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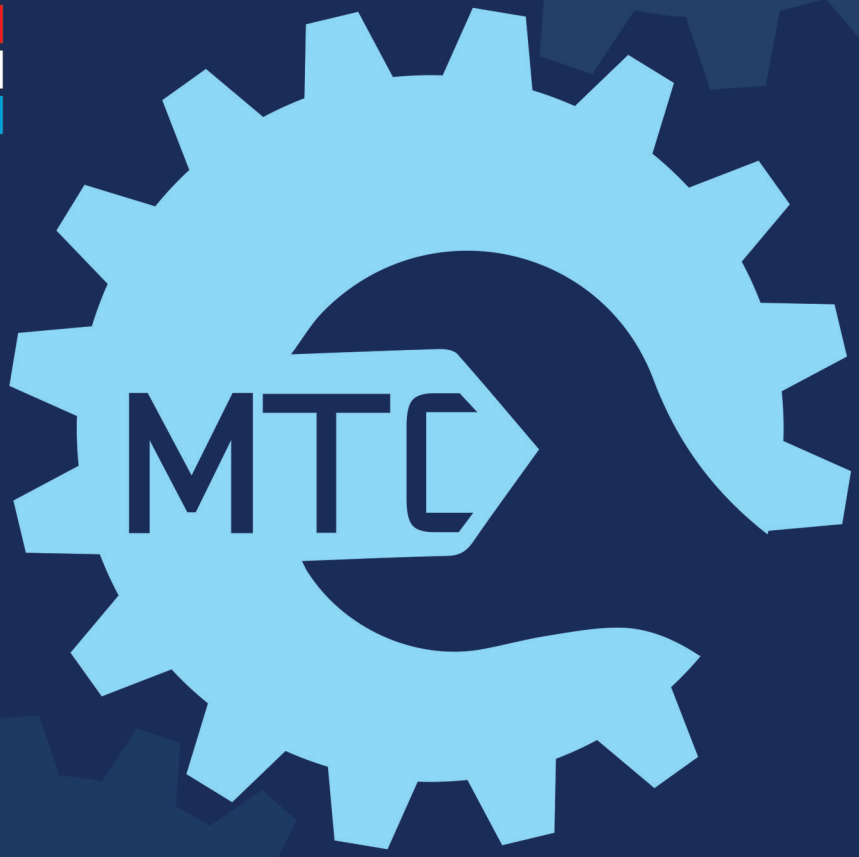

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An approach for solving transportation problem under Pythagorean fuzzy environment

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Abstract:

Introduction/purpose: In this paper, we introduce a new defuzzification function for trapezoidal Pythagorean fuzzy numbers (TrPFNs) and develop arithmetic operations associated with these numbers. Since the transportation problem is closely related to linear programming problems, we construct a transportation model in which all parameters are represented using TrPFNs. The purpose of this work is to address uncertainty and imprecision that often occur in real-life transportation planning.

Methods: A transportation model with trapezoidal Pythagorean fuzzy parameters is formulated. The proposed defuzzification function, along with the mathematical properties of TrPFNs, is used to transform the fuzzy transportation model into an equivalent deterministic model. The resulting deterministic problem is then solved using MATLAB.

Results: To demonstrate the effectiveness of the proposed approach, a case study involving the transportation of goods between factories and warehouses is presented. The example preserves the fuzzy nature of the parameters throughout the solution process. A sensitivity analysis is also conducted to examine the robustness of the model. Furthermore, the results obtained from the proposed method are compared with existing approaches to verify consistency.

Conclusion: The study shows that the proposed defuzzification function and the developed transportation model effectively handle uncertainty in transportation problems. The approach provides reliable and consis-

tent results, indicating its potential usefulness for solving real-world fuzzy transportation problems.
Key words: Pythagorean fuzzy numbers, Pythagorean fuzzy transportation problems, optimal solution, sensitivity analysis.

Introduction

The process of making decisions that are as optimal or efficient as possible is called optimization. It includes methods for maximizing or minimizing a function under particular circumstances. One kind of optimization problem that deals with one or more objectives is the transportation problem (TP). Since the expense of transporting raw materials and finished products plays a significant role, a decrease in this expense causes the commodity's final price to drop significantly. Thus, TPs are established in the decision-making domain to fulfill this need for price reduction. They offer a framework for addressing the problem of how to satisfy consumer demands while keeping costs down. A basic TP, first introduced by Hitchcock (Hitchcock, 1941), is a specialized form of linear programming that focuses on transporting a commodity from multiple sources to various destinations in the most efficient manner. However, since the input data may not always be deterministic, the problem does not always follow a standard approach. To address this uncertainty, different types of data representations are used, depending on the nature of the uncertainty.

In conventional decision-making situations, parameters are typically considered in crisp form. However, accurately determining the actual values of TP parameters such as transportation costs, availability, and demand can be challenging in practical applications. This uncertainty arises due to factors like incomplete data, inadequate statistical analysis, fluctuations in financial markets, road conditions, and other unpredictable influences.To address this, decision makers (DMs) are consulted to forecast parameter values. DMs frequently provide parameter values in linguistic terms, interval form, or another format. This is addressed by taking into account parameters in formats that can manage and depict ambiguity. To deal with such situations, Zadeh (Zadeh, 1965) introduced the fuzzy set theory (FST). For practical implications, fuzzy numbers and the operators that can be applied to the problems proposed, providing the mathematical basis for the use of FST. Fuzzy transportation problems (FTPs) are those in which the uncertainty of any or all parameters is represented in the form

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of fuzzy numbers. Several authors have explored FTPs and their solution methods. Kaur and Kumar (Kaur & Kumar, 2012) proposed a ranking function-based approach for generalized trapezoidal fuzzy transportation problems with crisp supply and demand values but fuzzy costs. Ebrahimnejad Ebrahimnejad (2015) introduced a bounded dual simplex method to solve transportation problems with both fuzzy supply and demand. Baykasoğlu and Subulan Baykasoğlu and Subulan (2019) presented a direct approach in which all parameters and decision variables are treated as fuzzy numbers, solved using fuzzy ranking and arithmetic operations. In a similar direction, Kane et al. Kané et al. (2021) proposed a two-step method that first transforms the fuzzy problem into interval problems and then converts them into crisp problems using midpoint values. Bisht and Dangwal Bisht and Dangwal (2022) addressed interval-valued transportation problems by transforming them into octagonal fuzzy problems, applying a ranking function to obtain a crisp model, and solving it using Vogel's approximation method and the modified distribution (MODI) method. More recently, Aroniadi and Beligiannis Aroniadi and Beligiannis (2024) applied particle swarm optimization with trigonometric acceleration coefficients to handle fuzzy transportation problems with uncertain costs, showing improved performance over conventional methods. Kokila and Deepa Kokila and Deepa (2024) considered a multi-objective FTP using triangular fuzzy numbers, converting it into a crisp model to simplify computations, while Akilbasha et al. Akilbasha et al. (2024) addressed stochastic transportation problems with additional budget constraints through fuzzy goal programming combined with octagonal fuzzy numbers to effectively manage uncertainty. Collectively, these studies illustrate various techniques for modeling real-world transportation systems under fuzzy conditions.

Moreover, in many situations the degree of reluctance must be considered alongside the degrees of acceptance and rejection. Traditional fuzzy numbers cannot capture both doubt and hesitation simultaneously, whereas intuitionistic fuzzy numbers are well suited for such cases. Atanassov (Atanassov, 1986) extended the concept of fuzzy sets by introducing intuitionistic fuzzy sets (IFS), which incorporate a hesitation margin arising from incomplete or uncertain information. In an IFS framework, both acceptance and non-acceptance degrees are represented, making it highly relevant for practical applications. Consequently, intuitionistic fuzzy modelling has been widely adopted in various decision-making problems. In

contexts such as transportation systems, inventory planning, logistics, supply chain management, and optimal control, hesitation often emerges in the available data. Representing such parameters through intuitionistic fuzzy numbers (IFNs) is therefore appropriate, giving rise to intuitionistic fuzzy transportation problem (IFTP). Solving IFTPs leads to the movement of raw materials and finished goods at minimal cost, even under uncertainty. Recent research on TPs under intuitionistic fuzzy environments has advanced both modeling approaches and solution techniques. Early contributions include Gani and Abbas Gani & Abbas (2014), who incorporated intuitionistic fuzzy production and consumption values with variable transportation costs, and Antony et al. Antony et al. (2014), who handled uncertainty in supply, demand, and costs using trapezoidal IFNs. Singh and Yadav Singh & Yadav (2015, 2016) extended this line of work by developing type-1 and type-2 IFTPs and solution procedures based on accuracy-function-based ordering for obtaining both the initial basic feasible solution (IBFS) and the optimal solution. Ebrahimnejad and Verdegay Ebrahimnejad & Verdegay (2016) later enhanced computational efficiency by adapting classical transportation algorithms to intuitionistic fuzzy settings. More recent studies focus on fully intuitionistic fuzzy models and multi-objective formulations: a 2021 work Ghosh et al. (2021) formulated a multi-objective fully intuitionistic fuzzy fixed-charge solid transportation problem using (α, β)-cuts and an accuracy function to derive a deterministic equivalent model. Niroomand et al. Niroomand et al. (2024) proposed a hybrid multi-objective optimization framework for fully IFTPs, converting fuzzy models to crisp form without relying on ranking functions. Jyothi et al. Jyothi et al. (2024) introduced generalized intuitionistic trapezoidal fuzzy numbers for modeling TP parameters and presented an efficient optimization-based approach for determining minimum transportation cost under uncertainty.

In IFS, the sum of the membership degree (MD) and the non-membership degree (NMD) should be less than or equal to 1. However, the assignment of these values by decision-makers, who adhere to this requirement, is not always justifiable. IFS is unable to address the problem in such instances. On the other hand, there exist situations in which the total squares of MD and NMD are larger than one, but their sum is less than or equal to one. In order to address this, the Pythagorean fuzzy set (PFS) (Yager & Abbasov, 2013), a superset of IFS, was introduced. Several recent studies have extended TPs to Pythagorean fuzzy

settings to better manage uncertainty in costs, supply, and demand. Kumar and Edalatpanah (Kumar et al., 2019) examined Pythagorean fuzzy arithmetic and numerical conditions across three models, while Prabha (Prabha, 2021) proposed a geometric-mean and scoring function based approach for solving Pythagorean fuzzy TPs. Jeyalakshmi et al. Jeyalakshmi et al. (2021) formulated a balanced Pythagorean fuzzy TP incorporating fuzzy costs, availability, and demand to support decision-making under imprecision. Nagar et al. Nagar et al. (2021) introduced a Pythagorean fuzzy species transportation model with a new IFBFS method and a Pythagorean fuzzy MODI method, obtaining solutions directly in fuzzy form to avoid information loss. In the context of perishable goods, Ghosh et al. Ghosh et al. (2022) developed a multi-objective solid TP with preservation technology in a Pythagorean fuzzy environment and solved it using the ϵ-constraint method, neutrosophic linear programming, and fuzzy TOPSIS. Nagar et al. (Nagar et al., 2022) further proposed a new score function for Pythagorean fuzzy numbers, applying it to obtain the IBFS and optimal solutions using the MODI method. Chhibber et al. Chhibber et al. (2022) contributed two direct solution techniques—one for the initial feasible solution and another for optimality—along with a defuzzification procedure. Bhatia et al. Bhatia et al. (2023) identified inconsistencies in Nagar et al.'s approach and introduced the Mehar method as a corrected solution procedure. Hemalatha and Venkateswarlu Hemalatha and Venkateswarlu (2023) proposed a novel sorting technique and mean square strategy for managing uncertainty in Pythagorean fuzzy TPs. More recently, Gahlawat et al. Gahlawat et al. (2024) developed a score-function-based method for solving Pythagorean fuzzy TPs, demonstrating superior ranking and solution performance through comparative analyses.

While several studies have addressed transportation problems under fuzzy, intuitionistic fuzzy, or even Pythagorean fuzzy environments, none of them has incorporated the parameterization of uncertainty in the same structured form as proposed in this work. In particular, the existing literature does not explore transportation cost, availability, and demand simultaneously through trapezoidal Pythagorean fuzzy parameters controlled by the (α, β)-pair, nor does it analyze their impact through a systematic sensitivity framework. This gap forms the key motivation for our study. Thus, in this paper, we propose a new defuzzification function and arithmetic operations for TrPFNs, and formulate a transportation problem with all parameters ex-

pressed in TrPFNs to effectively capture uncertainty. Using the proposed defuzzification approach, we transform the fuzzy transportation model into an equivalent crisp model and solve it using MATLAB. Further, we present a case study and sensitivity analysis to demonstrate the practicality and robustness of the proposed method. The primary contributions of this paper are as follows:

1. Introduction of a solution method for Trapezoidal Pythagorean Fuzzy Transportation Problems (TrPFTP): A new and efficient solution methodology is developed specifically for solving transportation problems under a trapezoidal Pythagorean fuzzy environment. This approach effectively incorporates both the trapezoidal structure and Pythagorean fuzzy logic, which allows for a more accurate representation of uncertainty and hesitation in transportation parameters such as cost, supply, and demand. The method is designed to improve decision-making in complex scenarios where traditional crisp or basic fuzzy models may fall short.
2. Development of a new linear defuzzification method for TrPFNs: A linear defuzzification technique is proposed for converting TrPFNs into crisp values. This method provides a straightforward yet powerful tool for interpreting fuzzy quantities in a precise and meaningful way. By ensuring linearity, the defuzzification process maintains the proportional relationships within fuzzy data, thereby preserving its structural integrity while enabling computational tractability in optimization models.
3. Demonstration through a practical example of TrPFTP: To validate the efficiency and applicability of the proposed method, the paper includes an example of a TrPFTP. This example illustrates the complete modeling process — from fuzzy representation and defuzzification to the final solution — showcasing how the new methodology can be effectively implemented in solving real-world transportation problems under uncertainty.

The remainder of the paper is structured as follows: The next section outlines the motivation for employing TrPFNs in modeling transportation problems parameters. The Preliminaries section introduces the fundamental concepts and definitions related to TrPFNs, which are essential for modeling and solving the problem under uncertainty. The Trapezoidal Pythagorean fuzzy transportation problem section presents the mathemat-

ical formulation of the TrPFTP along with the proposed solution methodology, including a flowchart that outlines the computational steps. The Numerical example section illustrates the application of the proposed approach through a detailed numerical example, demonstrating its effectiveness in handling uncertain transportation parameters. The Sensitivity analysis section provides sensitivity analysis under varying α and β-levels to examine the robustness of the proposed model. The Comparitive analysis section evaluates the performance of the proposed approach against existing methods in the literature. Finally, the conclusion section concludes the paper by summarizing the key findings and suggesting possible directions for future research.

