN. Kao glavni rezultat analize pokazano je da pravila prioriteta daju različita rešenja za problem FFS i da svako od tih rešenja predstavlja značajno dobar rezultat sa aspekta neke od razmatranih kriterijumskih funkcija.

Ključne reči: problemi raspoređivanja, protočna proizvodnja, fleksibilno-PROTOČNA PROIZVODNJA, pravila prioriteta
The Application of the Multi-criteria Analysis in Evaluating of the Road Designs

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The analysis of the suitability of applying multi-criteria ranking of road design variants places the emphasis on the danger of fixing the ranking results, by the impact of subjective factors, in the process of determining relevant criteria and their relative weights. This danger is illustrated using two real examples.

In the first example, subjective factors did not have a decisive influence since all of the most significant technical exploitation economic and ecological indicators, determined in the appropriate study and project documentation, were taken into account while determining relevant criteria and their relative weights.

In the second example, subjective factors had a more decisive influence since all of the most significant technical exploitation economic and ecological indicators, determined in the appropriate study and project documentation, were not taken into account while determining relevant criteria and their relative weights.

Key words: Multi-criteria ranking, design variant, SAW method, AHP method, criteria, weights of criteria, internal rate of return IRR, NSV

1. INTRODUCTION

Multi-criteria analyses which, as part of mathematical sciences, belong to operational research, have found the application, in the role of a “tool”, in the procedures of multi-criteria ranking (MCDM) of the variants of designed roads. Since 1957 numerous methods for conducting multi-criteria ranking have been developed. Some of them are: SAW (Simple Additive Weighting Method), TOPSIS (The Technique for Order of Preference by Similarity to Ideal Solution), ELECTRA (Elimination Et Choix Traduinsant Realite), PROMETHEE (A Preference Ranking Organization Method for Enrichment Evaluation), VIKOR, AHP (Analytic Hierarchy Process), etc.

2. BASIC STEPS IN THE APPLICATION OF MULTI-CRITERIA RANKING OF ROAD DESIGNS

Basic steps in the application of multi-criteria ranking in the procedures of choosing the optimal variant of the designed roads are:

- The first step – determining the variants
- The second step – determining the (sizes of) basic indicators, which were previously defined in the appropriate study and project documentation, for the designed variants

Table 1. Basic matrix

<table>
<thead>
<tr>
<th>Basic indicators $(X_i)$</th>
<th>Sizes (values) of basic indicators by variants $(Y_i)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_1$</td>
</tr>
<tr>
<td>$X_1$</td>
<td></td>
</tr>
<tr>
<td>$X_2$</td>
<td></td>
</tr>
<tr>
<td>$X_3$</td>
<td></td>
</tr>
<tr>
<td>................................</td>
<td></td>
</tr>
<tr>
<td>$X_n$</td>
<td></td>
</tr>
</tbody>
</table>

- The third step – determining the relevant criteria

In this phase, the basic indicators are defined and transformed into the relevant criteria on the basis of which the multi-criteria ranking of the variants is conducted by applying some of the multi-criteria evaluation methods.
The fourth step – determining the relative weights of the relevant criteria

In the application of any of the multi-criteria ranking methods, the selected relevant criteria, and especially the allocation (assigning) of relative weights to the relevant criteria, have a significant influence on the results. In addition to the influence of the value of the basic indicators per variant defined in the appropriate study and project documentation. Considering the fact that subjective criteria have a significant influence on the selection of relevant criteria and on the allocation of relative weights to the selected criteria, multi-criteria ranking for the selection of the variant is best applied in the cases where differences between the variants are minimal, when measured by technical exploitation, economic and ecological indicators. This is because a very precise scale is necessary for the relative ranking of variants in the situations when the differences between them are minimal, and if it happens that their ranking has been influenced by a strong subjective factor, no big harmful consequences can emerge.

However, there are situations where there are significant differences between the values of the basic, technical exploitation, economic and ecological indicators according to which the advantage of some variant is evident. In these situations, in the process of applying multi-criteria ranking of variants and as a consequence of the pronounced influence of the subjective factor, there could be a danger of choosing a variant which is clearly worse according to all of the most significant technical exploitation, economic and ecological indicators, which would cause enormous, various and long-term damages. In the described situations, where one of the considered variants is evidently and clearly the most favourable according to the values of technical exploitation, economic and ecological indicators, “the expert” who demands the application of the multi-criteria ranking for selecting the variant is obviously an ignorant or has a bad intention to fix results according to the principle of white becoming black, and black becoming white. It is most frequently a combination of the lack of knowledge and bad intentions, since the one who knows little is more inclined to faking results.

Thus, in the application of multi-criteria variant ranking, the biggest importance should be given to determining the relevant criteria and assigning relative weights to the selected criteria, while the choice of the method of multi-criteria ranking has less significance.

This is why the SAW multi-criteria ranking method is the only method described in the further text.

Also, we have shown two numerical examples of variant ranking where the relative sequence (order) is noticeable and based on the values of the main and most significant technical exploitation, economic and ecological indicators:

- the first numerical example shows the practical application of the SAW method where subjective factors virtually had no influence on the ranking results;
- the second numerical example is based on the application of the AHP method and here subjective factors had the decisive and practically sole influence on the ranking results.

3. SAW – SIMPLE ADDITIVE WEIGHTING METHOD

This method is one of the most common and most frequently used methods in multi-criteria ranking. In order to use this method, it is essential to define relevant criteria and relative weights of the selected criteria. Prior to applying this method, it is necessary to normalize the values that some variants Vi take according to particular criteria (the value from the basis matrix D). Non-dimensional elements \( r_{ij} \) of the normalized matrix R are obtained in the following way:

- for the “benefits” criteria by the relation \( r_{ij} = \frac{x_{ij}}{x_{j\max}} \)
- for the “costs” criteria by the relation \( r_{ij} = \frac{x_{j\min} - x_{ij}}{x_{ij}} \)

where \( i \) represents the variant and \( j \) represents the criterion.

The total number of points for particular variants is obtained when the value from the normalized matrix (R), which some of the variants take according to particular criteria, is multiplied by the corresponding weighting values of criteria (Wi). Thus obtained products, which relate to the particular variants, are added. The final result is the sum of these variants. The best variant is the one with the biggest sum total.

4. A NUMERICAL EXAMPLE OF THE SAW METHOD FOR VARIANT RANKING, WHERE SUBJECTIVE FACTORS PRACTICALLY HAD NO INFLUENCE ON THE VARIANT RANKING RESULTS

The main objective of showing the following numerical example is the detailed presentation of the SAW method application where subjective factors had no influence on ranking results.

The reason for this is the fact that the ranking brought to the selection of the criteria which represented the most significant, transformed technical exploitation, economic and ecological indicators; this brought to the ranking result by applying the SAW method which was identical to the result similarly evident through the basic, most important technical
expansion, economic and ecological indicators. This numerical example refers to the selection of the most favorable variant of the motorway Belgrade – Southern Adriatic on the stretch from Belgrade to Pozega.

1) The first step – determining the variants to be compared
- V1 – Belgrade-Obrenovac-Ljig-Takovo-Preljina-Pozega
- V2 – Belgrade-Obrenovac-Ub-Slovac-Cestobrodica-Pozega
- V3 – Belgrade-B.Potok-M.Pozarevac-Topola-Takovo-Pozeg

2) The second step - determining the values of the most significant indicators per variants (see table 2)

Table 2. Fulfilled basic matrix

<table>
<thead>
<tr>
<th>Basic indicators (X)</th>
<th>Unit of measure</th>
<th>Values of basic indicators by variants (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1 - Length of motorway route (L)</td>
<td>km</td>
<td>144.055, 126.650, 143.144</td>
</tr>
<tr>
<td>X2 - Total construction and operating costs discounted to the first year (( \sum T ))</td>
<td>million dinars</td>
<td>1,675,798, 1,684,849, 1,751,365</td>
</tr>
<tr>
<td>X3 - Internal Rate of Return (ISR)</td>
<td>(%)</td>
<td>13.30, 13.39, 10.60</td>
</tr>
<tr>
<td>X4 - Spatial urbanistic and ecological aspects</td>
<td>(points)</td>
<td>99.30, 98.30, 97.60</td>
</tr>
</tbody>
</table>

3) The third step - determining the criteria by which variants were ranked
- X1 – L – length of motorway route (km) (-) (**)
- X2 – \( \sum T \) – criteria of total construction and operating costs discounted to the first year (10^6) (-) (**)
- X3 – ISR – Internal Rate of Return (%) (+)**
- X4 – spatial urbanistic and ecological aspects (points) (+) (**)

4) The fourth step - forming base matrix (D) and non-dimensional matrix

Table 3. Base matrix (D)

<table>
<thead>
<tr>
<th>Variant</th>
<th>Criterion</th>
<th>X1 (-)</th>
<th>X2 (-)</th>
<th>X3 (+)</th>
<th>X4 (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td></td>
<td>144.055</td>
<td>1,675,798</td>
<td>13.30</td>
<td>99.30</td>
</tr>
<tr>
<td>V2</td>
<td></td>
<td>126.650</td>
<td>1,684,849</td>
<td>13.39</td>
<td>98.30</td>
</tr>
<tr>
<td>V3</td>
<td></td>
<td>143.144</td>
<td>1,751,365</td>
<td>10.60</td>
<td>97.60</td>
</tr>
</tbody>
</table>

5) The fifth step – determining weights of certain criteria

Taking into account the importance of the basic technical exploitation, economic and environmental indicators, weights (W) of certain criteria were defined.