Motivation for using TrPFNs

In classical transportation problems, the cost coefficients, supply availability, and demand at destinations are required to be crisp and precisely known. However, in many real-life decision-making environments, such as logistics, supply chain management, and freight distribution, these parameters are often imprecise, vague, or incomplete. To model such uncertainties effectively, fuzzy-based extensions of the transportation problem have been widely explored.

While FNs and IFNs effectively handle data uncertainty, they have certain limitations compared to TrPFNs. Triangular fuzzy numbers provide limited flexibility in representing uncertainty, as they capture only a single peak value and assume linear membership variation on both sides. This often fails to reflect situations where experts express uncertainty in terms of ranges or plateaus. Similarly, intuitionistic fuzzy numbers extend fuzzy sets by incorporating membership and non-membership degrees, but they impose the constraint that the sum of these degrees cannot exceed one. This hard restriction limits their expressive capability when describing higher-order hesitation or ambiguity in transportation parameters. However, TrPFNs overcome the above limitations through two major features. First, the trapezoidal shape allows for a flat region (core) in the membership function, which is more suitable for representing expert assessments of cost, supply, and demand that are not point-specific but lie within a range of equally plausible values. This makes TrPFNs more realistic for handling various parameters in different types of TPs. Second, the Pythagorean fuzzy environment relaxes the restrictive condition of intu-

itionistic fuzzy sets by allowing the squared sum of the membership degree and non-membership degree to be at most one. This additional degree of freedom enhances the ability to express hesitation, which is essential in transportation planning where uncertainty arises due to market volatility, unpredictable transit conditions, and unreliable data records.

The use of TrPFNs is highly relevant to transportation problems as they provide a more flexible and accurate way to model uncertainty in real-world decision-making. When the cost coefficients, supply quantities, and demand requirements are modeled as TrPFNs, the resulting transportation model can capture wider uncertainty intervals and reflect human judgment more accurately. The trapezoidal structure allows decision-makers to specify optimistic, most likely, and pessimistic scenarios for each parameter, whereas the Pythagorean framework quantifies the corresponding belief, disbelief, and hesitation in a more flexible manner. Consequently, the TrPFN-based formulation yields solutions that are more robust, realistic, and applicable to practical transportation systems facing ambiguous and fluctuating information.

In summary, TrPFNs provide a richer and more adaptable representation of uncertainty compared to triangular or intuitionistic fuzzy numbers, making them particularly suitable for modeling the cost, availability, and demand parameters of transportation problems.

Preliminaries

This section presents some key definitions pertaining to the proposed study.

Definition 1 (Fuzzy Number). *A fuzzy subset $\tilde{A}$ of the real line $\mathbb{R}$ is said to be a fuzzy number if its membership function $\mu_{\tilde{A}}(\Lambda) : \mathbb{R} \to [0,1]$ satisfies the following properties:*

1. *$\mu_{\tilde{A}}(\Lambda)$ is piecewise continuous in its domain.*
2. *$\tilde{A}$ is normal, i.e., there exists some $\Lambda_0 \in \mathbb{R}$ such that $\mu_{\tilde{A}}(\Lambda_0) = 1$.*
3. *$\tilde{A}$ is convex, i.e., $\mu_{\tilde{A}}(\lambda\Lambda_1 + (1-\lambda)\Lambda_2) \geq \min\left\{\mu_{\tilde{A}}(\Lambda_1), \mu_{\tilde{A}}(\Lambda_2)\right\}$ for every $\Lambda_1, \Lambda_2 \in \mathbb{R}$ and $\lambda \in [0,1]$.*
4. *The support of $\tilde{A}$, i.e., Supp$(\tilde{A}) = \left\{\Lambda \in \mathbb{R} : \mu_{\tilde{A}}(\Lambda) > 0\right\}$ is bounded.*

Definition 2 (Trapezoidal Fuzzy Number). *A fuzzy number $\tilde{\chi}$ is said to be a trapezoidal fuzzy number denoted by $\tilde{\chi} = (\varsigma_1, \varsigma_2, a_3, \varsigma_4)$, where $\varsigma_1, \varsigma_2, \varsigma_3, \varsigma 4 \in$*

$\mathbb{R}$ *such that* $\varsigma_1 < \varsigma_2 < \varsigma_3 < \varsigma_4$ *and its membership function* $\mu_{\tilde{\chi}}(\Lambda)$ *is given by:*

$$\mu_{\tilde{A}}(\Lambda) = \begin{cases} \frac{\Lambda-\varsigma 1}{\varsigma 2-\varsigma 1}, & \textit{if } \varsigma_1 \leq \Lambda \leq \varsigma_2, \\ 1, & \textit{if } \varsigma_2 < \Lambda < \varsigma_3, \\ \frac{\varsigma_4-\Lambda}{\varsigma_4-\varsigma_3}, & \textit{if } \varsigma_3 \leq \Lambda \leq \varsigma_4, \\ 0, & \textit{otherwise}. \end{cases}$$

Definition 3 (Intuitionistic Fuzzy Number). *An intuitionistic fuzzy subset* $\tilde{\chi}^I = \left\{\langle \Lambda, \mu_{\tilde{\chi}^I}(\Lambda), \nu_{\tilde{\chi}^I}(\Lambda)\rangle : \Lambda \in \mathbb{R}\right\}$ *of the real line* $\mathbb{R}$ *is said to be an IFN if:*

1. $\tilde{\chi}^I$ *is intuitionistic fuzzy convex and intuitionistic fuzzy normal.*
2. $\mu_{\tilde{\chi}^I}(\Lambda)$ *is upper semi-continuous and* $\nu_{\tilde{\chi}^I}(\Lambda)$ *is lower semi-continuous.*
3. *The support of* $\tilde{\chi}^I$*, i.e.,* $Supp(\tilde{\chi}^I) = \left\{\Lambda \in \mathbb{R} : \nu_{\tilde{\chi}^I}(\Lambda) < 1\right\}$ *is bounded.*

Definition 4 (Trapezoidal Intuitionistic Fuzzy Number (TrIFN)). *A TrIFN in* $\mathbb{R}$ *is denoted by* $\chi^I = \{[\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4]; [\varsigma_1', \varsigma_2, \varsigma_3, \varsigma_4']; \gamma_{\chi^I}(\Lambda), \lambda_{\chi^I}(\Lambda)\}$*, with* $\xi_1' < \xi_1 < \xi_2 < \varsigma_3 < \varsigma_4 < \varsigma_4'$*, where* $0 \leq \gamma_{\chi^I}(\Lambda) \leq 1$*,* $0 \leq \lambda_{\chi^I}(\Lambda) \leq 1$*, and* $0 \leq \gamma_{\chi^I}(\Lambda) + \lambda_{\chi^I}(\Lambda) \leq 1$*. For TrIFNs, the non-membership function (NMF)* $\lambda_{\chi^I}(\Lambda)$ *and the membership function (MF)* $\gamma_{\chi^I}(\Lambda)$ *are of the form:*

$$\gamma_{A^I}(\Lambda) = \begin{cases} \frac{\Lambda-\varsigma_1}{\varsigma_2-\varsigma_1}, & \textit{if } \varsigma_1 < \Lambda < \varsigma_2; \\ 1, & \textit{if } \varsigma_2 \leq \Lambda \leq \varsigma_3; \\ \frac{\varsigma_4-\Lambda}{\varsigma_4-\varsigma_3}, & \textit{if } \varsigma_3 < \Lambda < \varsigma_4. \end{cases} \quad \lambda_{A^I}(\Lambda) = \begin{cases} \frac{\varsigma_2-\Lambda}{\varsigma_2-\varsigma_1}, & \textit{if } \varsigma_1 < \Lambda < \varsigma_2; \\ 0, & \textit{if } \varsigma_2 < \Lambda < \varsigma_3; \\ \frac{\Lambda-\varsigma_3}{\varsigma_4-\varsigma_3}, & \textit{if } \varsigma_3 < \Lambda < \varsigma_4. \end{cases}$$

Definition 5 (Trapezoidal Pythagorean Fuzzy Number). *A TrPFN on the real axis is defined as* $\chi^P = \{(\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4); \gamma_{\chi^P}(\Lambda), \lambda_{\chi^P}(\Lambda)\} : \Lambda \in X$*, where* $0 \leq \gamma_{\chi^P}(\Lambda) \leq 1$*,* $0 \leq \lambda_{\chi^P}(\Lambda) \leq 1$*,* ${\gamma_{\chi^P}}^2(\Lambda) + {\lambda_{\chi^P}}^2(\Lambda) \leq 1$*,* $0 \leq \varsigma_1 \leq \varsigma_2 \leq \varsigma_3 \leq \varsigma_4$*, and* $(\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4)$ *is a trapezoidal fuzzy number. Here,* $\gamma_{\chi^P}(\Lambda)$ *and* $\lambda_{\chi^P}(\Lambda)$ *are the MF and NMF, respectively, defined as:*

$$\gamma_{\chi^P}(\Lambda) = \begin{cases} \dfrac{\Lambda - \varsigma_1}{\varsigma_2 - \varsigma_1}, & \text{if } \varsigma_1 < \Lambda < \varsigma_2; \\ 1, & \text{if } \varsigma_2 \leq \Lambda \leq \varsigma_3; \\ \dfrac{\varsigma_4 - \Lambda}{\varsigma_4 - \varsigma_3}, & \text{if } \varsigma_3 < \Lambda < \varsigma_4. \end{cases}$$

$$\lambda_{\chi^P}(\Lambda) = \begin{cases} \sqrt{(1 - \left(\dfrac{\Lambda - \varsigma_1}{\varsigma_2 - \varsigma_1}\right)^2}, & \text{if } \varsigma_1 < \Lambda < \varsigma_2; \\ 0, & \text{if } \varsigma_2 \leq \Lambda \leq \varsigma_3; \\ \sqrt{(1 - \left(\dfrac{\varsigma_4 - \Lambda}{\varsigma_4 - \varsigma_3}\right)^2}, & \text{if } \varsigma_3 < \Lambda < \varsigma_4. \end{cases}$$

Definition 6. *[Arithmetic Operations on TrPFNs] Let the two positive TrPFNs be* $\chi^P = (\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4)$ *and* $\varpi^P = (\psi_1, \psi_2, \psi_3, \psi_4)$*, and let* δ *be a scalar. Then the following arithmetic operations are defined for TpFFNs:*

- *Addition:*

$$\chi^P \oplus \varpi^P = (\varsigma_1 + \psi_1, \varsigma_2 + \psi_2, \varsigma_3 + \psi_3, \varsigma_4 + \psi_4).$$

- *Subtraction:*

$$\chi^P \ominus \varpi^P = (\varsigma_1 - \psi_4, \varsigma_2 - \psi_3, \varsigma_3 - \psi_2, \varsigma_4 - \psi_1).$$

- *Scalar Multiplication:*

$$\delta\chi^P = \begin{cases} (\delta\varsigma_1, \delta\varsigma_2, \delta\varsigma_3, \delta\varsigma_4), & \text{if } \delta \geq 0; \\ (\delta\varsigma_4, \delta\varsigma_3, \delta\varsigma_2, \delta\varsigma_1), & \text{if } \delta < 0. \end{cases}$$

- *Multiplication:*

$$\chi^P \otimes \varpi^P = (\varsigma_1\psi_1, \varsigma_2\psi_2, \varsigma_3\psi_3, \varsigma_4\psi_4).$$

Definition 7. *[*α*-cut of Trapezoidal Pythagorean Fuzzy Number] The* α*-cut of* $\chi^P = (\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4)$ *is* $\chi^P_\alpha = \{\Lambda : \gamma_{\chi^P}(\Lambda) \geq \alpha;\ \Lambda \in N\}$*, where* $0 \leq \alpha \leq 1$*. Thus, the* α*-cut of* $\chi^P = (\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4)$ *is*

$$[\chi^P_{\alpha,L}, \chi^P_{\alpha,U}] = [\alpha(\varsigma_2 - \varsigma_1) + \varsigma_1,\ \varsigma_4 - \alpha(\varsigma_4 - \varsigma_3)]\,.$$

Definition 8. *[β-cut of Trapezoidal Pythagorean Fuzzy Number] The β-cut of $\chi^P = (\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4)$ is $\chi^P_\beta = \{\Lambda : \lambda_{\chi^P}(\Lambda) \leq \beta;\ \Lambda \in N\}$, where $0 \leq \beta \leq 1$. Thus, the β-cut of $\chi^P = (\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4)$ is*

$$[\chi^P_{\beta,L}, \chi^P_{\beta,U}] = \left[\varsigma_1 + (\varsigma_2 - \varsigma_1)\sqrt{1-\beta^2}, \varsigma_4(1-\sqrt{1-\beta^2}) + \varsigma_3\sqrt{1-\beta^2}\right].$$

Definition 9 ((α, β)-cut of Trapezoidal Pythagorean Fuzzy Number). *The (α, β)-cut of a TrPFN $\chi^P = (\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4)$ is the set of all Λ whose NMD $\lambda_{\chi^P}(\Lambda)$ is less than or equal to β and MD $\gamma_{\chi^P}(\Lambda)$ is greater than or equal to α, i.e.,*

$$\chi^P_{\alpha,\beta} = \left\{\Lambda : \gamma_{\chi^P}(\Lambda) \geq \alpha;\ \lambda_{\chi^P}(\Lambda) \leq \beta;\ 0 \leq \alpha^2 + \beta^2 \leq 1;\ \Lambda \in \mathbb{R}\right\}.$$

Definition 10 (Defuzzification Function for Trapezoidal Pythagorean Fuzzy Number). *Let $\chi^P = (\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4)$ be a TrPFN. Then the defuzzification function for χ^P based on (α, β)-cut is defined as:*

$$\mathfrak{D}(\chi^P) = \frac{\chi^P_{\alpha,L} + \chi^P_{\alpha,U} + \chi^P_{\beta,L} + \chi^P_{\beta,U}}{4}.$$

Using Definitions 7 and 8, we obtain

$$\mathfrak{D}(\chi^P) = \frac{\left(\alpha + \sqrt{1-\beta^2}\right)(\varsigma_2 - \varsigma_1 - \varsigma_4 + \varsigma_3) + 2(\varsigma_1 + \varsigma_4)}{4}.$$

Definition 11 (Positive Trapezoidal Pythagorean Fuzzy Number). *A trapezoidal Pythagorean fuzzy number $\zeta^P = (\kappa_1, \kappa_2, \kappa_3, \kappa_4)$ is positive if $\kappa_1 \geq 0, \kappa_2 - \kappa_1 \geq 0$, $\kappa_3 - \kappa_2 \geq 0$ and $\kappa_4 - \kappa_3 \geq 0$.*

Definition 12 (Equality of Two Trapezoidal Pythagorean Fuzzy Numbers). *Let $\zeta^P = (\kappa_1, \kappa_2, \kappa_3, \kappa_4)$ and $\varpi^P = (\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4)$ be any two trapezoidal Pythagorean fuzzy numbers. Then $\zeta^P \cong \varpi^P$ if and only if $\kappa_1 = \varepsilon_1, \kappa_2 = \varepsilon_2$, $\kappa_3 = \varepsilon_3$ and $\kappa_4 = \varepsilon_4$.*

Theorem 1. *If $\chi^P = (\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4)$ and $\varpi^P = (\psi_1, \psi_2, \psi_3, \psi_4)$ are any two TrPFNs, and ϱ is any real number, then the defuzzification function $\mathfrak{D}$ is linear, i.e., $\mathfrak{D}(\chi^P + \varrho\varpi^P) = \mathfrak{D}(\chi^P) + \varrho\mathfrak{D}(\varpi^P)$.*

Proof. We have $\chi^P = (\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4)$ and $\varpi^P = (\psi_1, \psi_2, \psi_3, \psi_4)$.
Case I: When $\varrho \geq 0$. Using Definition 6,

$$\chi^P + \varrho\varpi^P = (\varsigma_1 + \varrho\psi_1, \varsigma_2 + \varrho\psi_2, \varsigma_3 + \varrho\psi_3, \varsigma_4 + \varrho\psi_4).$$

Using the defuzzification function,

$$\begin{aligned}
&\mathfrak{D}(\chi^P + \varrho\varpi^P) \\
&= \frac{1}{4}\Big[(\alpha + \sqrt{1-\beta^2})\{(\varsigma_2 + \varrho\psi_2) - (\varsigma_1 + \varrho\psi_1) - (\varsigma_4 + \varrho\psi_4) \\
&\qquad +(\varsigma_3 + \varrho\psi_3)\} + 2\{(\varsigma_1 + \varrho\psi_1) + (\varsigma_4 + \varrho\psi_4)\}] \\
&= \frac{1}{4}\Big[(\alpha + \sqrt{1-\beta^2})\{(\varsigma_2 - \varsigma_1 - \varsigma_4 + \varsigma_3) + \varrho(\psi_2 - \psi_1 - \psi_4 \\
&\qquad +\psi_3)\} + (2\varsigma_1 + 2\varsigma_4) + \varrho(2\psi_1 + 2\psi_4)] \\
&= \frac{1}{4}\Big[(\alpha + \sqrt{1-\beta^2})(\varsigma_2 - \varsigma_1 - \varsigma_4 + \varsigma_3) + 2(\varsigma_1 + \varsigma_4)\Big] \\
&\quad + \frac{1}{4}\varrho\Big[(\alpha + \sqrt{1-\beta^2})(\psi_2 - \psi_1 - \psi_4 + \psi_3) + 2(\psi_1 + \psi_4)\Big] \\
&= \mathfrak{D}(\chi^P) + \varrho\mathfrak{D}(\varpi^P)
\end{aligned}$$

Case II: When $\varrho < 0$. Using Definition 6,

$$\chi^P + \varrho\varpi^P = (\varsigma_1 + \varrho\psi_4, \varsigma_2 + \varrho\psi_3, \varsigma_3 + \varrho\psi_2, \varsigma_4 + \varrho\psi_1).$$

Using the defuzzification function,

$$\begin{aligned}
&\mathfrak{D}(\chi^P + \varrho\varpi^P) \\
&= \frac{1}{4}\Big[(\alpha + \sqrt{1-\beta^2})\{(\varsigma_2 + \varrho\psi_3) - (\varsigma_1 + \varrho\psi_4) - (\varsigma_4 + \varrho\psi_1) \\
&\qquad +(\varsigma_3 + \varrho\psi_2)\} + 2\{(\varsigma_1 + \varrho\psi_4) + (\varsigma_4 + \varrho\psi_1)\}] \\
&= \frac{1}{4}\Big[(\alpha + \sqrt{1-\beta^2})\{(\varsigma_2 - \varsigma_1 - \varsigma_4 + \varsigma_3) + \varrho(\psi_3 - \psi_4 - \psi_1 \\
&\qquad +\psi_2)\} + 2[(\varsigma_1 + \varsigma_4) + \varrho(\psi_4 + \psi_1)]] \\
&= \frac{1}{4}\Big\{\Big[(\alpha + \sqrt{1-\beta^2})(\varsigma_2 - \varsigma_1 - \varsigma_4 + \varsigma_3) + 2(\varsigma_1 + \varsigma_4)\Big]\Big\} \\
&\quad + \varrho\left\{\frac{1}{4}\Big[(\alpha + \sqrt{1-\beta^2})(\psi_3 - \psi_4 - \psi_1 + \psi_2) + 2(\psi_4 + \psi_1)\Big]\right\} \\
&= \mathfrak{D}(\chi^P) + \varrho\mathfrak{D}(\varpi^P).
\end{aligned}$$

Hence, proved. □

Trapezoidal Pythagorean fuzzy transportation problem

The primary goal of a TP is to determine the optimal way to distribute a product or item from several sources (origins) to various destinations, aiming to minimize the total transportation cost. This scenario is common in logistics and supply chain management, where efficient allocation of resources is essential to meet demand while minimizing operational expenses. The most common real-world example involves a company with multiple factories (serving as origins) and warehouses (acting as destinations).

Each factory has a specified supply limit, indicating the maximum quantity that can be shipped, while each warehouse has a certain demand, representing the amount required to satisfy customer needs. The objective is to determine a transportation plan that satisfies both supply and demand constraints while minimizing the overall transportation cost.

In real-world scenarios, however, many uncertainties affect the input parameters of the transportation model. These uncertainties may stem from fluctuating supply availability, inconsistent demand patterns, or variable transportation costs. Traditional models using crisp values may fall short in capturing such complexities. To better represent this inherent vagueness, the TrPFTP framework is employed, where the parameters—namely, supply, demand, and transportation costs—are expressed as TrPFNs.

Pythagorean fuzzy sets extend intuitionistic fuzzy sets by allowing the sum of squares of membership and non-membership degrees to be less than or equal to one, thereby offering a broader scope to model uncertainty. When these are further defined by a trapezoidal structure, they allow the representation of a range of possible values rather than single-point estimates, accommodating uncertainty in a more flexible and realistic way.

By integrating trapezoidal Pythagorean fuzzy numbers into the transportation model, the TrPFTP formulation captures a richer degree of imprecision and ambiguity in the data. This enhances the model's adaptability to real-world logistics, enabling the generation of transportation plans that are not only cost-effective but also robust under varying conditions. Such models equip decision-makers with deeper insight into potential fluctuations and prepare them for multiple scenarios, making TrPFTP a powerful tool in uncertain supply chain environments.

The notations and assumptions used for formulating the TrPFTP are as follows:

Notations and assumptions

The following notations and assumptions have been considered in formulation of the mathematical model:

- $\Delta_{ab}^{P} = (\delta_{ab1}, \delta_{ab2}, \delta_{ab3}, \delta_{ab4})$: Trapezoidal Pythagorean fuzzy number of units to be transported from the a^{th} origin to the b^{th} destination.
- $C_{ab}^{P} = (c_{ab1}, c_{ab2}, c_{ab3}, c_{ab4})$: Trapezoidal Pythagorean fuzzy transportation cost for a unit item/product from the a^{th} origin to the b^{th} destination.
- $S_{a}^{P} = (s_{a_1}, s_{a_2}, s_{a_3}, s_{a_4})$: Trapezoidal Pythagorean fuzzy supply at the a^{th} origin.
- $D_{b}^{P} = (d_{b_1}, d_{b_2}, d_{b_3}, d_{b_4})$: Trapezoidal Pythagorean fuzzy demand at the b^{th} destination.
- r: Number of sources ($a = 1, 2, 3, ..., r$).
- s: Number of destinations ($b = 1, 2, 3, ..., s$).
- $S_{a}^{P} > 0,\ D_{b}^{P} > 0,\ C_{ab}^{P} > 0\ , \Delta_{ab}^{P} > 0\ \forall\ a$ and b.

Model formulation

- **Objective Function:** The primary objective is to determine the quantities of goods Δ_{ab}^{P} to be transported from the a^{th} origin to the b^{th} destination in such a way that the demand at each destination is fulfilled, and the transportation cost is minimized. The total transportation cost is expressed through the following objective: minimizing the overall cost incurred during transportation.

$$\text{Minimize } Z^{P} = \sum_{a=1}^{r} \sum_{b=1}^{s} \{C_{ab}^{P} \otimes \Delta_{ab}^{P}\}.$$

This objective function seeks to minimize the total transportation cost, which is defined as the aggregated sum of the products of trapezoidal Pythagorean fuzzy per-unit transportation costs and the corresponding quantities transported, over all origins and destinations.

- **Supply Constraints:** The supply constraints ensure that the total quantity of goods shipped from each origin does not exceed its available supply capacity. These constraints are formulated to restrict the sum of all

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shipments from a particular source to all destinations. For a transportation model involving r sources, the supply constraints can be mathematically expressed as follows:

$$\sum_{b=1}^{s} \Delta_{ab}^{P} = S_{a}^{P} \text{ for } a = 1, 2, \ldots, r.$$

- **Demand Constraints:** The demand constraints ensure that each destination receives a total quantity of goods that satisfies its specified demand. These constraints are formulated to regulate the cumulative shipments directed to a given destination from all sources. In the proposed model comprising s destinations, the demand constraints can be mathematically expressed as follows:

$$\sum_{a=1}^{r} \Delta_{ab}^{P} = D_{b}^{P} \text{ for } b = 1, 2, \ldots, s.$$

- **Non-Negativity Constraints:** The non-negativity constraints ensure that the quantities of products transported from each source to each destination are zero or positive. These constraints are fundamental to the formulation of transportation models, as they reflect the practical reality that negative shipments are not physically meaningful or permissible in real-world distribution systems. In the proposed model with r sources and s destinations, the non-negativity constraints can be represented as follows:

$$\Delta_{ab}^{P} \geq 0 \text{ for } a = 1, 2, \ldots, r \text{ and } b = 1, 2, \ldots, s.$$

Therefore, by incorporating the defined objective function along with the associated constraints, the formulated model for the TrPFTP can be represented as follows:

Model 1: Trapezoidal Pythagorean fuzzy transportation problem

Based on the notations and assumptions described above, and considering all the parameters of the problem as trapezoidal Pythagorean fuzzy numbers in the initial stage, the mathematical model of the TrPFTP is formulated as follows:

$$\text{Min } Z^{P} = \sum_{a=1}^{r} \sum_{b=1}^{s} \{C_{ab}^{P} \otimes \Delta_{ab}^{P}\}$$

$$\text{subject to } \sum_{b=1}^{s} \Delta_{ab}^{P} = S_a^P \text{ for } a = 1, 2, \ldots, r,$$
$$\sum_{a=1}^{r} \Delta_{ab}^{P} = D_b^P \text{ for } b = 1, 2, \ldots, s,$$
$$\Delta_{ab}^{P} \geq 0 \text{ for } a = 1, 2, \ldots, r \text{ and } b = 1, 2, \ldots, s.$$

With the previously introduced notation, Model 1 is rewritten in the form of Model 2.

Model 2: Auxiliary transformation model

Directly solving the TrPFTP is difficult because it contains trapezoidal Pythagorean fuzzy variables. Therefore, Model 1 must first be converted into an equivalent deterministic form. To achieve this, we rewrite Model 1 by substituting the formal notations defined for all its parameters, which serves as an intermediate step before obtaining the final crisp model.

$$\text{Min } Z = \sum_{a=1}^{r} \sum_{b=1}^{s} (c_{ab_1}, c_{ab_2}, c_{ab_3}, c_{ab_4}) \otimes (\delta_{ab_1}, \delta_{ab_2}, \delta_{ab_3}, \delta_{ab_4})$$

subject to

$$\sum_{b=1}^{s} (\delta_{ab_1}, \delta_{ab_2}, \delta_{ab_3}, \delta_{ab_4}) = (s_{a_1}, s_{a_2}, s_{a_3}, s_{a_4}) \text{ for } a = 1, 2, \ldots, r,$$
$$\sum_{a=1}^{r} (\delta_{ab_1}, \delta_{ab_2}, \delta_{ab_3}, \delta_{ab_4}) = (d_{b_1}, d_{b_2}, d_{b_3}, d_{b_4}) \text{ for } b = 1, 2, \ldots, s,$$
$$(\delta_{ab_1}, \delta_{ab_2}, \delta_{ab_3}, \delta_{ab_4}) \geq 0 \text{ for } a = 1, 2, \ldots, r \text{ and } b = 1, 2, \ldots, s.$$

By applying the defuzzification and comparison techniques outlined in Definitions 10, 11, and 12, Model 2, which incorporates trapezoidal Pythagorean fuzzy parameters, is systematically converted into its equivalent crisp linear form, referred to as Model 3. Definition 10 provides the defuzzification function used to transform the fuzzy objective function into a crisp objective, while Definitions 11 and 12 are employed to convert the fuzzy inequality and equality constraints, respectively, into their deterministic counterparts. As a result, the fully crisp version of the transportation problem is obtained and presented as follows:

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Model 3: Equivalent deterministic model

$$\text{Min } Z = \sum_{a=1}^{r}\sum_{b=1}^{s}\frac{1}{4}\left[\left(\alpha+\sqrt{1-\beta^2}\right)\left(c_{ab_2}\delta_{ab_2}-c_{ab_1}\delta_{ab_1}-c_{ab_4}\delta_{ab_4}+c_{ab_3}\delta_{ab_3}\right)\right.$$
$$\left.+2\left(c_{ab_1}\delta_{ab_1}+c_{ab_4}\delta_{ab_4}\right)\right]$$

subject to

$$\sum_{b=1}^{s}\delta_{ab_1}=s_{a_1},\ \sum_{b=1}^{s}\delta_{ab_2}=s_{a_2},\ \sum_{b=1}^{s}\delta_{ab_3}=s_{a_3},$$
$$\sum_{b=1}^{s}\delta_{ab_4}=s_{a_4} \text{ for } a=1,2,\ldots,r,$$
$$\sum_{a=1}^{r}\delta_{ab_1}=d_{b_1},\ \sum_{a=1}^{r}\delta_{ab_2}=d_{b_2},\ \sum_{a=1}^{r}\delta_{ab_3}=d_{b_3},$$
$$\sum_{a=1}^{r}\delta_{ab_4}=d_{b_4} \text{ for } b=1,2,\ldots,s,$$
$$\delta_{ab_1}\geq 0,\ \delta_{ab_2}-\delta_{ab_1}\geq 0,\ \delta_{ab_3}-\delta_{ab_2}\geq 0,$$
$$\delta_{ab_4}-\delta_{ab_3}\geq 0 \text{ for } a=1,2,\ldots,r \text{ and } b=1,2,\ldots,s.$$

Ultimately, the optimal solution to this linear programming problem is derived using MATLAB. Fig. 1 illustrates the flowchart of the proposed solution approach for TrPFTPs.