- \( W_1 = 0.15 \); \( W_2 = 0.30 \); \( W_3 = 0.35 \); \( W_4 = 0.20 \)
- \( \sum W_i = 1 \) weights defined by method of ranking

6) The sixth step – performing the calculation of weights values for variants

\[
V_j = \sum_{i=1}^{4} r_{ij} \cdot W_j = 0.88 \cdot 0.15 + 1.00 \cdot 0.30 + 0.99 \cdot 0.35 + 1.00 \cdot 0.20 = 0.9785
\]

\[
V_2 = \sum_{i=1}^{4} r_{ij} \cdot W_j = 1.00 \cdot 0.15 + 0.99 \cdot 0.30 + 1.00 \cdot 0.35 + 0.99 \cdot 0.20 = 0.9950
\]

(** – “Benefits” (+) criterion. The best variant is one with the highest value according to this criterion

(*) – “Costs” (-) criterion. The best variant is one with the lowest value according to this criterion

Figure 1 - Schematic representation of the motorway Belgrade-Pozega corridor variants
The seventh step – determining the relative order of the considered variants

Based on the obtained results, the best variant is $V_2$ (0.9950) and the relative order of the considered variants is as follows (following):

I) $V_2$ (0.9950)
II) $V_1$ (0.9785)
III) $V_3$ (0.8975)

5. A NUMERICAL EXAMPLE OF APPLYING THE AHP METHOD FOR VARIANT RANKING, WHERE SUBJECTIVE FACTORS HAD THE DECISIVE (SOLE) INFLUENCE ON THE RESULTS OF VARIANT RANKING

The main goal of showing the following numerical example is to present the application of multi-criteria ranking (AHP method) where the variant of the designed motorway was selected exclusively with the maximum influence of subjective factors, and where it was "scientifically" proved how black becomes white and white becomes black.

This numerical example refers to the selection of the variant of the designed motorway Belgrade – South Adriatic on the stretch between the Belgrade bypass and Obrenovac.

(1) The first step – determining the variants to be compared

These are the variants of the designed motorway:
- $V_1$ – on the RIGHT bank of the Sava River from Ostruznica to the Obrenovac interchange
- $V_2$ – on the LEFT bank of the Sava River from the Surcin interchange to the Obrenovac interchange

![Variant Surcin-Obrenovac (on the left bank of the Sava River)](image1)

construction: 166.391.188 €

![Variant Ostruznica-Obrenovac (on the right bank of the Sava River)](image2)

construction: 136.850.000 €

*Figure 2 - Variant positions schematic representation of the future motorway from Belgrade bypass to Obrenovac*

(2) The second step – determining the values of the most significant indicators per variants
Table 5. Determining the values of the most significant indicators per variants

<table>
<thead>
<tr>
<th>Basic indicator ($X_i$)</th>
<th>Unit of measure</th>
<th>Values of basic indicators by variants ($V_i$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>Length of designed motorway route (km)</td>
<td>14.5</td>
</tr>
<tr>
<td>$X_2$</td>
<td>Orientation of dominant traffic flows (%)</td>
<td>60</td>
</tr>
<tr>
<td>$X_3$</td>
<td>Traffic volume on the motorway in the first year (veh/day)</td>
<td>32400</td>
</tr>
<tr>
<td>$X_4$</td>
<td>The costs of motorway construction (€)</td>
<td>136,850,000</td>
</tr>
<tr>
<td>$X_5$</td>
<td>The costs of landslides rehabilitation Duboko construction costs of urban road Surcin-Novin Beograd, which are not covered by the construction costs of motorway route (€)</td>
<td>0</td>
</tr>
<tr>
<td>$X_6$</td>
<td>Economic Internal Rate of Return (EISR) (%)</td>
<td>35.0</td>
</tr>
<tr>
<td>$X_7$</td>
<td>Financial Internal Rate of Return (FISR) (%)</td>
<td>10.0</td>
</tr>
<tr>
<td>$X_8$</td>
<td>The number of years in which invested capital returns from toll revenue (years)</td>
<td>15-20</td>
</tr>
</tbody>
</table>

According to the following illustration of the values of the most significant technical exploitation, economic and ecological indicators per variants, determined in the study and project documentation processed on the level of Conceptual Design, it is apparent that the treated variants significantly differ according to numerous characteristics and that one of the variants has the distinct advantage regarding the most important technical exploitation, economic and ecological indicators.

This means that in such cases the application of multi-criteria ranking only has the aim to fix ranking results by the inappropriate influence of subjective factors.

(3) The third step – determining the criteria by which variants were ranked

Figure 3 - The criteria by which variants were ranked
Determining the basic criteria and fragmenting them into over 30 subcriteria of dubious importance, while omitting and blurring some very important ones (EISR, FISR, the number of years needed for the capital invested in the motorway to be returned through the toll payment, costs of maintaining the relevant road networks etc.), clearly signalizes that the main goal of applying the AHP method of multi-criteria ranking is to “SCIENTIFICALLY” prove the selection of the highway variant Surcin - Obrenovac, although this variant is clearly worse than the variant Ostruznica - Beograd according to all of the most significant technical exploitation, economic and ecological indicators).

(4) The fourth step – conducting the pairwise comparison of all the variants on all the levels of the AHP model.

- Pairwise comparison on the first level – the level of main criteria

On this level, all the project participants compared technical and technological (T-T), social and economic (S-E) and ecological (ECL) criteria. On the basis of discussions and consideration of the results of these discussions it was stated that these three groups of criteria were equally important. One of the conclusions of the discussion was that this should be the premise and that the final analysis of results should point out to which extent the change of these criteria would influence the final result.

- Pairwise comparison on the second level

Experts, members of the work team, people from the field to which the considered level of comparison belonged, took part in each of the following levels of the pairwise comparison process. Technical and technological (T-T) criteria were divided into two main groups: urbanistic and traffic (URB&TRAFF) and construction and geological and hydrological (CGH). Social and economic criteria (S-E) were also put into two main groups: sociological (SOC) and economic (ECON). In the field of ecology (ECOL) the criteria were divided into three main groups: consequences of air pollution and consequences of vehicle noise (AN), soil and water pollution (SW) and flora and fauna destruction (FF).

- Pairwise comparison on the third level

On this level, as it can be seen in the picture (AHP diagram), it was necessary to conduct the pairwise comparison of those criteria which emerged as the consequence of the criterion division on the second level. Thus the criterion group URB&TRAFF was divided into urbanistic (URB) and traffic subcriteria (TRAFF).

On this level there is the division of sociological criteria (SOC) into the subcriteria of solving property rights (SOC1) and the influence on the so-called Social capital (SOC2).

On this level, ecological criteria were divided into subcriteria. The air and noise group (AN) was divided into the subcriteria of air pollution (AP) and consequences of noise pollution (CN). The group of criteria referring to soil and water pollution (SW) was divided into the subcriteria of soil pollution (SP) and water pollution (WP).

- Pairwise comparison on the fourth level

On this level it is necessary to conduct the pairwise comparison of those criteria which emerged as the consequence of the criterion division on the third level. Urbanistic criteria (URB) were divided into the following subcriteria: urbanistic norms, regulations and standards (URB1), attitude towards the adopted regional and urbanistic plans (URB2) and the protection of human-made and natural values (URB3).

The next division on this level is the division of traffic criteria (TRAFF) into the subcriteria of the accessibility of central attractions (TR1), the accessibility of economic zones (TR2), the variant's position in relation to the corridor E-763 (TR3) and in relation to the local traffic flows (TR4).

Furthermore, the construction criterion (Con) was divided into the subcriteria of the complexity of constructing bridges and buildings (CON1), supplying the construction material - logistics (CON2) and the period of the section's construction (CON3).

Geological criteria (GL) were divided into the next subcriteria: the constructional suitability of the terrain (GL1), the influence on terrain stabilization (GL2) and the sensitivity to tectonic disturbance (GL3).

The criteria in the field of hydrology and hydro-technical engineering (HD) were divided into the following subcriteria: the influence on underground water regime (HD1), the influence on the water sources (HD2) and influence on sailing conditions (HD3).

The criteria referring to the costs of the variant’s construction and maintenance (CCM) were separated into the subcriteria: total costs of the section construction (CC1), costs of maintaining the highway section (CC2) and costs of maintaining the bridges and buildings (CC3).

The last division on this level was the division of the exploitation costs criterion (EC) into the next subcriteria: the costs of the distances covered by passenger vehicles (EC11), the costs of the consumed time by passenger vehicles (EC12), the costs of the distances covered by freight vehicles (EC21) and the costs of the consumed time by freight vehicles (EC22).

- Pairwise comparison on the fifth level
In the fifth phase the comparison of the alternatives according to the superior criteria was carried out.

The described process of pairwise comparison on all the levels using the AHP method openly announced the decisive influence of subjective factors on the selection of the variant, in order to give advantage to the variant of the motorway Surcin-Obrenovac on the basis of the most (fictitious) artificially determined subcriteria of dubious significance.

(5) The fifth step – comparing variants according to superior criteria

After the given remarks in the third and fourth step, due to the crucial influence of subjective factors, the variant Surcin – Obrenovac was given precedence according to 24 subcriteria of doubtful significance, while the variant Ostruznica-Obrenovac was given advantage on the basis of 8 subcriteria.