Numerical example

To illustrate the applicability of the proposed methodology, we consider a TrPFTP. In this example, there are three factories—Factory A, Factory B, and Factory C—which serve as sources, supplying products to three destinations—Warehouse X, Warehouse Y, and Warehouse Z. The objective is to determine an optimal transportation plan that minimizes the total transportation cost while satisfying the supply capacities of the factories and the demand requirements of the warehouses.

In real-world logistics, transportation costs, supply capacities, and demand levels are often subject to uncertainty due to various factors such as fuel price fluctuations, changing road or weather conditions, and variability in labor costs. To effectively model and manage this inherent uncertainty,

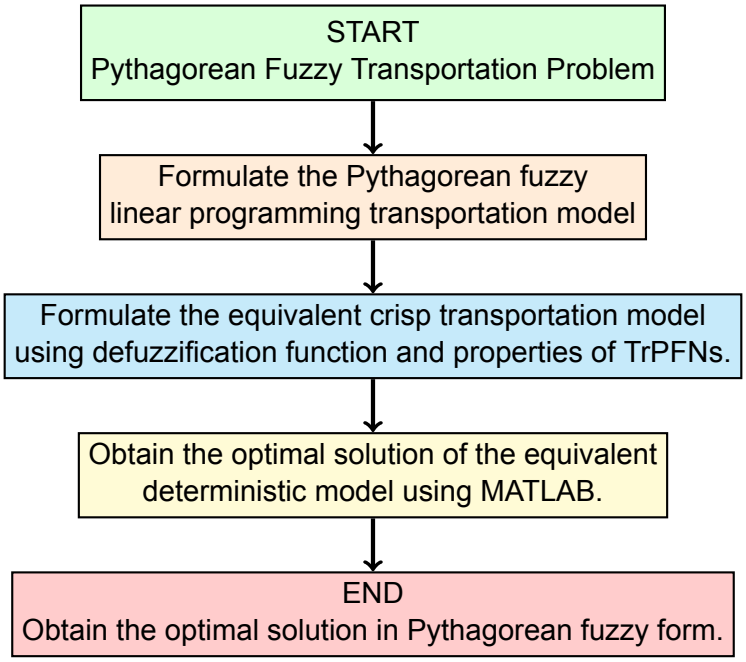


Figure 1 – Flowchart for the proposed solution procedure

all parameters in the problem, namely, transportation costs, supply, and demand, are represented using TrPFNs.

The fuzzy per-unit transportation costs (in dollars) from each factory to each warehouse are presented in Table 1. The fuzzy demand values (in tonnes) for Warehouses X, Y, and Z are given as $(180, 190, 220, 250)$, $(190, 270, 280, 320)$, and $(250, 290, 310, 330)$, respectively. Similarly, the fuzzy supply capacities (in tonnes) of Factory A, Factory B, and Factory C are given as $(100, 150, 170, 200)$, $(210, 250, 270, 300)$, and $(310, 350, 370, 400)$, respectively.

The goal is to determine the optimal transportation plan that minimizes the overall fuzzy transportation cost, taking into account the vagueness in the system parameters. The subsequent sections will detail the defuzzification process and solution procedure, ultimately leading to the computation of the crisp optimal transportation cost.

Table 1 – Transportation cost per unit item for the considered numerical example

Factory ↓ Warehouse →	**X**	**Y**	**Z**
A	$(5, 10, 15, 20)$	$(10, 11, 12, 13)$	$(6, 7, 8, 9)$
B	$(8, 9, 10, 11)$	$(20, 25, 30, 35)$	$(2, 3, 4, 5)$
C	$(10, 20, 30, 40)$	$(13, 14, 15, 16)$	$(21, 25, 28, 30)$

Solution

In this problem, we consider $\alpha = 0.9$ and $\beta = 0.3$, such that $\alpha + \beta > 1$ but $\alpha^2 + \beta^2 \leq 1$, and obtain the deterministic model as follows:

$$\begin{aligned}\text{Max} = \frac{1}{4}\,[1.8539\,(&10\delta_{112} - 5\delta_{111} - 20\delta_{114} + 15\delta_{113} + 11\delta_{122} - 10\delta_{121}\\ &-13\delta_{124} + 12\delta_{123} + 7\delta_{132} - 6\delta_{131} - 9\delta_{134} + 8\delta_{133} + 9\delta_{212} - 8\delta_{211}\\ &- 11\delta_{214} + 10\delta_{213} + 25\delta_{222} - 20\delta_{221} - 35\delta_{224} + 30\delta_{223} + 3\delta_{232}\\ &- 2\delta_{231} - 5\delta_{234} + 4\delta_{233} + 20\delta_{312} - 10\delta_{311} - 40\delta_{314} + 30\delta_{313} + 14\delta_{322}\\ &-13\delta_{321} - 16\delta_{324} + 15\delta_{323} + 25\delta_{332} - 21\delta_{331} - 30\delta_{334} + 28\delta_{333})\\ &+ 2\,(5\delta_{111} + 20\delta_{114} + 10\delta_{121} + 13\delta_{124} + 6\delta_{131} + 9\delta_{134} + 8\delta_{211}\\ &+11\delta_{214} + 20\delta_{221} + 35\delta_{224} + 2\delta_{231} + 5\delta_{234} + 10\delta_{311} + 40\delta_{314}\\ &+13\delta_{321} + 16\delta_{324} + 21\delta_{331} + 30\delta_{334})]\end{aligned}$$

subject to

$$\begin{aligned}&\delta_{111} + \delta_{121} + \delta_{131} = 100, \delta_{112} + \delta_{122} + \delta_{132} = 150,\\ &\delta_{113} + \delta_{123} + \delta_{133} = 170, \delta_{114} + \delta_{124} + \delta_{134} = 200,\\ &\delta_{211} + \delta_{221} + \delta_{231} = 210, \delta_{212} + \delta_{222} + \delta_{232} = 250,\\ &\delta_{213} + \delta_{223} + \delta_{233} = 270, \delta_{214} + \delta_{224} + \delta_{234} = 300,\\ &\delta_{311} + \delta_{321} + \delta_{331} = 310, \delta_{312} + \delta_{322} + \delta_{332} = 350,\\ &\delta_{313} + \delta_{323} + \delta_{333} = 370, \delta_{314} + \delta_{324} + \delta_{334} = 400,\\ &\delta_{111} + \delta_{211} + \delta_{311} = 180, \delta_{112} + \delta_{212} + \delta_{312} = 190,\\ &\delta_{113} + \delta_{213} + \delta_{313} = 220, \delta_{114} + \delta_{214} + \delta_{314} = 250,\\ &\delta_{121} + \delta_{221} + \delta_{321} = 190, \delta_{122} + \delta_{222} + \delta_{322} = 270,\\ &\delta_{123} + \delta_{223} + \delta_{323} = 280, \delta_{124} + \delta_{224} + \delta_{324} = 320,\\ &\delta_{131} + \delta_{231} + \delta_{331} = 250, \delta_{132} + \delta_{232} + \delta_{332} = 290,\end{aligned}$$

$$\delta_{133}+\delta_{233}+\delta_{333}=310, \delta_{134}+\delta_{234}+\delta_{334}=330,$$
$$\delta_{111}\geq 0, \delta_{112}-\delta_{111}\geq 0, \delta_{113}-\delta_{112}\geq 0, \delta_{114}-\delta_{113}\geq 0,$$
$$\delta_{121}\geq 0, \delta_{122}-\delta_{121}\geq 0, \delta_{123}-\delta_{122}\geq 0, \delta_{124}-\delta_{123}\geq 0,$$
$$\delta_{131}\geq 0, \delta_{132}-\delta_{131}\geq 0, \delta_{133}-\delta_{132}\geq 0, \delta_{134}-\delta_{133}\geq 0,$$
$$\delta_{211}\geq 0, \delta_{212}-\delta_{211}\geq 0, \delta_{213}-\delta_{212}\geq 0, \delta_{214}-\delta_{213}\geq 0,$$
$$\delta_{221}\geq 0, \delta_{222}-\delta_{221}\geq 0, \delta_{223}-\delta_{222}\geq 0, \delta_{224}-\delta_{223}\geq 0,$$
$$\delta_{231}\geq 0, \delta_{232}-\delta_{231}\geq 0, \delta_{233}-\delta_{232}\geq 0, \delta_{234}-\delta_{233}\geq 0,$$
$$\delta_{311}\geq 0, \delta_{312}-\delta_{311}\geq 0, \delta_{313}-\delta_{312}\geq 0, \delta_{314}-\delta_{313}\geq 0,$$
$$\delta_{321}\geq 0, \delta_{322}-\delta_{321}\geq 0, \delta_{323}-\delta_{322}\geq 0, \delta_{324}-\delta_{323}\geq 0,$$
$$\delta_{331}\geq 0, \delta_{332}-\delta_{331}\geq 0, \delta_{333}-\delta_{332}\geq 0, \delta_{334}-\delta_{333}\geq 0.$$

Using MATLAB, the optimal solution obtained is:

$$\Delta_{11}^{P}=(60,70,70,70), \quad \Delta_{12}^{P}=(0,40,40,50), \quad \Delta_{13}^{P}=(40,40,60,80),$$
$$\Delta_{21}^{P}=(0,0,20,50), \quad \Delta_{23}^{P}=(210,250,250,250),$$
$$\Delta_{31}^{P}=(120,120,130,130), \quad \Delta_{32}^{P}=(190,230,240,270),$$

and the rest of the variables are trapezoidal Pythagorean fuzzy zero. Thus, the optimal transportation cost is given by:

$$\begin{aligned}
Z_{ab}^{P} &= C_{ab}^{P}\otimes\Delta_{ab}^{P}\\
&=(5,10,15,20)\otimes(60,70,70,70)\oplus(10,11,12,13)\otimes(0,40,40,50)\\
&\quad\oplus(6,7,8,9)\otimes(40,40,60,80)\oplus(8,9,10,11)\otimes(0,0,20,50)\\
&\quad\oplus(20,25,30,35)\otimes(0,0,0,0)\oplus(2,3,4,5)\otimes(210,250,250,250)\\
&\quad\oplus(10,20,30,40)\otimes(120,120,130,130)\oplus(13,14,15,16)\\
&\quad\otimes(190,230,240,270)\oplus(21,25,28,30)\otimes(0,0,0,0)\\
&=\$(4630,7790,10710,14090).
\end{aligned}$$

The crisp value of the optimal transportation cost by the proposed approach is $\$9258$ (see Figure 2(ii)).

Sensitivity analysis with varying α and β

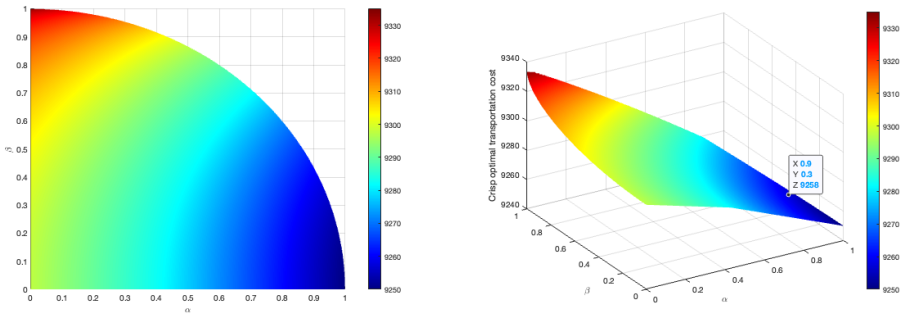
In real-world transportation problems, the parameters represented as TrPFNs inherently carry uncertainty. To investigate the robustness of the

proposed model, we perform a sensitivity analysis by varying the parameters α and β within the feasible range, i.e., $\alpha^2 + \beta^2 \leq 1$. For each pair (α, β), we solve the deterministic equivalent of the TrPFTP and record the corresponding objective function value.

From Figure 2, we can see that the value of the objective function exhibits a smooth and monotonic variation with respect to both parameters. As α increases and β decreases, the objective value gradually decreases, indicating that higher degrees of membership tend to favor lower total transportation cost in the crisp model. Conversely, larger values of β (with lower α) increase the objective value, reflecting the influence of stronger non-membership components of trapezoidal Pythagorean fuzzy numbers.

The surface plot does not contain abrupt jumps or oscillations, which confirms that the proposed crisp transformation method is numerically stable and the resulting transportation model responds continuously and predictably to variations in fuzzy uncertainty. This regularity is particularly important in decision-making environments where the selection of (α, β) reflects managerial preference, reliability of data, or uncertainty tolerance. The sensitivity structure also indicates that no region of the feasible (α, β) domain leads to infeasible or unstable solutions, further supporting the soundness of the proposed modeling approach.

Thus, the crisp transportation model derived from trapezoidal Pythagorean fuzzy numbers is both robust and well-behaved under varying levels of membership and non-membership information. The objective value changes smoothly across the feasible (α, β) region, confirming that the model is not overly sensitive to small perturbations in fuzzy parameters. This behavior ensures reliability in practical applications where uncertainties in transportation cost, supply, or demand may influence the selection of (α, β). Overall, the analysis validates that the proposed transformation technique yields stable and interpretable solutions, strengthening the applicability of the model in real-world logistics and decision-making scenarios.



(i) *(ii)*

Figure 2 – Sensitivity analysis with varying α and β (i) feasible region of Pythagorean fuzzy numbers represented over the (α, β)-plane; (ii) corresponding variation of the objective value of the transformed transportation model

Comparative analysis for the proposed approach

1. To assess the validity and robustness of the proposed Pythagorean fuzzy transportation model and its solution method, we construct a TP (Table 2) whose structure is general enough to be compatible with the modelling assumptions used in several existing studies. It can be directly aligned with the forms employed in the literature through slight modifications in their respective frameworks.

Table 2 – Transportation problem for comparative analysis

Source	**A**	**B**	**C**	**Availability**
X	$(3, 5, 8, 12)$	$(2, 5, 7, 10)$	$(3, 4, 6, 9)$	50
Y	$(12, 15, 18, 20)$	$(3, 6, 9, 12)$	$(4, 7, 9, 13)$	80
P	$(5, 7, 10, 12)$	$(4, 8, 10, 15)$	$(5, 9, 12, 16)$	70
Demand	100	55	50	50

We solve the TP considered in Table 2 using different methods (Aggarwal & Gupta (2015); Beaula & Priyadharsini (2015); Ebrahimnejad & Verdegay (2018); Hunwisai et al. (2019)) and observe that all approaches lead to identical value of objective function (Min $Z = (770, 1230, 1780, 2370)$) and same allocations ($\Delta_{11}^P = (30, 30, 30, 30)$, $\Delta_{13}^P = (20, 20, 20, 20)$, $\Delta_{22}^P = (50, 50, 50, 50)$, $\Delta_{23}^P = (30, 30, 30, 30)$, $\Delta_{31}^P = (70, 70, 70, 70)$ and rest of the variables are trapezoidal Pythagorean fuzzy zero). This agreement across multiple methodologies confirms that our model is both mathematically

sound and computationally reliable. Moreover, it demonstrates that the proposed method integrates smoothly with established solution techniques, strengthening confidence in the correctness and applicability of the proposed formulation.

2. Several studies in the literature, for example, Kumar et al. (2019); Prabha (2021); Jeyalakshmi et al. (2021); Nagar et al. (2021, 2022); Hemalatha and Venkateswarlu (2023); Bhatia et al. (2023); Gahlawat et al. (2024) used Pythagorean fuzzy cost parameters expressed directly as membership–non-membership pairs such as $[0.8, 0.3]$. However, the interpretation of such pairs as actual transportation costs is not well-defined, and their operational significance within the transportation framework is unclear. Our formulation addresses this limitation by adopting a more structured and meaningful fuzzy parameter representation.

Conclusion

In this paper, we present a simple and complete framework for solving transportation problems using TrPFNs. We introduce basic arithmetic operations for TrPFNs and propose a new defuzzification function. To include the uncertain nature of real-world data, we model all cost values, supply, and demand as TrPFNs. We then convert this fuzzy transportation problem into a deterministic model using the proposed defuzzification function, which makes use of the special mathematical features of TrPFNs. This transformation keeps the uncertainty information but allows the problem to be solved using standard optimization methods. The final crisp model is solved in MATLAB. To demonstrate its usefulness, we provide a numerical example involving the transportation of goods between warehouses and factories. Throughout the process, we maintain the fuzzy nature of the data to show how well the model handles uncertainty and imprecision in real logistics situations. We also carry out a sensitivity analysis to study how the objective value behaves when the α and β values change within their feasible region. The results show that the objective value varies smoothly, meaning the model is stable and not heavily affected by small changes in fuzzy parameters. This confirms that the proposed approach remains reliable even when cost, supply, or demand values are uncertain. In addition, a comparative analysis with existing methods shows that all approaches lead to the same objective value and similar allocations once transformed through our defuzzification process. This agreement across methods fur-

ther supports that the model is consistent, dependable, and suitable for real-world decision-making.

For future work, we suggest extending this approach to unbalanced transportation problems, improving the defuzzification method further, and extending the work to other optimization problems such as assignment problems, supply chain systems, and multi-objective decision-making involving TrPFNs.

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Pristup rešavanju transportnog problema u Pitagorinom fazi okruženju

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OBLAST: matematika

KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: U ovom radu se uvodi nova funkcija defazifikacije za trapezoidne Pitagorine fazi brojeve (eng. TrPFN) i razvijaju se aritmetičke operacije koje se na njih odnose. S obzirom na blisku povezanost transportnog problema sa problemom linearnog programiranja, konstruisan je transportni model u kom su svi parametri predstavljeni pomoću trapezoidnih Pitagorinih fazi brojeva. Cilj rada je da obuhvati neizvesnost i nepreciznost koje se često javljaju u realnim problemima planiranja transporta.

Metode: Formulisan je transportni model sa trapezoidnim Pitagorinim fazi parametrima. Predložena funkcija defazifikacije i matematička svojstva trapezoidnih Pitagorinih fazi brojeva se koriste za transformaciju fazi transportnog modela u ekvivalentni deterministički model koji se potom rešava upotrebom programskog jezika MATLAB.

Rezultati: U cilju demonstracije efikasnosti predloženog pristupa, predstavljena je studija slučaja koja se odnosi na transport robe između fabrika i skladišta. U primeru je očuvana fazi priroda parametara tokom čitavog postupka rešavanja, a sprovedena je i analiza osetljivosti kako bi se ispitala robusnost predloženog modela. Rezultati dobijeni predloženim metodom upoređeni su sa postojećim pristupima radi provere konzistentnosti.

Zaključak: Rezultati istraživanja pokazuju da predložena funkcija defazifikacije i razvijeni transportni model efikasno upravljaju neizvesnošću u transportnim problemima. Predloženi pristup daje pouzdane i konzistentne rezultate i može biti koristan za rešavanje realnih fazi transportnih problema.

Ključne reči: Pitagorini fazi brojevi, Pitagorini fazi transportni problem, optimalno rešenje, analiza osetljivosti.

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Multi-criteria analysis applied to the hydro-chemical classification of bottled waters marketed in Algeria

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Abstract:

Introduction/purpose: Mineral and spring waters play a crucial role in daily nutrition due to their taste and health benefits. In Algeria, the bottled water market is rapidly growing, yet there remains a lack of precise, objective systems to classify these waters based on organoleptic qualities and safety. This study aims to develop a reliable numerical model for the hydrochemical classification of bottled waters marketed in Algeria.

Methods: A hybrid multi-criteria decision-making approach was employed, integrating the DIBR II method to determine the weights of criteria based on expert judgments and the Bonferroni operator to aggregate these opinions. To effectively manage uncertainty and imprecision in the data, Triangular Neutrosophic Numbers (TNN) were utilized. Subsequently, the CODAS (COmbinative Distance-based ASsessment) method was applied to rank the bottled water brands. The evaluation focused on four key quality criteria: nitrate concentration, hardness, total mineralization, and hydrochemical nature. After constructing and aggregating the neutrosophic decision matrices and performing de-neutrosophication, CODAS computed a proximity coefficient for each brand, resulting in the final ranking.

Results: The study identified the top five brands of mineral waters (Daouia, Mansourah, Youkous, Alma, and N'Gaous) and spring waters (Taya, Ariaf, Arwa, Sidi Rached, and Hirouche). Sensitivity analysis confirmed the robustness of the ranking, validating the model's reliability and showed that nitrate content is the most influential criterion, highlighting its key role in assessing water quality. Comparative analysis also demonstrated that CODAS produces consistent and reliable rankings compared to other multi-criteria methods, with good discrimination among closely ranked alternatives.

Conclusion: This study developed an innovative and robust numerical model combining DIBR II and CODAS within a neutrosophic framework, providing a reliable hydrochemical classification of bottled mineral and spring waters in Algeria. The model incorporates expert weighting and accounts for data uncertainty to generate a clear and coherent brand ranking. Sensitivity analysis confirmed the stability of the rankings, particularly emphasizing the dominance of the nitrate criterion, demonstrating the model's value as a decision-support tool for various stakeholders in the sector.

Key words: multi-criteria classification, mineral water, spring water, DIBR II, CODAS, neutrosophic numbers.

Introduction

The bottled water sector in Algeria has experienced remarkable growth in recent years, marked by the multiplication of production units and a significant increase in per capita consumption (Hazzab, 2011). Faced with this expansion, it has become essential to evaluate and classify the quality of bottled waters available on the Algerian market (Lourenço et al., 2010).

Traditionally, hydrochemical analyses rely on graphical and statistical methods such as Piper and Schoeller-Berkaloff diagrams or Principal Component Analysis (PCA) (Ouhamdouch et al., 2018). Although these approaches are effective for visualizing the chemical composition of waters, they do not allow for an integrated and quantitative evaluation of water quality when several, sometimes conflicting, criteria are involved.

To overcome these limitations, multi-criteria decision-making (MCDM) methods have established themselves as powerful tools in complex decision-making processes involving multiple evaluation parameters. MCDM is a structured approach that enables decision-makers to rank or select alternatives based on multiple, often conflicting, criteria, each weighted according to its relative importance (Rahman et al., 2024). These methods are increasingly used in environmental management,

water resource assessment, and hydrogeochemical classification (Božanić et al., 2024).

Recent MCDM approaches can be grouped into two main categories. The first includes methods for determining criteria weights, which express the relative importance of each decision factor. Among these are AHP (Analytic Hierarchy Process) (Saaty, 1980), BWM (Best–Worst Method) (Rezaei, 2015), the entropy method (Zhou et al., 2023), and DIBR-II (Defining Interrelationships Between Ranked Criteria II) (Božanić et al., 2024). The second category concerns ranking or selection methods for the optimal alternative, which combine weighted criteria to produce a final ranking, such as CODAS (COmbinative Distance-based ASsessment) (Ghorabaee et al., 2016), VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) (Rahman et al., 2024), WASPAS (Weighted Aggregated Sum Product Assessment) (Lan et al., 2023), COPRAS (Complex Proportional Assessment) (Egbueri et al., 2023), as well as MOORA, EDAS, and their fuzzy or neutrosophic extensions (Wang et al., 2023).

In this study, the CODAS method, recognized for its clarity, robustness, and efficiency in multi-criteria ranking, was used in combination with the DIBR-II method for criteria weighting. Integrated within a neutrosophic framework, this approach offers an objective and reproducible model for hydrochemical classification.

The proposed model was applied to a representative sample of mineral and spring waters marketed in Algeria, considering four main criteria: hardness, nitrate content, mineralization, and hydrochemical nature, with the aim of establishing a scientific and transparent classification.

A sensitivity analysis confirmed the robustness of the ranking obtained by CODAS against variations in criteria weighting, while a comparison with other multi-criteria methods validated the relevance and reliability of the approach.

Thus, the study contributes to improving the quality and transparency of the bottled water sector in Algeria by providing consumers and professionals with a reliable tool for evaluating and comparing the different brands available on the market.

Materials and methods

Methodology for classifying bottled water marketed in Algeria

This study proposes a numerical model based on the CODAS method for the hydrochemical classification of bottled waters marketed in Algeria. The process, illustrated in Figure 1, begins with the collection and recording of physico-chemical data obtained from the labels of various brands. The classification criteria are then defined and weighted according to expert opinions using the DIBR II method, with the weights merged through the Bonferroni operator. A neutrosophic decision matrix is developed for each expert, aggregated, and de-neutrosophicated to produce a single matrix. The CODAS method is subsequently applied to compute an assessment score based on the Euclidean and Taxicab distances from the negative-ideal solution, thereby enabling the ranking of the water samples. Finally, a sensitivity and comparative analysis was conducted to evaluate the robustness of the rankings against variations in criteria weighting and to assess the consistency of CODAS relative to other multi-criteria decision-making methods.

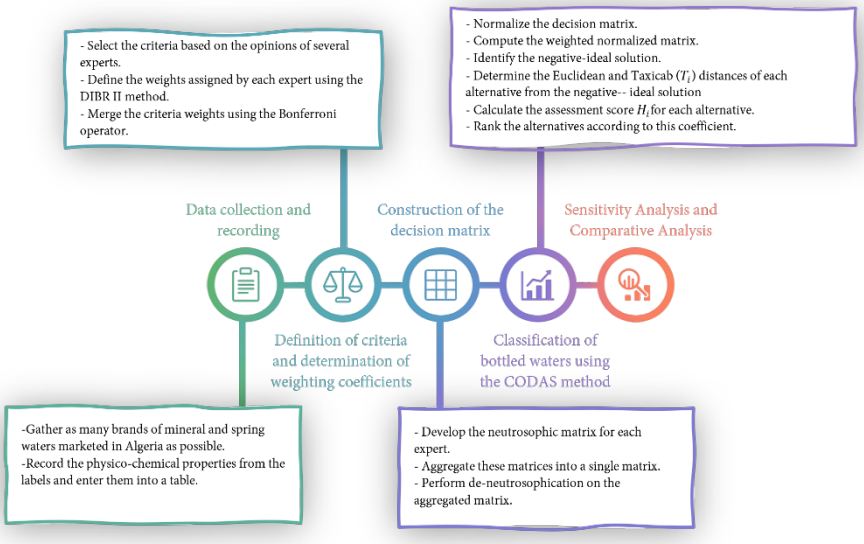

Figure 1 – Procedure for the classification of bottled water marketed in Algeria

Mathematical concepts

This section presents the fundamental mathematical tools used in this article, beginning with the DIBR II method employed to determine the relative importance of decision criteria. It then addresses fuzzy and neutrosophic sets along with their properties and definitions. Finally, the steps of the CODAS method, a multi-criteria technique, are presented.

The DIBR and DIBR II methods (defining interrelationships between ranked criteria)

The DIBR method is a mathematical technique that determines the relative importance of decision criteria in multi-criteria problems, providing essential weighting coefficients that reflect each criterion's influence on the overall objective. Used as a complementary tool, it generates reliable weights integrated into other methods such as AHP or CODAS, establishing a solid basis for ranking options or selecting the best alternative.

The DIBR II version, published by Božanić et al. in 2024, enhances this initial method with a process summarized as follows:

- Identification and ranking of criteria: The user or a group of experts identifies relevant criteria $(C_i)_{i=1,\dots,n}$for the decision problem and ranks them in descending order of importance ($C_1 > C_2 > \cdots > C_n$).

- Definition of relationships: For each pair of adjacent criteria in the ranking, the experts define the importance relationship:

$$r_{i,i+1} = \frac{w_i}{w_{i+1}} \quad for \quad i = 1,\dots,n-1 \tag{1}$$

Where w_i represents the weight of the criterion C_i.

- Calculation of weights: First, the weight (w_1) attributed to the main criterion C_1 is calculated using the following formula:

$$w_1 = \frac{1}{1 + \frac{1}{r_{1,2}} + \frac{1}{r_{1,2} * r_{2,3}} + \dots + \frac{1}{r_{1,2} * r_{2,3} * \dots * r_{n-1,n}}} \tag{2}$$

For $i = 2, \dots, n$, the other weights w_i are obtained using the formula:

$$w_i = \frac{w_1}{\prod_{j=1}^{i-1} r_{j,j+1}} \tag{3}$$

- Evaluation of the quality of defined relationships: To ensure the quality of the relationships between criteria, the deviation coefficient D_n of the criterion C_n is calculated according to the expression:

$$D_n = \left|1 - \frac{w_n}{w_n^k}\right| \quad \text{with} \quad w_n^k = \frac{w_n}{v_{1,n}} \tag{4}$$

It must be between 0 and 0.1 (a tolerance margin of 10%) and applies to the most and least important criteria. If this condition is not met, the relationships between adjacent criteria should be reviewed to ensure their consistency.

Definition of a single-valued neutrosophic fuzzy set

Consider a universe of discourse X. A single-valued neutrosophic fuzzy set on X is defined as follows:

$$A = \{(x, T_A(x), I_A(x), F_A(x)); x \in X\}$$

The functions $T_A(x), I_A(x)$ and $F_A(x)$ represent respectively the degrees of membership, indeterminacy, and non-membership of the element x to the set A.

These functions satisfy $0 \leq T_A(x), I_A(x), F_A(x) \leq 1$, and their sum is constrained by the relation: $0 \leq T_A(x), I_A(x), F_A(x) \leq 3$ (Zhou et al., 2023).