6. THE ANALYSIS OF THE NEGATIVE EFFECTS WHICH WILL BE BROUGHT BY SELECTING THE MOTORWAY VARIANT SURCIN-OBRENOVAC INSTEAD OF THE MOTORWAY VARIANT OSTRUZNICA-OBRENOVAC

The analysis of the most significant technical and technological, economic and ecological indicators per variants, determined in the study and project documentation for both variants, has shown that the construction of the motorway variant Surcin – Obrenovac instead of the variant Ostruznica – Obrenovac would cause numerous negative consequences, such as:

1. Total expenses from the budget of the republic of Serbia for the construction of motorway surcin-obrenovac instead of the motorway Ostruznica-Obrenovac will be higher by approximately 149,200,000€.

The above-mentioned amount includes:

a) Approximately 30,000,000€ in terms of the motorway construction by the left bank of the Sava River from Surcin to Obrenovac, on the basis of both Conceptual Designs of the motorway from the Belgrade bypass by the “right” and “left” bank of the Sava River which were audited by the same Audit Committee;

b) Approximately 80,000,000€ for restoring the landslide site of Umka-Duboku and adjusting the Sava River’s hydraulic and sailing parameters to the European standards, which are included in the price of constructing the motorway by the right bank of the Sava River, while the Conceptual Design was audited by the same Republic Audit Committee;

c) Approximately 39,200,000€ for the expenses of the urban road construction, which would connect the motorway from Surcin to Novi Beograd. The given cost is included in the Feasibility Study for the construction of the motorway by the left bank of the Sava River, which was audited by the same Republic Audit Committee.

2. Regarding the motorway variant by the left bank of the Sava, from Surcin to Obrenovac, all of the most important technical exploitation, economic and ecological parameters are clearly less favourable than the variant of the motorway by the right bank of the Sava from Ostruznica to Obrenovac:

d) The road will be longer by around 9,5 km for more than 60% of vehicles in the traffic flow.

e) The traffic flow will be smaller by around 13%, which will remain on the existing, less safe roads 22 (M22) and 26 (M19).

f) In the process of the motorway construction, the road 26 (M19) from Umka to Obrenovac will not be brought into the quality exploitation state.

g) In the process of the motorway construction, the hydraulic and sailing parameters of the Sava River will not be adjusted to the European standards.

h) In the process of the motorway construction, the landslide Umka-Duboko will not be restored, which means that around 500 facilities will be in danger of falling in and around 200 hectares of the devastated land will not be restored into the quality building land.

i) The costs of vehicle operating will rise by more than 300,000,000€ in the period of thirty years.

j) The costs of the travelling time of passengers in passenger vehicles and buses will rise by more than 50,000,000€ in the period of thirty years.

k) The costs of maintaining the motorway and part of the existing road network will rise by more than 10,000,000€ in the period of thirty years.

l) More than 120 hectares of farmland will be destroyed for all the future time.

7. THE NEGATIVE CONSEQUENCES IN THE IMPLEMENTATION AND OPERATION OF THE MOTORWAY VARIANTS SELECTED THROUGH MCA UNDER THE DECISIVE INFLUENCE OF SUBJECTIVE FACTORS

The analysis of the most significant technical and technological, economic and ecological indicators per variants, determined in the study and project documentation for both variants, has shown that the construction of the motorway variant Surcin – Obrenovac instead of the variant Ostruznica – Obrenovac would cause numerous negative consequences, such as:

- The higher construction costs by over 20%.
- Costs of repairs of landslide Umka will not be a part of the motorway construction cost.
- Improved hydraulic and navigation parameters of the Sava river in line with European standards will not be a part of the motorway construction cost.
- There will be no indirect effect of motorway construction on improved road conditions to state road first rank number 26 (M19).
- Road will be longer about 9.5km for 60% of vehicles in the traffic flow.
- There will be less traffic flow on the motorway for about 13% (in the first year of operation). This traffic flows will remain on existing roads which is less safe road mark 22 (M22) and road mark 26 (M19).
- It will be much higher Road user cost of using the highway (vehicle operating costs, time costs of passengers and cargo, accident costs, maintenance costs of the road network).
- It will be required significantly longer concession period for the return of capital invested in highway trough toll collection;
- Jeopardize the water-source (water wells) located not left bank of the Sava river.
- It will destroys for all time over 120 hectares of agricultural land.

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REZIME

PRIMENA VIŠEKRITERIJUMSKE ANALIZE U VREDNOVANJU PROJEKATAPUTEVA

U analizi podobnosti primene višekriterijumskog rangiranja projektnih varijanti puteva, naglasak je dat na opasnost da se delovanjem subjektivnih faktora, pri određivanju merodavnih kriterijuma i njihovih relativnih težina, može nameštati rezultat rangiranja. Ova opasnost je ilustrovana kroz dva realna primera.

U prvom primeru subjektivni faktori nisu odlučujuće uticali, jer su, pri utvrđivanju merodavnih kriterijuma i njihovih relativnih težina, uvažavani najznačajniji tehničko-eksploatacioni, ekonomski i ekološki pokazatelji, koji su utvrđeni u odgovarajućoj studijsko-projektnoj dokumentaciji.

U drugom primeru subjektivni faktori su odlučujuće uticali, jer, pri utvrđivanju merodavnih kriterijuma i njihovih relativnih težina, nisu uvažavani najznačajniji tehničko-eksploatacioni, ekonomski i ekološki pokazatelji, koji su utvrđeni u odgovarajućoj studijsko-projektnoj dokumentaciji.

Ključne reči: višekriterijumsko rangiranje, SAW metod, AHP metod, kriterijumi, težine kriterijuma, interna stopa ISR, NSV, varijanta, projekat
TECHNICS

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Research on Student Satisfaction with Service of Higher Education

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Under conditions of general globalization, higher education institutions should develop mechanisms for sustainable development and success in the competitive academic area. Designing a quality management system is the basis for continuous improvement of services, as well as recognition of obligations towards the users. In order to reach its goals, a higher education institution should offer continuously improving values to its users. Understanding, meeting and exceeding the needs and expectations of higher education users is of utmost importance for gaining competitive advantage, positioning in the academic area, sustainable development, and thus, reaching sustainable success.

The aim of the research presented in this paper is to emphasize the significance of implementation of the quality management system model as an efficient tool for quality assurance in the educational process, improvement of the higher education service and achievement of user satisfaction. Such an approach enables the management structure of a higher education institution to maintain continuous monitoring of the key parameters of its business activities, and make decisions in the field of constant quality improvement.

Key words: quality management system, a higher education institution, users, students, satisfaction, sustainable success

1. INTRODUCTION

One of the key issues that are nowadays raised in the area of higher education is "sustainable development" i.e. "sustainable success" of a higher education institution.

The term "sustainable development" can refer to the constant improvement of and innovations in the achieved results with the aim of improving satisfaction of the higher education users. Achievement of sustainable development implies achievement of sustainable success of a higher education institution in a complex, demanding and changeable environment. The main idea and purpose of this research was to explore satisfaction of the higher education service users.

Research within the framework of this paper indicates the importance of implementation of the quality management system model as an efficient tool for quality assurance in the educational process, improvement of the higher education service and achievement of user satisfaction.

2. RESEARCH PROGRAM

Place and conditions of research

The research program included three higher education institutions: College of Applied Sciences, Belgrade Polytechnics, Technical College of Applied Sciences, Novi Sad, Academy of Diplomacy and Security, Belgrade. Two of the above institutions belong to a state-funded sector while the Academy of Diplomacy and Security, Belgrade is a privately-funded higher education institution. All three higher education institutions implement a quality management system.

For the requirements of this research, the following secondary data were used:
• Report on the institution evaluation by students for the school year 2012/2013, College of Applied Sciences, Belgrade Polytechnics [4],
• Presentation of the results of self-evaluation for the school year 2012/2013, Technical College of Applied Sciences, Novi Sad [3],

Methodology of research
Descriptive research was applied for the purpose of obtaining response regarding student satisfaction with the quality parameters of the institution. The parameters were examined by means of a comparative analysis of secondary data as a synthesis of individual values.

Namely, application of the descriptive research enabled obtaining response to the question:

What is the level of student satisfaction with service of higher education?

The strategy of research is based on a combination of quantitative and qualitative methods.

Sample description
• College of Applied Sciences-Belgrade Polytechnics (the sample equals 406 students in the population of 1391, the relevance and significance of the sample has been achieved);
• Academy of Diplomacy and Security (the sample equals 186 filled-in surveys);
• Technical College of Applied Sciences (the sample varies from 20 to 157 respondents depending on the parameter).

Testing and hypotheses analysis
The basic (null) hypothesis was presented, reading:

\[ H_0: \text{Establishment of a quality management system makes it possible for the higher education user to achieve satisfaction and for the higher education institution to reach sustainable success.} \]

Satisfaction of the higher education user is possibly achieved through the fulfilment of several parameters:
• The level of satisfaction with the quality of the program of study;
• The level of satisfaction with the work of the non-teaching staff (administrative office and student services);
• The level of satisfaction with the level of technical equipment of the work area and library;
• The level of satisfaction with the quality of work of the teaching staff
• The level of satisfaction with the quality of the teaching process.

Sustainable success of a higher education institution is achieved by means of reaching certain levels of satisfaction with the quality of the above stated items.

After that, it is possible to work on improvement of the satisfaction level if there is room for improvement as defined through the QMS (Quality Management System) structure. The above stated five quality parameters were tested on a sample of three higher education institutions.

FWER (familywise error) test was previously carried out in order to determine the probability of incorrect rejection of at least one null hypothesis in a comparison group.