Definition of neutrosophic number (NN)

Let A be a single-valued neutrosophic fuzzy set on the set of real numbers. A is called a neutrosophic fuzzy number if it satisfies the following conditions (Wang et al., 2023):

(i) Normality of A: there exists $x_0 \in R$ such that

$$T_A(x_0) = 1, I_A(x_0) = 0 \text{ and } F_A(x_0) = 0$$

(ii) Convexity of T_A : for all $x_1 and\ x_2 \in R$ and $\lambda \in [0,1]$,

$$T_A(\lambda x_1 + (I - \lambda)x_2) \geq \min\{T_A(x_1); T_A(x_2)\} \tag{5}$$

(iii) Convexity of I_A : for all $x_1 and\ x_2 \in R$ and $\lambda \in [0,1]$,

$$I_A(\lambda x_1 + (I - \lambda)x_2) \leq \max\{I_A(x_1); I_A(x_2)\} \tag{6}$$

(iv) Convexity of F : for all $x_1 and\ x_2 \in R$ and $\lambda \in [0,1]$,

$$F_A(\lambda x_1 + (I - \lambda)x_2) \leq \max\{F_A(x_1); F_A(x_2)\} \tag{7}$$

Definition of triangular neutrosophic number (TNN)

Let $\tilde{T} = \left\langle (x, T_T(x), I_T(x), F_T(x)); (d_1, d_2, d_3, X_N, Y_N, Z_N) \right\rangle$ be a single-valued triangular neutrosophic number, where:

- $d_1, d_2, d_3 \in \mathbb{R}$ with $d_1 \leq d_2 \leq d_3$,
- $X_N, Y_N \; and \; Z_N \in [0,1]$ represent respectively the maximum degrees of truth, indeterminacy, and falsity.

The membership, indeterminacy, and non-membership functions, denoted respectively by $T_{\tilde{T}}(x)$, $I_{\tilde{T}}(x)$ and $F_{\tilde{T}}(x)$ are defined as follows:

$$T_T(x) = \begin{cases} X_N \dfrac{x - d_1}{d_2 - d_1} \; if \; d_1 \leq x \leq d_2 \\ X_N \; if \; x = d_2 \\ X_N \dfrac{d_3 - x}{d_3 - d_2} \; if \; d_2 \leq x \leq d_3 \\ 0 \; if \; elsewhere \end{cases} \tag{8}$$

$$I_T(x) = \begin{cases} \dfrac{(x - d_1)Y_N + (d_2 - x)}{d_2 - d_1} \; if \; d_1 \leq x \leq d_2 \\ Y_N \; if \; x = d_2 \\ \dfrac{(d_3 - x)Y_N + (x - d_2)}{d_3 - d_2} \; if \; d_2 \leq x \leq d_3 \\ 0 \; if \; elsewhere \end{cases} \tag{9}$$

$$F_T(x) = \begin{cases} \dfrac{(x - d_1)Z_N + (d_2 - x)}{d_2 - d_1} \; if \; d_1 \leq x \leq d_2 \\ Z_N \; if \; x = d_2 \\ \dfrac{(d_3 - x)Z_N + (x - d_2)}{d_3 - d_2} \; if \; d_2 \leq x \leq d_3 \\ 0 \; if \; elsewhere \end{cases} \tag{10}$$

with the condition: $0 \leq T_T(x) + I_T(x) + F_T(x) \leq 3; \forall x \in \mathbb{R}$ (Wang et al., 2023).

De-neutrosophication

De-neutrosophication consists of reducing a composite neutrosophic number to a single scalar value. This is essential due to the lack of a classical ordering relationship among neutrosophic values.

For a triangular neutrosophic number (TNN), various de-neutrosophication algorithms can be applied to extract distinct characteristic values. The method proposed here, called the Area of

Withdrawal (AW) method (or Area of Removal/Retirement), calculates this single value by combining geometric parameters (distances) and the Truth, Indeterminacy, and Falsity components according to the given formula (11), thus ensuring a faithful and usable synthesis of the neutrosophic number (Chakraborty et al., 2018).

$$D(\tilde{T}) = \left[\frac{d_1 + 2d_2 + d_3}{5}\right](3X_N - Y_N - 2Z_N) \quad (11)$$

The CODAS method for decision support

The CODAS method (COmbinative Distance-based ASsessment), developed by Ghorabaee (2016), is designed to evaluate and rank alternatives according to multiple conflicting criteria by combining Euclidean and Taxicab (Manhattan) distances from a negative ideal solution (NIS), thereby ensuring a robust and accurate ranking. Since its introduction, CODAS and its fuzzy extensions have been applied across various domains: Mishra (2021) used intuitionistic fuzzy CODAS to rank low-carbon suppliers in the maritime sector; and Ashofteh (2023) integrated CODAS with SWARA to optimize reservoir management using performance indicators. Thus, CODAS has established itself as a flexible and reliable multi-criteria approach, suitable for complex decision-making contexts such as human resource management, energy sustainability, and hydrology.

The different steps of this method can be summarized as follows (Ghorabaee et al., 2016):

- Define the decision matrix $X = (x_{ij})_{m\times n}$, where a set of alternatives $a_1, a_2, \ldots, a_m$is evaluated according to criteria $c_1, c_2, \ldots, c_n$.
- Normalize the matrix *X* to obtain the normalized matrix $R = (r_{ij})_{m\times n}$

$$r_{ij} = \begin{cases} \frac{x_{ij}}{\max\limits_i x_{ij}}, & if j \in N_b \\ \frac{\min\limits_i x_{ij}}{x_{ij}}, & if j \in N_c \end{cases} \quad (12)$$

where N_b and N_c denote the sets of benefit and cost criteria, respectively.

- Calculate the weighted normalized matrix $V = (v_{ij})_{n\times m}$,

$$v_{ij} = \pi_j \times r_{ij} \quad (13)$$

where $\pi_j$represents the weight assigned to criterion $c_j$by the decision makers, such that $\sum_{j=1}^{n} \pi_j = 1$.

- Determine the negative-ideal solution $NS = \{NS_1, NS_2, \ldots, NS_m\}$:

$$NS_j = min_{1\le i\le n}\{v_{ij}\} \quad (14)$$

- Calculate the Euclidean (E_i) and Taxicab (Manhattan) (T_i) distances of each alternative from the negative-ideal solution:

$$E_i = \sqrt{\sum_{j=1}^{n}(v_{ij} - NS_j)^2} \quad (15), \qquad T_i = \sum_{j=1}^{n} | v_{ij} - NS_j | \quad (16)$$

- Compute the assessment score H_i for each alternative:

$$H_i = \sum_{k=1}^{n}[(E_i - E_k) + (\psi(E_i - E_k) \times T_i)] \quad (17)$$

where $\psi(E_i - E_k)$ is an indicator function defined as:

$$\psi(E_i - E_k) = \{1, if \ | E_i - E_k | \geq \tau \ 0, otherwise \quad (18)$$

where τ is a threshold parameter (typically $\tau = 0.02$).

- Alternatives are ranked in descending order of their H_i values, with the highest CODAS score indicating the best option.

Physicochemical characteristics of mineral water and spring water in Algeria

Tables 1 and 2 present the physicochemical properties of the waters considered. These characteristics, obtained through the labelling of different products, are in agreement with the results of analyses performed in officially accredited laboratories (Khelifa et al., 2024).

Table 1 - Physicochemical characteristics of natural waters in Algeria

Water	Ca^{2+} mg/l	Mg^{2+} mg/l	Na^{+} mg/l	K^{+} mg/l	Cl^{-} mg/l	SO_4^{-2} mg/l	HCO_3^{-} mg/l	NO_3^{-} mg/l	NO_2^{-} mg/l	Dry residue at 180°C
Saïda	68	50	58	2	81	65	376	15	0	478
Messerghine	52	42	45	3	78	50	260	5	0	320
Sfid	74	35	28	2	68	91	268	27	0	650
Mouzaïa	136	75	145	3	150	120	60	20	0.02	1280
Ifri	99	24	15.8	2.1	72	68	265	15	<0.02	380
Guedila	78	37	29	2	40	95	/	4.5	<0.01	564
Toudja	56.6	15.2	36	0.7	54.6	19.6	/	2.55	<0.02	256
Mansourah	85	37	30	1	48	53	362	12	0	660
Lalla khedidja	53	7	5.5	0.54	11	7	160	0.42	0	187
Batna	59	45	15	2	22	40	378.2	0	0	650
Texanna	30	9.1	11	1	28.4	11	60	0	0	152
Thevest	89.95	34	47.25	0.99	65	188	231.8	2.35	0.01	
El Goléa	35	16	36	5	21	32	118	2.4		180
N'Gaous	143	65.4	63.4	3.76	75	44.4		2.07	0	962
Youkous	77.4	14.5	13.4	4.65	25.7	35.8	218	2	0	231
Sidi Okba	143	65.4	63.4	3.76	75	445	213	2.07	0	425
Sidi Idris	38.87	3.16	7.14	0.72	16.97	10	127.95	0.15	0.02	202
Milok	62.6	5.5	5.7	3.7	13	72	118.95	16.36		180
Daouia	31.9	19.9	75	0.7	40.4	18.3	288	0.4		325
Alma	91	37	31	2	55	87	350	15	0.01	682

Table 2 - Physicochemical characteristics of spring waters in Algeria

Water	Ca^{2+} mg/l	Mg^{2+} mg/l	Na^{+} mg/l	K^{+} mg/l	Cl^{-} mg/l	SO_4^{2-} mg/l	HCO_3^{-} mg/l	NO_3^{-} mg/l	NO_2^{-} mg/l	Dry residue at 180°C
Besbassa	54.16	2.64	5	2	10	4	164.7	9	0.01	206
Messad	79	27	50	2	40	156	275	23	0.01	611
Tazliza	48	20	48	8	76	96	104	19.97	0.01	407
Ain Bouglez	4.6	3.75	29	1	30	10	48.8	9	0.06	140
Sidi rached	134.38	6.69	29.21	2.45	50	139	235	21.8	0	610
Taya	42.75	12.48	55	1	110	82		17.37	0.01	400
Star	115	33	30	1.8	82	95	330	37.2	<0.02	490
Ayris	65.6	6.8	28.5	1.9	37	75	234.24	2.7	0.01	276
Qniaa	111.66	26.97	48.22	2.48	92.12	66.66	259.02	12.39	0.01	602
Guerioune	72	27	11	2	21	11	336	20.2	<0.01	475
Ovitale	91	14	30	1	50	86	214	14	0	420
Ichemoul	101	2	10	0.6	10	54	262	13	<0.01	344
Arwa	120	23	56	1	100	104	256	46.5	<0.01	450
Soumam	114	32	71	2	78	196	293	19.2	0.01	755
Hirouche	107.4	18.2	22.2	1.6	62.2	54	262.8	32.8	<0.01	550.8
Ifren	68.8	10.69	32	2.4	17.04	62.5	283.04	3.22	<0.01	300
Ariaf	102.4	29.16	88.8	1.4	196.32	175.43	200.08	5.31	<0.01	732
Mont Djurjura	103	28	54	1	97	56	357	30	<0.01	700
Fezguia	35.23	13.44	31	1	30	28	305	19	0	412
Ouwis	106	25	60	2	48.59	117	261	18.3	0	724
Nestle	55	17	> 12	0.5	15	33	210	4.6	< 0.01	372

Results and discussion

Water quality indicators

Although all bottled waters comply with health standards and are therefore safe to drink, their quality assessment was based on taste preference, the ability to be consumed regularly without discomfort, and their potability in a broad sense, including long-term health implications.

For this purpose, the expert group identified four essential criteria:

❖ Nitrate content (C_1) is an essential criterion due to the health risks posed by high concentrations, especially for infants and pregnant women. Even if the samples meet the standards, a lower content remains preferable for safe and sustainable daily consumption (Jensen et al., 2023; Bryan et al., 1973).

❖ Hardness (C_2), which reflects the concentration of calcium and magnesium salts influencing the taste of water (Rosen and Booth, 1971), is measured in mg/L of CaCO3, a unit equivalent to French degrees (°f), where 1°f corresponds to 10 mg/L of CaCO3. This parameter directly affects the taste and digestibility of water: excessive hardness can impart a chalky taste and a "heavy" water sensation, while moderate hardness is

generally perceived as more pleasant and better assimilated by the body (Bryan et al., 1973; Galan et al., 2002).

❖ Water mineralization (C_3), essential for a balanced mineral intake and daily nutritional needs, influences long-term health depending on its excess or deficiency; it is generally classified according to the total dissolved solids concentration (in mg/L): low mineralization with a dry residue at 180°C below 50 mg/L, weak mineralization between 50 and 500 mg/L, moderate mineralization between 500 and 1500 mg/L, and high mineralization above 1500 mg/L (Kamalapriya et al., 2023).

❖ The hydrochemical nature (C_4) is a key indicator of the geological origin of the water. Its analysis reveals the underground path, the rocks encountered, and can highlight specific characteristics or risks related to its stability over time (Patel et al., 2023).

Establishing criteria weights

A weighting system, established by consensus among four experts, was used to prioritize the major health and organoleptic issues. The DIBR II method was applied to assess the importance of each criterion, whose relationships are presented in the following table.

Table 3 - Importance relationships defined by the experts

	Importance relationship of the criteria			
Experts	r_{12}	r_{23}	r_{34}	r_{45}
E 1	1.33	1.50	2.00	4.00
E 2	2.00	0.67	3.00	4.00
E 3	1.40	1.43	2.00	4.00
E 4	1.33	3.00	0.5	2.00

Equations (1) to (4) were used to calculate the weights of the criteria for each expert, as presented in Table 4.

Table 4 - Criteria weights according to each expert

	Criteria weights				
Experts	w_1	w_2	w_3	w_4	D_n
E 1	0.399	0.300	0.200	0.100	0
E 2	0.401	0.200	0.299	0.100	0
E 3	0.406	0.101	0.290	0.203	0
E 4	0.399	0.300	0.100	0.200	0

All deviations D_n are less than 0.1, therefore the evaluations are consistent.

Aggregation of expert opinions using the Bonferroni operator

In this study, the Bonferroni $BM^{p,q}$ operator (Zhou et al., 2019) was applied to aggregate experts' opinions and determine the criteria weights under the DIBR II method, as defined by:

$$BM^{p,q}(x_1, x_2, ..., x_m) = \left[\frac{1}{m(m-1)} \sum_{\substack{i,j=1 \\ i \neq j}}^{m} (w_i^e)^p (w_j^u)^q \right]^{\frac{1}{p+q}} \quad (19)$$

Here, m denotes the number of experts, p,q ≥ 0 are the stabilization parameters, and e and u respectively represent the e-th and u-th experts, with 1≤e,u ≤ m.

The aggregation of opinions, performed using equation (19) with m = 4 and p= q = 1, yielded the final criteria weights presented in Figure 2.