As the Student’s t-test should be used to analyse means of three institutions, FWER formula (1) is to be applied in the following way:

\[
\text{FWER} = 1 - (1 - 0.05)^m = 1 - (1 - 0.05)^3 = 1 - 0.857 = 0.143 = 14% \tag{1}
\]

The limit values which are necessary for conducting this test are 0 ≤ FWER ≤ α, where α is a minimum limit value that denotes probability of the type I error, and it equals α = 0.142525.

The probability of making FW error is 14%, which is a permitted value (within the stated limits), so that reliability of the results of this comparison could be ensured.

3. RESEARCH RESULTS
1. The level of satisfaction with the program of study:

As regards testing of the first parameter, the three observed institutions made the reports on self-evaluation in different ways.

Accordingly, in the report on the institution evaluation by students that was carried out for the school year 2012/2013 in the Belgrade Polytechnics, table 1 is presented.

A high level of match between all variables except for the schedule of subjects per years (the highest value of standard deviation) is noticeable.

Then, in the Technical College of Applied Sciences, only the variables the level of theoretical knowledge and the level of practical knowledge (corresponding to the variables “gaining general knowledge” and “gaining professional knowledge and skills”) were assessed.
Table 1. Testing of variables related to the level of satisfaction with the quality of the program of study in the Belgrade Polytechnics

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability of information on the program of study /major</td>
<td>402</td>
<td>1</td>
<td>5</td>
<td>3.97</td>
<td>.98</td>
</tr>
<tr>
<td>Gaining general knowledge</td>
<td>404</td>
<td>1</td>
<td>5</td>
<td>3.86</td>
<td>.92</td>
</tr>
<tr>
<td>Gaining professional knowledge and skills</td>
<td>401</td>
<td>1</td>
<td>5</td>
<td>3.74</td>
<td>1.00</td>
</tr>
<tr>
<td>Schedule (sequence and connection) of subjects per years at the program of study /major</td>
<td>397</td>
<td>1</td>
<td>5</td>
<td>3.45</td>
<td>1.16</td>
</tr>
<tr>
<td>Valid N (listwise)</td>
<td>394</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results from the report are presented in table 2. It can be noted that the satisfaction with the level of theoretical knowledge (mean of the responses on the scale of 1 to 5 is 4.5; standard deviation is 0.51) is higher than satisfaction with the level of practical knowledge (mean is 3.25; standard deviation is 0.44).

Table 2. Testing of the parameter in the Technical College of Applied Sciences

<table>
<thead>
<tr>
<th>Variable</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>Average score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of theoretical knowledge</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.50</td>
</tr>
<tr>
<td>Level of practical knowledge</td>
<td>0</td>
<td>5</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>3.25</td>
</tr>
</tbody>
</table>

And finally, as regards the Academy of Diplomacy and Security, the variables such as "organizational unit structure" and "organization of work" which can be correlated to the schedule of subjects per years at the program of study /major were observed. A high level of satisfaction with the above mentioned variables can be noted (mean of this parameter is 4.09).

Table 3. Testing of the parameter at the Academy of Diplomacy and Security

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organization of work</td>
<td>4.16</td>
</tr>
<tr>
<td>Organizational unit structure</td>
<td>4.02</td>
</tr>
<tr>
<td>Mean</td>
<td>4.09</td>
</tr>
</tbody>
</table>

It was necessary to compare the means measured in all three institutions in order to defend the importance of analysis of the first (out of five) parameter. Analysis of the means using Student's t-test with 2 degrees of freedom was implemented for this purpose. Firstly, the means of the variables "gaining general knowledge" and "the level of theoretical knowledge" were compared and the probabilities of significance which correspond to the t-test values are shown in table 4.

Table 4. Probabilities of the samples significance after Student's t-test of the parameter the level of satisfaction with the quality of the programs of study (first part).

<table>
<thead>
<tr>
<th>Limit value</th>
<th>t-test value</th>
<th>Probability of the sample significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.93</td>
<td>0.49%</td>
</tr>
<tr>
<td>2</td>
<td>6.81</td>
<td>1.04%</td>
</tr>
<tr>
<td>3</td>
<td>3.68</td>
<td>3.32%</td>
</tr>
<tr>
<td>4</td>
<td>0.56</td>
<td>31.59%</td>
</tr>
<tr>
<td>5</td>
<td>-2.56</td>
<td>93.76%</td>
</tr>
</tbody>
</table>

Afterwards, the means of the variables "gaining professional knowledge and skills" and "the level of practical knowledge" were compared, and the probabilities of significance which correspond to the t-test values are shown in table 5.

Table 5. Probabilities of the samples significance after Student's t-test of the parameter the level of satisfaction with the quality of the programs of study (second part).

<table>
<thead>
<tr>
<th>Limit value</th>
<th>t-test value</th>
<th>Probability of the sample significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.18</td>
<td>0.47%</td>
</tr>
<tr>
<td>2</td>
<td>6.1</td>
<td>1.29%</td>
</tr>
<tr>
<td>3</td>
<td>2.02</td>
<td>9.04%</td>
</tr>
<tr>
<td>4</td>
<td>-2.06</td>
<td>91.22%</td>
</tr>
<tr>
<td>5</td>
<td>-6.14</td>
<td>98.72%</td>
</tr>
</tbody>
</table>

Then, comparison was made between the means of the variable "schedule of subjects per years at the program of study /major" and related means of two variables from the Academy of Diplomacy and Security.
The probabilities of significance which correspond to the t-test values are shown in table 6.

Table 6. Probabilities of the samples significance after the Student’s t-test of the parameter the level of satisfaction with the quality of the programs of study (third part)

<table>
<thead>
<tr>
<th>Limit value</th>
<th>t-test value</th>
<th>Probability of the sample significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.65</td>
<td>0.65%</td>
</tr>
<tr>
<td>2</td>
<td>5.53</td>
<td>1.55%</td>
</tr>
<tr>
<td>3</td>
<td>2.40</td>
<td>6.92%</td>
</tr>
<tr>
<td>4</td>
<td>-0.71</td>
<td>72.43%</td>
</tr>
<tr>
<td>5</td>
<td>-3.84</td>
<td>96.91%</td>
</tr>
</tbody>
</table>

After analysis of the probabilities of significance in all three cases, it can be concluded that the level of satisfaction with the quality of the programs of study in all three institutions is as required and sufficient. (Probabilities which correspond to the limit values "4" and "5" confirm that the level requested for certain parameter is fully accomplished).

2. The level of satisfaction with the quality of work of the non-teaching staff:

As regards testing of the second parameter, the three observed institutions made the reports on self-evaluation in a different way. Accordingly, the following three tables are presented:

Table 7. Testing of variables related to operation of the student services in the Belgrade Polytechnics

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>N</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student services working time</td>
<td>402</td>
<td>1</td>
<td>5</td>
<td>2.50</td>
<td>1.203</td>
</tr>
<tr>
<td>Readiness of the student services employees to provide services within the set time limits</td>
<td>398</td>
<td>1</td>
<td>5</td>
<td>2.99</td>
<td>1.243</td>
</tr>
<tr>
<td>Willingness of the student services employees to assist students with their requirements</td>
<td>401</td>
<td>1</td>
<td>5</td>
<td>2.92</td>
<td>1.274</td>
</tr>
<tr>
<td>Attitude of the student services employees towards students</td>
<td>399</td>
<td>1</td>
<td>5</td>
<td>2.87</td>
<td>1.308</td>
</tr>
<tr>
<td>Valid N (listwise)</td>
<td>393</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It can be calculated that the mean of the responses to the question on the overall satisfaction with the operation of the student services is 2.82, while standard deviation (agreement in the respondents' responses) is 1.25.

Table 8. Testing of variables related to operation of the student services in the Technical College of Applied Sciences

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude of the staff</td>
<td>4.2</td>
</tr>
<tr>
<td>Period of responding</td>
<td>3.92</td>
</tr>
<tr>
<td>Data accuracy</td>
<td>4.08</td>
</tr>
<tr>
<td>Working time</td>
<td>3.92</td>
</tr>
<tr>
<td>Service price</td>
<td>3.75</td>
</tr>
<tr>
<td>Information process</td>
<td>3.92</td>
</tr>
<tr>
<td>Mean of the student services</td>
<td>3.96</td>
</tr>
</tbody>
</table>

Table 9. Testing of the second parameter in the Academy of Diplomacy and Security

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation of student organizations</td>
<td>3.59</td>
</tr>
<tr>
<td>Operation of student services</td>
<td>4.44</td>
</tr>
</tbody>
</table>

It is necessary to compare the means measured in all three institutions in order to defend significance of analysis of the second (out of five) parameter. For this purpose, analysis of the means using Student's t-test was applied.

Means (per limit values 1, 2, 3, 4 and 5) were tested first in order to find the limit value to which the three tested means correspond most. The value of the Student's t-test was obtained as a report from SPSS. It was necessary to subsequently transform this value by calculations into the value of probability of the sample significance - p. The probabilities of significance which correspond to the values of the t-test are shown in table 10.

Table 10. Probabilities of the samples significance after Student’s t-tests of the parameter the level of satisfaction with the work of the non-teaching staff

<table>
<thead>
<tr>
<th>Limit value</th>
<th>t-test value</th>
<th>Probability of the sample significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.70</td>
<td>1.4%</td>
</tr>
<tr>
<td>2</td>
<td>3.62</td>
<td>3.4%</td>
</tr>
<tr>
<td>3</td>
<td>1.54</td>
<td>13.1%</td>
</tr>
<tr>
<td>4</td>
<td>-0.54</td>
<td>67.8%</td>
</tr>
<tr>
<td>5</td>
<td>-2.62</td>
<td>93.99%</td>
</tr>
</tbody>
</table>

It can be noticed after table analysis that the probability of significance of the three means (from three observed institutions) rises with the rise of the test limit.
value. Values "4" and "5" are the limit values that are desirable for the null hypothesis to be satisfied, with respect to the second parameter testing.

As the probability of significance for all three samples amounts to 67.8%, for the limit value "4", and 93.99% for the test limit value "5", it can be concluded that the level of satisfaction with the quality of work of the non-teaching staff is on the required level (Technical College of Applied Sciences and Academy of Diplomacy and Security) and on the sufficient level (Belgrade Polytechnics).

3. The level of satisfaction with technical equipment of the working area and library:

In regard to testing of the third parameter, the three observed institutions prepared the reports on self-evaluation in different ways. Accordingly, the following three tables are presented:

Table 11. Testing of the quality level of the working area and library in the Belgrade Polytechnics

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>N</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical equipment of the teaching premises</td>
<td>402</td>
<td>1</td>
<td>5</td>
<td>3.23</td>
<td>1.18</td>
</tr>
<tr>
<td>Conditions of work in relation to the existing equipment (number of computers per a student)</td>
<td>399</td>
<td>1</td>
<td>5</td>
<td>3.23</td>
<td>1.23</td>
</tr>
<tr>
<td>Conducting of teaching activities on several locations</td>
<td>397</td>
<td>1</td>
<td>5</td>
<td>2.94</td>
<td>1.33</td>
</tr>
<tr>
<td>Microclimatic conditions (lighting, heating, air-conditioning)</td>
<td>401</td>
<td>1</td>
<td>5</td>
<td>3.83</td>
<td>1.07</td>
</tr>
<tr>
<td>Valid N (listwise)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>393</td>
</tr>
</tbody>
</table>

The result of the above table is the following table 12 which provides an overall assessment of the quality level of the working area and library in the Belgrade Polytechnics.

Table 12. Mean of the variable "the quality level of the working area and library" in the Belgrade Polytechnics

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>N</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working area quality</td>
<td>403</td>
<td>1.00</td>
<td>5.00</td>
<td>3.3071</td>
<td>.9391</td>
</tr>
<tr>
<td>Valid N (listwise)</td>
<td>403</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regarding the level of technical equipment of the working area and library, the following table 13 presents the report on the related variables.

Table 13. The level of technical equipment of the working area and library in the Belgrade Polytechnics

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>N</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage of subjects with literature</td>
<td>402</td>
<td>1</td>
<td>5</td>
<td>3.85</td>
<td>.96</td>
</tr>
<tr>
<td>Up-to-date content of the library holdings</td>
<td>400</td>
<td>1</td>
<td>5</td>
<td>3.82</td>
<td>.92</td>
</tr>
<tr>
<td>Availability of presentations, bases of magazines and other publications in a digital form</td>
<td>399</td>
<td>1</td>
<td>5</td>
<td>3.97</td>
<td>.95</td>
</tr>
<tr>
<td>Reading room equipping with computers</td>
<td>400</td>
<td>1</td>
<td>5</td>
<td>3.87</td>
<td>1.01</td>
</tr>
<tr>
<td>Working time of the library</td>
<td>400</td>
<td>1</td>
<td>5</td>
<td>4.20</td>
<td>.93</td>
</tr>
<tr>
<td>Working conditions in the reading room</td>
<td>397</td>
<td>1</td>
<td>5</td>
<td>3.80</td>
<td>1.06</td>
</tr>
<tr>
<td>Attitude of the library staff towards the students</td>
<td>392</td>
<td>1</td>
<td>5</td>
<td>4.45</td>
<td>.79</td>
</tr>
<tr>
<td>Valid N (listwise)</td>
<td>386</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The result of the above table 13 is the following table 14 which provides an overall assessment of the level of technical equipment of the library in the Belgrade Polytechnics.
As for the Technical College of Applied Sciences, the quality level of the working area was assessed through the following variables, as presented in table 15.

Table 16. The level of technical equipment of the working area and library in the Technical College of Applied Sciences

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude of the staff</td>
<td>4.0</td>
</tr>
<tr>
<td>Period of response to the requirement for service</td>
<td>4.25</td>
</tr>
<tr>
<td>Method of informing of the procurement of a library item</td>
<td>3.67</td>
</tr>
<tr>
<td>Working time</td>
<td>4.2</td>
</tr>
<tr>
<td>Working conditions</td>
<td>3.83</td>
</tr>
<tr>
<td>Process computerisation</td>
<td>4.13</td>
</tr>
<tr>
<td>Mean of assessment of all variables</td>
<td>4.01</td>
</tr>
</tbody>
</table>
Table 17. Mean of the level of technical equipment and operation of the library in the Academy of Diplomacy and Security

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation of the library</td>
<td>4.1</td>
</tr>
<tr>
<td>Technical equipment of the area</td>
<td>3.95</td>
</tr>
</tbody>
</table>

It is necessary to compare means measured in all three institutions in order to defend validity of testing of the third (out of five) parameter.

Analysis of the means of the assessed level of technical equipment of the working area and library on one hand, and the quality level of working area, on the other hand, was implemented for this purpose. Student's t-test was used in both processes for testing the probabilities of the samples significance, which are required for acceptance of the null hypothesis. In the first process, the quality level of the working area and library in the Belgrade Polytechnics was analysed using Student's t-test with 2 degrees of freedom.

The limit values ranged from "1" to "5", and the values of the t-test were transformed by calculation into the probability of the sample significance. Probabilities of significance of the tested means which correspond to the t-test values are shown in table 18.

Table 18. Probabilities of the samples significance after Student's t-test (of the variable "the quality level of the working area and library")

<table>
<thead>
<tr>
<th>Limit value</th>
<th>t-test value</th>
<th>Probability of the sample significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.53</td>
<td>0.5%</td>
</tr>
<tr>
<td>2</td>
<td>6.20</td>
<td>1.2%</td>
</tr>
<tr>
<td>3</td>
<td>2.87</td>
<td>5.14%</td>
</tr>
<tr>
<td>4</td>
<td>-0.45</td>
<td>65.16%</td>
</tr>
<tr>
<td>5</td>
<td>-3.78</td>
<td>96.82%</td>
</tr>
</tbody>
</table>

In the second process, the level of satisfaction with the technical equipment of the working area and library was tested using Student's t-test with limit values ranging from "1" to "5", with 2 degrees of freedom. Probabilities of significance of the tested means, which correspond to the t-test values, are shown in table 19.

Table 19. Probabilities of the samples significance after Student's t-test of the variable the level of satisfaction with the technical equipment of the working area and library

<table>
<thead>
<tr>
<th>Limit value</th>
<th>t-test value</th>
<th>Probability of the sample significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>169.13</td>
<td>0.001%</td>
</tr>
<tr>
<td>2</td>
<td>112.44</td>
<td>0.003%</td>
</tr>
<tr>
<td>3</td>
<td>55.75</td>
<td>0.01%</td>
</tr>
<tr>
<td>4</td>
<td>-0.94</td>
<td>77.6%</td>
</tr>
<tr>
<td>5</td>
<td>-57.64</td>
<td>99.98%</td>
</tr>
</tbody>
</table>

After analysis of both processes of testing of probabilities of the samples significance, it can be stated, with the probability of 65.16% (for the quality level of the working area) and 77.6% (for the level of satisfaction with the technical equipment of the working area and library) that the three assessed institutions satisfy sufficient quality level (point "4" on the scale), and that they also satisfy, with the probability of 99.82% (for the quality level of the working area) and 99.98% (for the level of satisfaction with the technical equipment of the working area and library), the required level of quality related to these two variables (point "5" on the scale, perfect level of satisfaction).

4. The level of satisfaction with the quality of work of the teaching staff:

As far as testing of the fourth parameter is concerned, the three observed institutions prepared the reports on self-evaluation in different ways. Accordingly, the following tables are presented:
Table 20. Testing of means of the variables related to the quality of work of the teaching staff in the Belgrade Polytechnics

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct teacher/student relationship (respect)</td>
<td>402</td>
<td>1</td>
<td>5</td>
<td>4.21</td>
<td>.90</td>
</tr>
<tr>
<td>Consistence of teachers in conveying content of the subjects</td>
<td>402</td>
<td>1</td>
<td>5</td>
<td>4.06</td>
<td>.83</td>
</tr>
<tr>
<td>Capability of the teachers to convey content of the subjects</td>
<td>403</td>
<td>1</td>
<td>5</td>
<td>3.96</td>
<td>.88</td>
</tr>
<tr>
<td>Valid N (listwise)</td>
<td>399</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The result of the previous table is table 21 which shows mean of all variables related to the fourth parameter.

Table 21. Mean of the tested variables related to the quality of work of the teaching staff in the Belgrade Polytechnics

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teaching staff</td>
<td>404</td>
<td>1.00</td>
<td>5.00</td>
<td>4.0743</td>
<td>.7552</td>
</tr>
<tr>
<td>Valid N (listwise)</td>
<td>404</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Then, the means of the variables related to the level of satisfaction with the work of the teaching staff in the Technical College of Applied Sciences are shown in table 22.