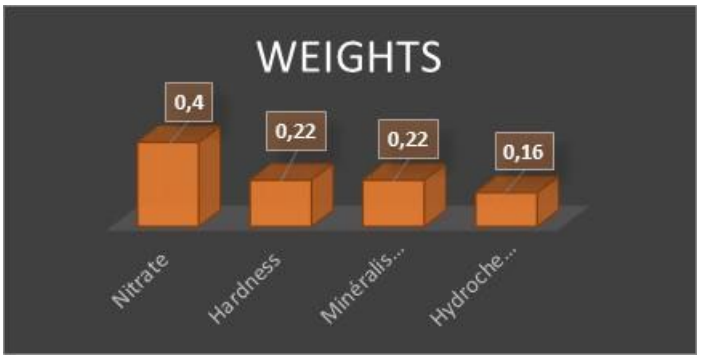

Figure 2 - Weights associated with the criteria

The final (de-neutrosophic) decision matrix

The final (de-neutrosophic) decision matrix is obtained by consolidating the m criteria evaluations for n alternatives, initially expressed by decision-makers in the form of triangular neutrosophic numbers (TNN).

To do this, the following procedure was followed:

Construction of individual neutrosophic decision matrices

Each decision-maker α ($\alpha = 1, \ldots, k$) develops a decision matrix

$$\tilde{D}_\alpha = \left[(\tilde{B}_{ij})_\alpha \right]_{n \times m} \quad \text{with}$$

$$(\tilde{B}_{ij})_\alpha = \left((d_1)_{ij}^\alpha, (d_2)_{ij}^\alpha, (d_3)_{ij}^\alpha, (X_N)_{ij}^\alpha, (Y_N)_{ij}^\alpha, (Z_N)_{ij}^\alpha \right) \quad (20)$$

where the element $\left(\tilde{B}_{ij}\right)_{\alpha}$ represents the evaluation of alternative i with respect to criterion j by decision-maker α.

Tables 5 and 6 illustrate these evaluations for mineral and spring waters, based on the criteria of hardness, mineralization, nitrate content, and hydrochemical nature, as provided by two experts.

Table 5 - Neutrosophic decision matrix (NNT) of mineral waters

	EXPERT 01												EXPERT 02											
Water	C1			C2			C3			C4			C1			C2			C3			C4		
Saida	1	1	2	1	1	2	3	4	5	5	6	7	1	1	1	1	2	3	3	5	6	7	8	10
Messerghine	5	6	7	1	2	5	7	9	9	5	6	7	5	7	7	1	2	4	7	9	10	7	8	10
SFID	1	1	1	1	1	3	6	7	9	5	6	7	1	1	1	1	2	5	6	7	8	6	6	8
Mouzaia	1	1	1	1	1	1	4	4	5	2	3	4	1	1	1	1	1	1	4	4	4	2	4	5
Ifri	1	1	1	1	1	4	7	8	9	5	6	7	1	1	2	1	2	3	7	9	9	6	6	8
Guedila	6	6	7	1	2	3	2	3	3	3	3	3	6	7	7	1	2	2	3	3	3	2	3	3
Toudja	7	7	8	3	3	5	1	1	2	2	3	4	7	8	8	5	6	8	1	1	2	2	4	5
Mansourah	2	3	3	1	1	2	5	6	7	5	6	8	3	3	3	1	1	4	6	7	8	5	6	8
Lala khedidja	8	9	9	4	6	7	1	2	2	5	6	7	8	9	9	4	6	8	2	2	1	6	6	8
Batna	9	9	10	1	1	2	8	8	8	5	6	7	8	9	10	2	2	5	8	8	9	7	8	10
Texanna	8	9	9	7	8	8	1	1	1	5	6	7	8	9	10	7	7	8	1	1	1	6	6	8
Thevest	7	7	9	1	2	2	5	6	7	3	3	3	7	8	9	2	2	2	6	6	7	2	3	3
El Goléa	7	7	8	5	6	7	2	2	3	5	6	8	7	8	9	6	7	8	2	2	2	7	6	8
N'Gaous	7	7	8	1	1	1	5	6	7	2	3	4	7	8	9	1	1	1	4	6	6	2	4	5
Youkous	7	7	8	3	3	7	5	5	6	5	6	7	8	9	9	2	3	7	5	6	6	6	6	8
Sidi Okba	7	7	8	1	1	1	4	4	5	3	3	3	7	8	9	1	1	1	4	5	5	2	3	3
Sidi Idris	8	8	10	7	7	8	1	2	2	5	6	7	9	9	10	7	8	9	1	1	2	6	6	8
Milok	1	1	1	3	4	7	2	3	4	4	5	6	1	1	2	5	7	9	2	3	3	4	7	9
Daouia	7	9	10	5	6	7	6	7	8	4	4	6	8	9	10	7	7	7	7	8	9	3	5	5
Alma	1	1	1	1	1	2	5	6	7	5	6	8	1	1	2	2	2	3	6	6	7	6	6	8

Table 6 - Neutrosophic decision matrix (NNT) of spring waters

	EXPERT 01												EXPERT 02											
Water	C1			C2			C3			C4			C1			C2			C3			C4		
Besbassa	3	1	2	5	6	7	1	1	3	5	6	7	3	4	5	6	7	8	1	2	3	5	7	7
Messad	1	1	1	1	2	5	5	6	7	5	6	7	1	1	1	1	2	4	6	7	7	5	7	7
Tazliza	1	1	1	4	4	5	4	5	8	2	3	7	1	1	2	5	6	6	7	8	9	2	3	5
Ain bouglez	4	4	5	8	9	9	1	1	1	1	1	2	3	4	5	9	9	9	1	1	1	1	1	4
Sidi rached	1	1	1	1	2	2	5	6	7	5	6	7	1	1	1	1	2	2	8	9	9	5	7	7
Taya	1	1	1	5	6	8	2	3	5	1	1	2	1	1	2	5	6	7	4	5	5	1	1	4
Star	1	1	1	1	1	3	3	5	5	6	7	1	1	1	1	1	2	1	5	6	8	5	7	7
Ayris	6	7	9	3	4	5	6	7	5	5	6	7	6	7	8	5	6	8	5	9	8	5	7	7
Qniaa	2	3	3	1	1	3	5	6	7	5	6	7	3	3	3	1	1	2	6	7	8	5	7	7
Guerioune	1	1	1	2	2	2	7	8	8	5	6	7	1	1	1	2	2	6	7	8	9	5	7	7
Ovitale	1	1	2	2	2	2	7	7	8	5	6	7	2	2	5	2	3	5	7	8	9	5	7	7
Ichemoul	1	2	5	2	3	4	6	7	9	5	6	7	1	2	4	2	3	6	6	7	8	5	7	7
Arwa	1	1	1	1	1	3	3	3	4	5	6	7	1	1	1	1	1	2	5	6	8	5	7	7
Soumam	1	1	1	1	1	1	3	4	5	5	6	7	1	1	2	1	1	2	3	5	6	5	7	7
Hirouche	1	1	1	1	1	4	7	8	9	5	6	7	1	1	1	1	2	4	7	9	10	5	7	7
Ifren	6	7	9	2	3	5	7	7	8	5	6	7	6	7	8	5	6	8	7	8	9	5	7	7
Ariaf	5	6	7	1	2	2	3	5	6	2	3	7	6	6	7	1	2	2	3	4	5	2	3	5
Mont djurdjura	1	1	1	1	2	2	3	3	5	5	6	7	1	1	1	1	2	2	5	6	8	5	7	7
Fezguia	1	1	2	3	6	8	6	7	9	5	6	7	1	1	1	6	9	9	7	7	8	5	7	7
Ouwis	1	1	2	1	2	2	6	6	7	5	6	7	1	1	1	2	2	2	6	7	7	5	7	7
Nestlé	6	6	7	3	3	5	3	4	6	5	6	7	6	7	7	5	6	8	2	3	7	5	7	7

Aggregation of decision matrices

The individual matrices are combined into a single aggregated global matrix (Lan et al., 2023):

$$\tilde{D} = \left[(\tilde{B}_{ij}) \right]_{n \times m}$$

Where $\tilde{B}_{ij} = \left((d_1)_{ij}, (d_2)_{ij}, (d_3)_{ij}, (X_N)_{ij}, (Y_N)_{ij}, (Z_N)_{ij} \right)$ (21)

And

$$\begin{cases} (d_1)_{ij} = \min_{\alpha} (d_1)_{ij}^{\alpha} \\ (d_2)_{ij} = \sqrt[k]{\prod_{\alpha=1}^{k} (d_2)_{ij}^{\alpha}} \\ (d_3)_{ij} = \max_{\alpha} (d_3)_{ij}^{\alpha} \\ (X_N)_{ij} = \min_{\alpha} (X_N)_{ij}^{\alpha} \\ (Y_N)_{ij} = \max_{\alpha} (Y_N)_{ij}^{\alpha} \\ (Z_N)_{ij} = \max_{\alpha} (Z_N)_{ij}^{\alpha} \end{cases} \quad (22)$$

The Tables 7 and 8 present the result of this step for the two water sets (mineral and spring), with

$$(X_N)_{ij}^{\alpha} = 0.60; (Y_N)_{ij}^{\alpha} = 0.15 \text{ and } (Z_N)_{ij}^{\alpha} = 0.20$$

Table 7 - The aggregated matrix for mineral waters

	Nitrate			Hardness			Mineralization			Hydro-Chemical Nature		
Saida	1	1.000	2	1	1.41	3	3	4.472	6	5	6.928	10
Messerghine	5	6.481	7	1	2.00	5	7	9.000	10	5	6.928	10
Sfid	1	1.000	1	1	1.41	5	6	7.000	9	5	6.000	8
Mouzaia	1	1.000	1	1	1.00	1	4	4.000	5	2	3.464	5
Ifri	1	1.000	2	1	1.41	4	7	8.485	9	5	6.000	8
Guedila	6	6.481	7	1	2.00	3	2	3.000	3	2	3.000	3
Toudja	7	7.483	8	3	4.24	8	1	1.000	2	2	3.464	5
Mansourah	2	3.000	3	1	1.00	4	5	6.481	8	5	6.000	8
Lala khedidja	8	9.000	9	4	6.00	8	1	2.000	2	5	6.000	8
Batna	8	9.000	10	1	1.41	5	8	8.000	9	5	6.928	10
Texanna	8	9.000	10	7	7.48	8	1	1.000	1	5	6.000	8
Thevest	7	7.483	9	1	2.00	2	5	6.000	7	2	3.000	3
El Goléa	7	7.483	9	5	6.48	8	2	2.000	3	5	6.000	8
N'Gaous	7	7.483	9	1	1.00	1	4	6.000	7	2	3.464	5
Youkous	7	7.937	9	2	3.00	7	5	5.477	6	5	6.000	8
Sidi Okba	7	7.483	9	1	1.00	1	4	4.472	5	2	3.000	3
Sidi Idris	8	8.485	10	7	7.48	9	1	1.414	2	5	6.000	8
Milok	1	1.000	2	3	5.29	9	2	3.000	4	4	5.916	9
Daouia	7	9.000	10	5	6.48	7	6	7.483	9	3	4.472	6
Alma	1	1.000	2	1	1.41	3	5	6.000	7	5	6.000	8

Table 8 - The aggregated matrix for spring waters

Water	Nitrate			Hardness			Mineralization			Hydro-Chemical Nature		
Besbassa	3	4	5	5	6.481	8	1	1.414	3	5	6.481	7
Messad	1	1	1	1	2.000	5	5	6.481	7	5	6.481	7
Tazliza	1	1	2	4	4.899	6	4	6.325	9	2	3.000	7

Table 8 –(continued)

Water	Nitrate			Hardness			Mineralization			Hydro-Chemical Nature		
Ain bouglez	3	4	5	8	9.000	9	1	1.000	1	1	1.000	4
Sidi rached	1	1	1	1	2.000	2	5	7.348	9	5	6.481	7
Taya	1	1	2	5	6.000	8	2	3.873	5	1	1.000	4
Star	1	1	1	1	1.414	1	3	4.243	8	5	6.481	7
Ayris	6	7	9	3	4.899	8	5	7.937	8	5	6.481	7
Qniaa	2	3	3	1	1.000	3	5	6.481	8	5	6.481	7
Guerioune	1	1	1	2	2.000	6	7	8.000	9	5	6.481	7
Ovitale	1	1.414	5	2	2.449	5	7	7.483	9	5	6.481	7
Ichemoul	1	2	5	2	3.000	6	6	7.000	9	5	6.481	7
Arwa	1	1	1	1	1.000	3	3	4.243	8	5	6.481	7
Soumam	1	1	2	1	1.000	2	3	4.472	6	5	6.481	7
Hirouche	1	1	1	1	1.414	4	7	8.485	10	5	6.481	7
Ifren	6	7	9	2	4.243	8	7	7.483	9	5	6.481	7
Ariaf	5	6	7	1	2.000	2	3	4.472	6	2	3.000	7
Mont djurdjura	1	1	1	1	2.000	2	3	4.243	8	5	6.481	7
Fezguia	1	1	2	3	7.348	9	6	7.000	9	5	6.481	7
Ouwis	1	1	2	1	2.000	2	6	6.481	7	5	6.481	7
Nestlé	6	6.481	7	3	4.243	8	2	3.464	7	5	6.481	7

De-neutrosophication of the aggregated matrix

The final step consists of converting the aggregated NNT matrix into a final decision matrix $\widetilde{D}$ with unique scalar values, obtained by formula (11). Table 9 presents the consolidated and precise values resulting from this step, constituting the final decision matrix.

Table 9 - De-neutrosophic valued decision matrix for mineral and spring water

Mineral water	C1	C2	C3	C4	Spring water	C1	C2	C3	C4
Saida	1.400	1.912	5.024	8.080	Besbassa	4.480	7.269	1.912	6.989
Messerghine	6.989	2.800	9.800	8.080	Messad	1.120	2.800	6.989	6.989
SFID	1.120	2.472	8.120	7.000	Tazliza	1.400	5.543	7.182	4.200
Mouzaia	1.120	1.120	4.760	3.900	Ain bouglez	4.480	9.800	1.120	1.960
Ifri	1.400	2.192	9.232	7.000	Sidi rached	1.120	1.960	8.035	6.989
Guedila	7.269	2.240	3.080	3.080	Taya	1.400	7.000	4.129	1.960
Toudja	8.391	5.456	1.400	3.900	Star	1.120	1.352	5.456	6.989
Mansourah	3.080	1.960	7.269	7.000	Ayris	8.120	5.823	8.085	6.989
Lala khedidja	9.800	6.720	1.960	7.000	Qniaa	3.080	1.680	7.269	6.989
Batna	10.080	2.472	9.240	8.080	Guerioune	1.120	3.360	8.960	6.989
Texanna	10.080	8.391	1.120	7.000	Ovitale	2.472	3.332	8.671	6.989
Thevest	8.671	1.960	6.720	3.080	Ichemoul	2.800	3.920	8.120	6.989
El Goléa	8.671	7.269	2.520	7.000	Arwa	1.120	1.680	5.456	6.989
N'Gaous	8.671	1.120	6.440	3.900	Soumam	1.400	1.400	5.024	6.989
Youkous	8.925	4.200	6.147	7.000	Hirouche	1.120	2.192	9.512	6.989
Sidi Okba	8.671	1.120	5.024	3.080	Ifren	8.120	5.176	8.671	6.989
Sidi Idris	9.792	8.671	1.632	7.000	Ariaf	6.720	1.960	5.024	4.200
Milok	1.400	6.323	3.360	6.953	Mont Djurdjura	1.120	1.960	5.456	6.989

Table 9 –(continued)

Mineral water	C1	C2	C3	C4	Spring water	C1	C2	C3	C4
Daouia	9.800	6.989	8.391	5.024	Fezguia	1.400	7.475	8.120	6.989
Alma	1.400	1.912	6.720	7.000	Ouwis	1.400	1.960	7.269	6.989
					Nestlé	7.269	5.456	4.460	6.989

Water classification

Based on the weights shown in Figure 2 and the scores from the final decision matrix (Table 9), the CODAS method is applied to classify mineral waters and spring waters. The results obtained are presented in the table below.