Table 22. Testing of the means of variables related to the level of satisfaction with the work of the teaching staff in the Technical College of Applied Sciences

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efforts aimed at improvement of the program of study</td>
<td>3.28</td>
</tr>
<tr>
<td>Initiating development of cooperation with business organizations</td>
<td>3.47</td>
</tr>
<tr>
<td>Readiness for changes</td>
<td>3.82</td>
</tr>
<tr>
<td>Timely decision making</td>
<td>3.5</td>
</tr>
<tr>
<td>Investment into equipment in the aim of improvement of the practical part of teaching</td>
<td>3.91</td>
</tr>
<tr>
<td>Communication/interpersonal relations</td>
<td>3.94</td>
</tr>
<tr>
<td>Cooperation with teachers</td>
<td>3.72</td>
</tr>
<tr>
<td>Total mean of variables</td>
<td>3.66</td>
</tr>
</tbody>
</table>

Finally, the variables which are related to the assessment of the fourth parameter in the Academy of Diplomacy and Security (report on self-evaluation in this institution has not presented these variables in more detail) are also shown in table 23.

Table 23. Testing of the means of variables related to assessment of the level of satisfaction with work of the teaching staff in the Academy of Diplomacy and Security

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality of teaching</td>
<td>4.47</td>
</tr>
<tr>
<td>Modernization of teaching</td>
<td>4.24</td>
</tr>
<tr>
<td>Mean</td>
<td>4.35</td>
</tr>
</tbody>
</table>
It is necessary to compare the means measured in all three institutions in order to defend validity of the fourth (out of five) parameter. For this purpose, analysis of the means, using Student's t-test with 2 degrees of freedom, was implemented. Probabilities of significance of the tested means which correspond to the t-test values are shown in table 24.

Table 24. Probabilities of the samples significance after Student's t-test of the level of satisfaction with the parameter the quality of work of the teaching staff

<table>
<thead>
<tr>
<th>Limit value</th>
<th>t-test value</th>
<th>Probability of the sample significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.10</td>
<td>0.2%</td>
</tr>
<tr>
<td>2</td>
<td>10.11</td>
<td>0.4%</td>
</tr>
<tr>
<td>3</td>
<td>5.12</td>
<td>1.8%</td>
</tr>
<tr>
<td>4</td>
<td>0.133</td>
<td>45.31%</td>
</tr>
<tr>
<td>5</td>
<td>-4.85</td>
<td>98%</td>
</tr>
</tbody>
</table>

Analysis of the probability of the sample significance leads to the satisfactory conclusions: probability of 45.31% corresponds to the limit value "4", while the probability of 98% corresponds to the limit value "5". It can be considered that the fourth parameter has been satisfied to the required and sufficient level.

5. The level of satisfaction with the teaching process:
In regard to the fifth parameter, the three observed institutions prepared the reports on self-evaluation in a different way. Accordingly, the following tables are presented:

Table 25. Testing of variables related to the level of satisfaction with the teaching process in the Belgrade Polytechnics

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>N</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teaching plan and schedule - consistency</td>
<td>402</td>
<td>1</td>
<td>5</td>
<td>4.02</td>
<td>.95</td>
</tr>
<tr>
<td>Conformity of the teaching plan and schedule with the expectations</td>
<td>404</td>
<td>1</td>
<td>5</td>
<td>3.47</td>
<td>1.00</td>
</tr>
<tr>
<td>Timely presentation of the plan of work and pre-examination obligations for each subject</td>
<td>404</td>
<td>1</td>
<td>5</td>
<td>4.12</td>
<td>.97</td>
</tr>
<tr>
<td>Teaching process is interactive</td>
<td>403</td>
<td>1</td>
<td>5</td>
<td>3.84</td>
<td>.96</td>
</tr>
<tr>
<td>Encouraging creativity</td>
<td>402</td>
<td>1</td>
<td>5</td>
<td>3.59</td>
<td>1.06</td>
</tr>
<tr>
<td>Examples from practice are good and illustrative</td>
<td>404</td>
<td>1</td>
<td>5</td>
<td>3.74</td>
<td>.99</td>
</tr>
<tr>
<td>Capacity for teamwork</td>
<td>403</td>
<td>1</td>
<td>5</td>
<td>3.71</td>
<td>1.05</td>
</tr>
<tr>
<td>Capacity for individual work</td>
<td>402</td>
<td>1</td>
<td>5</td>
<td>3.86</td>
<td>.95</td>
</tr>
<tr>
<td>Valid N (listwise)</td>
<td>398</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The result of the above table is the following table 26 which shows the mean and the standard deviation for the entire parameter in the Belgrade Polytechnics.

Table 26. Testing of the mean and the mean deviation of the variables related to the satisfaction with the quality of teaching process in the Belgrade Polytechnics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>The level of satisfaction with the quality of the teaching process</td>
<td>3.79</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Then, the assessments of the parameter per programs of study were observed in the Technical College of Applied Sciences.

Table 27. Testing of the quality level of the teaching process per programs of study in the Technical College of Applied Sciences

<table>
<thead>
<tr>
<th>Program of study</th>
<th>Mean of the assessment of the teaching process quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer Science</td>
<td>3.81</td>
</tr>
<tr>
<td>Electronic Business</td>
<td>4.43</td>
</tr>
<tr>
<td>Electrical Engineering</td>
<td>4.12</td>
</tr>
<tr>
<td>Metallurgy</td>
<td>4.29</td>
</tr>
<tr>
<td>Mechanical Engineering-Thermal Energy and Maintenance</td>
<td>4.28</td>
</tr>
<tr>
<td>Mechanical Engineering-Production Engineering</td>
<td>4.3</td>
</tr>
<tr>
<td>Environment Protection</td>
<td>4.37</td>
</tr>
<tr>
<td>Fire Protection</td>
<td>4.33</td>
</tr>
<tr>
<td>Civil Protection</td>
<td>4.33</td>
</tr>
<tr>
<td>Occupational Health and Safety</td>
<td>4.36</td>
</tr>
<tr>
<td>Graphic Design</td>
<td>4.35</td>
</tr>
<tr>
<td>Graphic Engineering</td>
<td>4.19</td>
</tr>
<tr>
<td>Applied Photography</td>
<td>4.35</td>
</tr>
<tr>
<td>Web Design</td>
<td>4.34</td>
</tr>
<tr>
<td>Mean of the quality assessment</td>
<td>4.27</td>
</tr>
</tbody>
</table>

Table 28. Testing of variables related to the level of satisfaction with the quality of teaching process in the Academy of Diplomacy and Security

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timetable</td>
<td>3.89</td>
</tr>
<tr>
<td>Premises</td>
<td>4.17</td>
</tr>
<tr>
<td>Number of examination terms</td>
<td>3.31</td>
</tr>
<tr>
<td>Cleanliness and hygiene of the premises</td>
<td>3.05</td>
</tr>
<tr>
<td>Cooperation with students</td>
<td>4.49</td>
</tr>
<tr>
<td>Mean of the assessment of all variables</td>
<td>3.78</td>
</tr>
</tbody>
</table>

It is necessary to compare the means measured in all three institutions in order to defend the validity of the fifth parameter testing. Analysis of the means, using Student's t-test with 2 degrees of freedom, was implemented for this purpose. Probabilities of significance of the tested means, which correspond to the t-test values, are shown in table 29.

Table 29. Probabilities of the sample's significance after Student's t-test of the parameter the level of satisfaction with the quality of teaching process

<table>
<thead>
<tr>
<th>Limit value</th>
<th>t-test value</th>
<th>Probability of the sample's significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.22</td>
<td>0.1%</td>
</tr>
<tr>
<td>2</td>
<td>12.03</td>
<td>0.3%</td>
</tr>
<tr>
<td>3</td>
<td>5.85</td>
<td>1.4%</td>
</tr>
<tr>
<td>4</td>
<td>-0.33</td>
<td>61.36%</td>
</tr>
<tr>
<td>5</td>
<td>-6.51</td>
<td>98.86%</td>
</tr>
</tbody>
</table>

Analysis of probabilities of the samples significance leads to the satisfactory conclusions; the probability of 61.36% corresponds to the limit value "4", while the probability of 98.86% corresponds to the limit value "5". It can be considered that the fourth parameter has been satisfied to the required and sufficient level. The above mentioned five quality parameters, by means of which the null hypothesis has been confirmed, were
tested on a sample of three higher education institutions which have implemented and conducted the quality management system.

It is necessary to carry out further research and compare these results with some future results in order to get an idea about the trend of evolution of the quality level in the tested institutions.

4. CONCLUSION

We are witnesses of the time when the service and product user is in the focus of interest of all organizations, including education institutions, which are or intend to be recognizable in the society.

To achieve its aims, the higher education institution should offer its users constantly improving values. Understanding, meeting and exceeding needs and expectations of the higher education service user is of vital importance for achieving competitive advantage, positioning in the academic area, sustainable development and thus, sustainable success.

The research results indicate that the satisfaction of students, as most numerous and direct users of the higher education service, is in direct correlation with the quality assurance in a higher education institution. Sustainable success of a higher education institution is achieved by reaching certain levels of student satisfaction with:

- the quality of the programs of study;
- the quality of work of the non-teaching staff (administrative office and student services);
- the level of satisfaction with technical equipment of the working area and library;
- the quality of work of the teaching staff;
- the quality of teaching process.

With the establishment of a quality management system, a higher education institution raises the level of its organization and improves the performance of institution, which implies satisfaction of all higher education service users. It is, therefore, recommended that legislation should enable establishment of a flexible concept capable of responding to global changes and requirements of the contemporary world and keep in balance the entire sequence of insufficiently clear, and sometimes contradictory, demands that are put on the university.

REFERENCES

Mechanical - Physical Treatment of Used Motor Oil Within a Sustainable Waste Management System

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Review paper
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Waste oils are all mineral or synthetic oils that cannot be used for the purpose for which they were originally produced. These are: hydraulic oils, motor oils, ship oils, liquids for the transfer of heat or insulation, oily remains from reservoirs, oil-water emulsions and various oil-water mixtures. In its chemical makeup used motor oil contains hydrocarbons, organic minerals, heavy metals (cobalt, magnesium, iron, zinc), sulfur, chlorine, nitrogen, phosphorus, compounds from additives and other products that are dangerous as they have cancerous effects on health.

As it is considered the biggest contaminant of the environment and classified as hazardous waste; special attention must be given in the handling of used motor oil to ensure its appropriate disposal.

Setting up of a viable system for Mechanical-Physical Treatment of used motor oil makes it possible to re-use it as a secondary raw material i.e. the problem of collection, transportation, treatment and storing of the used motor oil is being solved.

The subject of this research is the advantage of the mechanical-physical treatment of used motor oil. Re-refined motor oil can be used for multiple purposes such as a base for the other synthetic oils, for heating etc.

Improper disposal of used motor oil causes multiple damage; firstly, losing the valuable secondary base which, with the addition of certain additives, can be used as the basis for the other synthetic oils; secondly, causing damage to the environment by the pollution with inability to repair the damage to all environmental components.

Key words: motor oils, mechanical-physical treatment

1. INTRODUCTION

When we say that waste is a relative concept or idea, we are referring to something that represents a burden to someone or is considered unusable by one; but for somebody else it could be a useful commodity or material. Our attitude towards the waste itself is important in determining if something is waste or not. Actually, waste means anything that remains after the production of a certain product that has lost its original characteristics and therefore cannot be used as an original product but with additional treatment, stabilization or upgrade can be used for other purposes in order to get some other secondary product[1].

“Waste oils are all mineral, synthetic oils that cannot be used for the purpose for which they were or-
According to The Environmental Protection Agency (EPA) the one drop of used motor oil can contaminate 1cm³ of the water. From this, we can conclude that disposal or effluence of waste motor oil into the environment can lead to the greater scale pollution. At the surface of the water, motor oil blocks sunrays and oxygen which can result in the death of the fish and the water vegetation. On the soil, it changes micro floras, affecting fertility, endangering the growth and causes metabolic plant disruption.

Incineration in the stoves with inadequate burning plate/firebox, results in the emission of the poisonous gases (NOx, COx, Sx) into the atmosphere affecting the air quality.

Studies done by the WHO (called The WHO Report) on the effect on human health which determined that: on the skin it causes appearance of benign and malign illnesses, occurrence of papilloma and tumors. Inhaling gases after the combustion of the motor oils shall result in permanent and acute lung condition, lung cancer and prostate cancer.

But, as everything else, it has its positive side, too. The used motor oil, if treated in an appropriate manner, represents valuable resource. It can be used as a base for new synthetic base oils or as fuel for heating. Refined secondary oils have weaker oil characteristics than the original oil. That is why they are used as the base for synthetic oils, asphalt bitumen, for heating. Therefore, used motor oil can be used again, but before that it has to be prepared i.e. water, oil and sludge (solid particles) must be removed. In the other words, it has to be cleared, re-refined and only then, can be used. It represents valuable secondary raw-material. In this way, the natural resources are preserved and saved, and the used motor oil represents secondary resource able to finance itself. The level of the economic development conditions the level of production of the waste in general but also the production of the used motor oils[4].

By using the treated waste motor oil has its economic effect; using the waste motor oil does not demand for purchase of the new motor oil (40% of the new secondary oil can be generated from a tone of the used motor oil - information acquired by the research done in "Tehnosint" Laktasi company.)

In this way, the hierarchy level of the waste management is being followed i.e. by avoiding the generation of the huge amounts of waste oils; reduction in the quantity of the waste motor oil; by recycling, it is being reused; and all is done by the appropriate mechanical-physical treatment of the waste motor oil which means removal of the water, pure oil and sludge. Sludge is being dehydrated, stabilized and disposed of as the solid waste.

There are two types of motor oil treatments: combustion, by burning the waste oil in the stoves construed for combustion, such stoves have filters for impurities; and re-regeneration, which can be either re-refining or re-conditioning.

Assessed annual quantities of generated waste oil in B&H is between 21 500 and 23 000 t/a. In respect of the facilities for treatment of the used motor oil, in the Republic of Srpska, there is one installation for mechanical-physical treatment of the motor oil; and, in Oil Refinery Modrica with capacity to re-refine used motor oil is 10 000 t/a but only 10-15% is being used.

Setting up the viable system of the mechanical-physical treatment of the used motor oil enables to use waste motor oil as secondary raw-material i.e. the problem of collection, transport, treatment, disposal of the used motor oil is being solved.

2. EUROPEAN UNION POLICY ON WASTE MANAGEMENT

EU Policy states development of the measures such as promotion of the clean production, treating the product to remove dangerous waste characteristics; setting up the technical standards which would limit concentration of the certain dangerous materials in products; by promoting re-use of the waste and recycling of the waste; applying economic instruments; analysis of the life cycle of the product; development of the eco-marking system.

The Geological Survey of Ireland, with Jonathan Durham as lecturer, on 12th of May 2011 held the seminar called “The European Union’s Waste Management Policy”. According to J. Durham, the European Union Policy in the waste management is composed of three elements:


![Figure 1 - Symbiotic interaction of the three EU Policy elements [5]](image-url)
Under The Strategy, The VI Action Waste Management Plan had been developed. It is the program of activities which has the following priorities: climate change, nature and biodiversity, health and quality of life, natural resources and waste. This program develops the vision to integrate policy on resources, waste and products. It calls on seven theme strategies including the strategy of viable use of natural resources and waste recycling. It has been extended to prevention and recycling.

The Strategy in effect entails viable use of the waste called “Prevention and Recycling Theme Strategy”[6]. This Strategy aims to ensure higher level of the environment protection through modernization of the existing legal framework. A long term aim is Europe as recycling society i.e. society trying to avoid production of waste and society using waste as resource. By setting the higher environmental standards internal market will enable activities on recycling and re-use.

Effects of the Strategy:
1. Less waste at the disposal sites
2. More waste materials used for compost
3. More energy from the waste
4. Higher and better recycling
5. Better waste prevention
6. Cleaner environment

3. SETTING UP THE WASTE ECONOMY

Waste management economy in Bosnia and Herzegovina is defined as:

“Waste management economy represents the sum of all political, science, mechanical and other measures to achieve waste reduction, use of the waste and safe waste disposal in order to maintain the existing quantity of production and consummation” [7].

3.1. The importance of establishing the waste economy for the environment

Not only has progress in the economy and technology in the past few decades significantly endangered the health of people, but also has degraded environment in its basic elements: air, water, soil, flora and fauna. In order to protect eco-system many countries have adopted certain legal framework to ensure proper eco-actions in the countries that are not eco-friendly[8]. Today, waste disposal in the EU countries has been done in the modern dump yards with high degree of security for the environment; but without unlimited power of absorption. Therefore, the amount of waste should be reduced in order to re-use its certain components.

The main task of waste management economy is to use waste generated in the production process, consumption and other actions in order to employ it in the circular flow. Total recycling of the waste is impossible to achieve because the recycling itself generates certain amount of waste. Recycling can be viewed from many different aspects and the load it does to the environment is the most important.

Generally accepted solution of the overall waste management economy system in Europe is known as “4R” which means:
1. REDUCTION - reducing or avoiding production of the waste
2. REUSE - Use of waste without treatment
3. RECYCLING - recycling of the waste i.e. waste treatment in order to use it’s materials or as energy
4. RECOVERY - renewal, reuse for the same purpose after treatment (reusable packaging)

Regenerating as the waste management procedure based on thermal, chemical or physical treatment or biological re-production of materials from which the product was made in order to make new production material i.e. energy that can be directly used. Reusing of the waste saves primary resources (iron ore, copper, aluminum, led) and primary energy (fossil fuels). The disposal of the waste is final procedure in the waste management system and should be used for all other waste that cannot be used again, recycled or regenerated. Although, the full applications of these rules have not yet been achieved, they have become the part of the legal framework in many countries.

The ultimate aim in the waste economy is: “Not using dump disposals anymore i.e. developing non-dump disposals in the waste management system, creating dumpless society”[7].

4. CHANICAL–PHYSICAL TREATMENT OF USED MOTOR OIL

4.1 Concept of mechanical-physical treatment of used motor oil

Mechanical-physical treatment is a complex process including separation and removal of the impurities found in the used motor oil. It is a process of cleaning and removing solid particles and water from the used motor oil. This treatment prepares used motor oil for re-use. Mechanical-physical treatment is based on
circulation of oil through the installation and removal of the work medium being done through the rotating container of the separator. The separation of the additives, acids, soluble products from very contaminated oil, and the poor qualities oil; there is a separation of sulphur, non-saturated asphalt compounds, coloured compounds.

Schematic draft of the installation describes process of mechanical-physical treatment of the motor oil (picture 2 and 3.):

1. A specialized vehicle is used for transport waste motor oil from the collection point to the installation. From the specialized vehicle, the used motor oil is being poured into the tank for used motor oil. From tank containing the used motor oil is pumped for the further treatment, into separator.

2. A separator is turned on to achieve 6300 - 6400 rotations in a minute. Then, the separator is automatically performing washing and closing for 2-4 minutes. The heaters are turned on at the tank under the separator.

3. Work medium is automatically pumped from the tank for used motor oil through the heater at the separator’s base in order to reach work temperature of 85⁰C. Work-medium is being pumped and keeps on circulating through electrical-heater. The separation of motor oil and water is being done in the separator.

4. During the separation, work medium is being divided into treated oil and which is being pumped via centripetal pump into the tank number 2- clean oil.

5. The water from the separator goes into the existing reservoir under separator, equipped with minimum - maximum regulator and safety tank with chambers- than, is automatically being pumped and transported into tank number 3 (water and oil).

6. Air compressor, installed on the side, automatically regulates air to open all electro-magnetic valves programmed in the main computer panel.

7. Washing water is in the tank on top and being heated at the temperature of 60⁰-75⁰C via electrical heater of the boiler and directly sent into the valve for the pressure regulation installed at the separator base for automatic shutting/ opening. It is automatic process depending of the temperature on the heater, after which the separator is clean.

Temperature is being checked after the display process:

a. Set temperature of 40⁰C is in the tank under the separator

b. In front of and behind electrical heater temperature should always be 85⁰C at 77 minutes.

IR QUALITY ANALYSIS AFTER INCINERATION OF THE USED MOTOR OIL

Within the scientific-research work the analysis of the air had been conducted on the location of the installation in order to introduce regular use of mechanical - physical treatment in the centrifugal separator and to protect the air from the pollution. For the air quality monitoring, GASMET DX 4030 portable
The examination results are represented in the tables 1 and 2.

**Table 1. Outside measuring results at location**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>23.6°C</td>
</tr>
<tr>
<td>Relative air humidity</td>
<td>68.3%</td>
</tr>
<tr>
<td>Air flow speed</td>
<td>0.8 m/s</td>
</tr>
<tr>
<td>Air pressure</td>
<td>988.0 mbar</td>
</tr>
</tbody>
</table>

**Table 2. The results of the concentration of the pollutants**

<table>
<thead>
<tr>
<th>Measured pollutants</th>
<th>Sampling period</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>S 2</td>
<td>µg/ m³</td>
<td>1 hour</td>
</tr>
<tr>
<td>N 2</td>
<td>µg/ m³</td>
<td>1 hour</td>
</tr>
<tr>
<td>C</td>
<td>µg/m³</td>
<td>1 hour</td>
</tr>
<tr>
<td>3</td>
<td>µg/m³</td>
<td>1 hour</td>
</tr>
<tr>
<td>LČ 10</td>
<td>µg/m³</td>
<td>1 hour</td>
</tr>
</tbody>
</table>

The presented results in the table 2 shows that concentration of sulphur dioxide, soot, nitrogen dioxide and flying particles in total is below average values. Daily concentration of sulphur dioxide, nitrogen dioxide and flying particles do not exceed average value of the target values in the air. Concentration of sulphur dioxide, nitrogen dioxide in the sampling period of 1 hr is below annual average value and below target values and for the flying particles in the period of 24 hrs. Carbon monoxide and ozone showed high values for the period of eight hours have not exceeded prescribed values.

Comparing the results of measuring of one-hour emission concentration with those prescribed in the Decision on The Air Pollution Protection in Banjalu-Ka Area it is visible that:

1. **Average concentration of sulphur dioxide based on the values of emission concentration at the location, determined that the air quality belongs to the first class air quality with minor pollution.**

2. **Average concentration of the flying particles at the location has placed the air quality in the first class quality (zone with the minor, insignificant pollution).**

3. **Concentration of the carbon monoxide, based on the emission concentration at the location has placed the air quality into the first air quality class.**

4. **Based on the one hour concentration of the nitrogen oxide, the air quality is placed into the first class i.e. the minor polluting zone, clean air.**

6. **COSTS TO ESTABLISH Viable Waste Oil Management System**

Costs to setting the used motor oil management system should cover the cost to determine authorized receiving spots for authorised legal and physical entities, to conduct the collection, authorised legal and physical entities for the processing of the used motor oil and financial investment into the infrastructure treatment of the used motor oil.

Financial planning includes calculation of the cost, capital investment and refund of the cost. By detailed financial analysis the cost should cover expenditures during implementation of the project, find and confirm
the existence of the financial resources to cover further costs, determine the price level for the refund of the investment and prove the financial viability of the project.

In the assessment of the investment and operation costs as well as potential financial sources, the following should be determined:

- Material capacities necessary to achieve the aims of re-use of the refined motor oil without any danger for the environment;
- Identification of the system, facility and equipment in order to manage these capacities;
- Defining the capital investment and operation costs;
- Assessment of the scope to the expected costs;
- Identification of the domestic and foreign investment sources available for this purpose;
- Carry out the assessment to cover resources deficit;
- Identify economic instruments of imbalance between investments costs and sources of financing, as well as conduct the assessment of the instrumental resources necessary as the priority measures.

Analysis should be based on identification of the system, facilities and equipment necessary and carried out in the surrounding countries.

Those obligated to pay the fee would be: manufacturers, i.e. importers of the new mineral and synthetic oil.

The compensation fee would be calculated according to the quantity of the products or imported mineral or synthetic oil or lubricants except or the edible oils and emulsions. The height and the manner of calculation and payment for the waste oil management would be determined in waste oil management in the certain amount as net and salary would be determined when products are firstly put on market.

Funds realised from the collection of waste motor oils shall become a part of the budget, and shall be used in accordance with The Waste Management Law prescribed as “intentional use of funds realised from the compensation for special waste flow-financing of the program, projects and other investment operative activities related to waste management”.

The Provision on the amount and conditions for allocation of incentive funds related to oil shall be brought pursuant to the Waste Management Law which determines incentive funds for reprocessing, recycling and the use of waist oil as a secondary raw material in a fixed amount per kilogram.

Incentive funds shall be allocated to the investors engaged on the waste oil management in order to:
- Implement the legal framework,
- Establish the organization of the waste oil management,
- Create capacities for waste oil management (private and public sector).

7. CONCLUSION

Waste motor oil is a valuable resource. It is classified as the hazardous waste because of its characteristics and dangerous effects on health and the environment. The waste oils and oily waste represent one of the biggest pollutants of the environment. Therefore, the used motor oils are required to be handled in a proper manner. Handling entails correct actions of collection, receiving treatment and disposing of the waste motor oil. Using the motor oil is being ensured through setting up the legal system, procedures in the collection system through the delivery points, the treatment system in the facilities for the treatment of the used motor oil and which have to meet the requirements in order to protect the environment.

Combustion i.e. co-combustion can use the used motor oil as the fuel. When used for heating, co-combustion must be done in the facilities constructed for such a purpose, with the burning plate/firebox constructed for those purposes and also, that level of the bad emissions of $\text{CO}_x$, $\text{NO}_x$, TFP must not exceed concentration prescribed by the Rulebook on Level of Concentration into the Air in order to avoid pollution of the atmosphere.

The development of the viable system for mechanical-physical treatment of the used motor oil in Republic of Srpska means:
- Prevention and reduction of non-consumption of the used motor oil.
- Re-use and recycling.
- Organizing the collection and transportation.
- Safety disposal of used motor oil.
- Costs to establish the viable management system of the used motor oil.

REFERENCES


**REZIME**

**MEHANIČKO-FIŽIČKA OBRADA ISTROŠENOG MOTORNOG ULJA U SISTEMU ODRŽIVOG UPRAVLJANJA OTPADOM**

Pod otpadnim uljima podrazumijevamo sva mineralna, sintetička ulja neupotrebljiva za svrhu za koju su prvobitno namijenjena, kao što su hidraulična ulja, motorna, turbinska, brodskija ulja ili tečnosti za prenos toplote ili izolaciju, uljni ostaci iz rezervoara, mješavina ulje-voda i emulzije. U hemijskom sastavu istrošeno motorno ulje sadrži hidrokarbonate, teške metale i organske minerale (kobalt, magnezij, željezo, cink) sumpor, azot, hlor, fosfor, jedinjenja iz aditiva, i ostalih produkata koji imaju kancerogena svojstva i opasni su po zdravlje. Smatraju se jednim od najvećih zagađivača životne sredine pa se prilikom postupanja sa otpadnim motornim uljima mora voditi računa o njihovom pravilnom odlaganju. Uspostavljanje održivog sistema mehaničko-fizičke obrade istrošenog motornog ulja omogućava da se istrošeno motorno ulje upotrijebi kao sekundarna sirovina odnosno rješava se problem sakupljanja, transporta, obrade, zbrinjavanja istrošenog motornog ulja. Predmet istraživanja su prednosti mehaničko-fizičke obrade istrošenog motornog ulja. Preradeno ulje se može koristiti za više namjena kao npr. baza za druga sintetička ulja, kao energent za dobijanje toplotne energije itd. Nevrijedno odlaganje istrošenog motornog ulja uzrokuje višestruke štete: kao prvo gubimo vrijedan sekundarni proizvod koji, uz dodavanje održenih aditiva, može da se koristi kao baza za druga sintetička ulja; kao drugo, uzrokovanjem havarije u komponentama životne sredine, koja se ogleda u njenom zagađenju te nemogućnosti sanacije uzrokovane štete.

**Ključne riječi:** motorna ulja, mehaničko-fizička obrada, održivo upravljanje

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PE “JUGIOISTOK”, NIŠ
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