Table 10 - Ranking of mineral and spring waters based on the CODAS method

Mineral waters				Spring waters			
Water	Rank	Water	Rank	Water	Rank	Water	Rank
Daouia	1	Messerghine	11	Taya	1	Qniaa	11
Mansourah	2	Lala khedidja	12	Ariaf	2	Ayris	12
Youkous	3	Guedila	13	Arwa	3	Fezguia	13
Alma	4	Batna	14	Sidi rached	4	Nestlé	14
N'Gaous	5	Toudja	15	Hirouche	5	Ovitale	15
El Goléa	6	Thevest	16	Soumam	6	Messad	16
Texanna	7	SFID	17	Ouwis	7	Ain bouglez	17
Sidi Idris	8	Sidi Okba	18	Besbassa	8	Mont Djurdjura	18
Ifri	9	Saida	19	Guerioune	9	Star	19
Mouzaia	10	Milok	20	Ichemoul	10	Ifren	20
						Tazliza	21

Sensitivity analysis

A sensitivity analysis was carried out to evaluate the robustness of the CODAS ranking results under variations in the criteria weights. Three alternative weighting scenarios (Case 1, Case 2, and Case 3) were compared with the main model to examine the impact of these changes on the final ranking of alternatives (Table12).

Table 11 - Criteria weights for the different scenarios of the sensitivity analysis

Scenario	W1(%)	W2(%)	W3(%)	W4(%)	Key observations on weighting
Main Model	40	22	22	16	W1 is the dominant criterion. W2 and W3 have the same weight.
Case 1	35	23.67	23.67	17.66	Decrease in W1, slight increase in the other criteria.
Case 2	41.7	23.65	23.65	11	Increase in W1, strong reduction in W4. W2 and W3 increase slightly.
Case 3	45.34	27.33	27.33	0	W1, W2, and W3 are strongly increased, W4 is completely eliminated (zero weight).

As shown in Table 11, each scenario applies a different distribution of weights among the four criteria.

Table 12 - Comparison of mineral water rankings obtained using the main model and different weighting scenarios

Mineral water	Main Model	Case 01	Case 02	Case 03
Daouia	1	1	1	1
Mansourah	2	15	2	2
Youkous	3	3	3	3
Alma	4	4	4	4
N'Gaous	5	6	5	5
El Goléa	6	5	6	6
Texanna	7	7	7	7
Sidi Idris	8	8	8	8
Ifri	9	9	9	9
Mouzaia	10	10	10	10
Messerghine	11	17	11	11
Lala khedidja	12	12	12	12
Guedila	13	13	13	13
Batna	14	14	14	14
Toudja	15	2	15	15
Thevest	16	16	16	16
Sfid	17	11	17	17
Sidi Okba	18	18	18	18
Saida	19	19	19	19
Milok	20	20	20	20

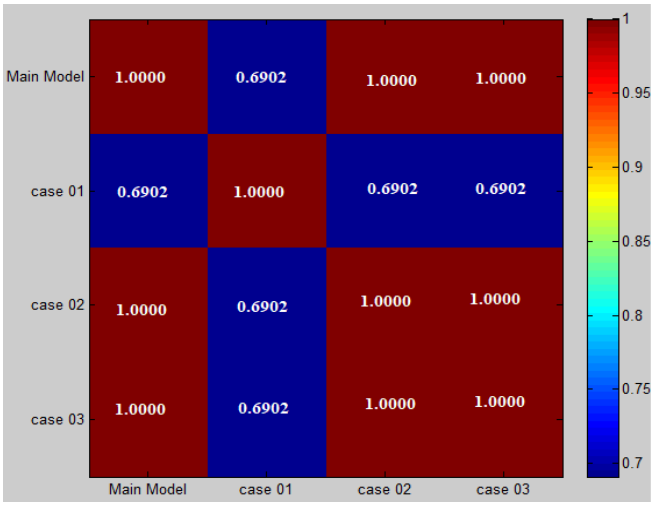

Figure 3 - Correlation matrix between the main model and different weighting scenarios

The correlation matrix in Figure 3 illustrates the level of agreement between the main model and the tested scenarios. Correlation values close to 1 indicate a strong consistency, confirming that the CODAS method provides stable and reliable results despite variations in weighting.

Comparative analysis

The comparative analysis in Table 13 demonstrates the consistency of rankings produced by the CODAS method relative to other multi-criteria decision-making (MCDM) approaches, including WASPAS, VIKOR, COPRAS, SAW, and MOORA. CODAS generally yields a coherent ranking pattern, particularly for top-performing brands such as Daouia, Alma, Youkous, and El Goléa. Some variation is observed for mid-ranked alternatives (Ifri, Mansourah, Toudja, and Mouzaïa), reflecting differences in criteria weighting and distance computation.

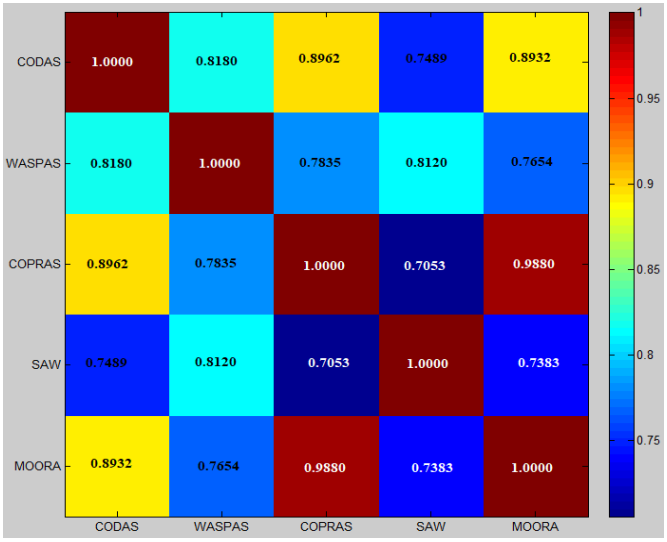

Figure 4 - Spearman correlation coefficient matrix for MCDM methods

The Spearman correlation matrix (Figure 4) indicates a strong positive correlation between CODAS and other MCDM methods, confirming the method's reliability and robustness. By effectively combining Euclidean and Taxicab distances, CODAS provides a discriminative ranking that clearly distinguishes closely ranked alternatives.

Table 13 - Comparison of CODAS with other MCDM methods

Mineral Water	CODAS	WASPAS	COPRAS	SAW	MOORA	Mineral Water	CODAS	WASPAS	COPRAS	SAW	MOORA
Daouia	1	1	1	1	1	Messerghine	11	10	10	10	10
Mansourah	2	11	2	13	2	Lala khedidja	12	12	12	12	12
Youkous	3	5	5	5	5	Guedila	13	9	13	15	15
Alma	4	4	4	4	4	Batna	14	14	7	14	7
N'Gaous	5	8	8	8	6	Toudja	15	13	15	2	13
El Goléa	6	6	6	6	8	Thevest	16	16	16	16	16
Texanna	7	7	14	7	14	SFID	17	15	17	17	17
Sidi Idris	8	3	3	3	3	Sidi Okba	18	18	18	18	18
Ifri	9	2	9	9	9	Saida	19	19	19	19	19
Mouzaia	10	17	11	11	11	Milok	20	20	20	20	20

Conclusion and perspectives

This study presents a hybrid DIBR II–CODAS approach integrating triangular neutrosophic numbers to classify bottled waters in Algeria. Water quality criteria - nitrate content, hardness, mineralization, and hydrochemical characteristics - were weighted based on expert opinions using the Bonferroni operator, and CODAS was applied to the de-neutrosophicated decision matrix to obtain proximity coefficients and final rankings. The top mineral waters were Daouia, Mansourah, Youkous, Alma, and N'Gaous, while the top spring waters were Taya, Ariaf, Arwa, Sidi Rached, and Hirouche.

Sensitivity analysis confirmed the model's robustness, with minor ranking changes, the nitrate criterion being the most influential. High correlation with other multi-criteria methods and the combination of Euclidean and Taxicab distances demonstrate that CODAS provides reliable and discriminative rankings.

This model provides a reliable decision-support tool for hydrochemical classification of bottled waters in Algeria. Additionally, this research creates new avenues for further studies, such as expanding the water sample size, incorporating additional criteria (like trace elements and stable isotopes), and monitoring water quality evolution over time. Ultimately, it forms a scientific basis for recommendations targeting industry stakeholders, regulatory bodies, and consumers aimed at sustainable and transparent water management.

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Višekriterijumska analiza primenjena na hidrohemijsku klasifikaciju flaširanih voda na tržištu u Alžiru

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OBLAST: nauka o odlučivanju, hidrologija
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Mineralne i izvorske vode imaju ključnu ulogu u svakodnevnoj ishrani zbog svog ukusa i zdravstvenih benefita. Tržište flaširane vode u Alžiru brzo raste, ali i dalje ne postoji dovoljno preciznih i objektivnih sistema za klasifikaciju voda na osnovu organoleptičkih svojstava i bezbednosti. Cilj ove studije je da razvije pouzdan numerički model za hidrohemijsku klasifikaciju flaširanih voda na tržištu u Alžiru.

Metode: U radu se koristi hibridni pristup višekriterijumskog odlučivanja koji integriše metodu DIBR II za određivanje težina kriterijuma na osnovu mišljenja eksperata i Bonferonijevu sredinu za agregaciju tih mišljenja. Radi efikasnog upravljanja neizvesnošću i nepreciznošću podataka, koriste se trougaoni neutrosofični brojevi (eng. TNN). Nakon toga, primenjuje se metoda CODAS (eng. COmbinative Distance-based ASsessment) za rangiranje brendova flaširane vode. Evaluacija obuhvata četiri ključna kriterijuma kvaliteta: koncentraciju nitrata, tvrdoću, ukupnu mineralizaciju i hidrohemijsku prirodu. Nakon konstruisanja i agregacije neutrosofičnih matrica odlučivanja i sprovođenja deneutrosofikacije, metodom CODAS je izračunat koeficijent blizine za svaki brend, što je dovelo do konačnog rangiranja.

Rezultati: U radu je identifikovano pet najboljih brendova mineralnih voda (Daouia, Mansourah, Youkous, Alma i N'Gaous) i izvorskih voda (Taya, Ariaf, Arwa, Sidi Rached i Hirouche). Analiza osetljivosti potvrdila je robusnost rangiranja, čime je validirana pouzdanost modela, i pokazala je da je sadržaj nitrata najuticajniji kriterijum, naglašavajući njegovu ključnu ulogu u proceni kvaliteta vode. Komparativna analiza je takođe pokazala da metoda CODAS daje konzistentna i pouzdana rangiranja u poređenju sa drugim višekriterijumskim metodama, uz dobru diskriminaciju između blisko rangiranih alternativa.

Zaključak: U studiji je razvijen inovativan i robustan numerički model koji kombinuje metode DIBR II i CODAS u neutrosofičkom okviru i pruža pouzdanu hidrohemijsku klasifikaciju flaširanih mineralnih i izvorskih voda u Alžiru. Model obuhvata težine zasnovane na mišljenju eksperata i uzima u obzir neizvesnost podataka kako bi generisao jasan i dosledan redosled brendova. Analiza osetljivosti potvrdila je stabilnost rangiranja, posebno naglašavajući dominaciju kriterijuma nitrata, čime se potvrđuje vrednost modela kao instrumenta za podršku odlučivanju različitim zainteresovanim stranama u ovom sektoru.

Ključne reči: višekriterijumska klasifikacija, mineralna voda, izvorska voda, DIBR II, CODAS, neutrosofični brojevi.

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Prediction of students' performance based on heterogeneous and ambiguous data

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FIELD: computer sciences
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Abstract:

Introduction/purpose: The presented research describes the application of artificial neural networks for prediction of students' performance based on heterogeneous and ambiguous data.

Methods: The students' data collected during three school years on subject "Object-Oriented Design" at the School of Electrical and Computer Engineering, Academy of Technical and Art Applied Studies in Belgrade represent the basis of the research. The sample size is one hundred fifty-nine students. The initial dataset consists of thirty-six different features from three different sources of collected data. The presented data and results are completely anonymized. The research describes the complexity of data preparation, as well as the processes of modeling, training, testing and evaluation of an artificial neural network, applied for the prediction of students' performance.

Results: The main results of the research are the handling the ambiguity and heterogeneity of data and the design of the prediction model. In addition, the research includes discussions about data preprocessing and machine learning techniques applied on prediction models.

Conclusion: The development methods, prediction models and prediction results, their critical review, the limitations of the research, and the possibilities for improvements represent the main conclusions of the research.

Key words: artificial neural networks, students' performance prediction, Web service architecture, data analysis.

Introduction

The presented research describes the application of artificial neural networks (ANN) for the prediction of students' performance based on heterogeneous and ambiguous data. The students' data collected during three school years on the subject Object-Oriented Design (OOD) at the School of Electrical and Computer Engineering (Academy of Technical and Art Applied Studies in Belgrade) represent the basis of the research. The sample size is one hundred and fifty-nine students. The research includes thirty-six different features from three different sources of collected data.

Contemporary educational management requires fast responses to questions related to students' enrollments and academic progression by year. On the other hand, the data sources necessary for this purpose are often distributed and stored in different formats. For instance, the student service collects historical data from the students' previous education (e.g. annual results, finished schools, etc.) and final examination results. In contrast, intermediate results and information about students' educational activities are commonly stored in e-learning systems and maintained by teachers and assistants. Moreover, data from different sources are processed manually (sometimes separately), which provides unsatisfactory results. It is obvious that improvements are necessary, and the mentioned facts provide the primary motivation for the development of the prediction model presented in the manuscript.

The next section gives a review of research related to the topic, as well as the arguments for the selection of an appropriate machine learning (ML) model for the prediction of students' performance. The third section describes the new method used for designing prediction models. The complex nature of the data requires a combined consideration of data preparation and prediction model design. This iterative process enables improved accuracy of prediction models through modified and redesigned datasets. The fourth section presents the results of the research. For utilizing the model and proving the feasibility of the solution, *Python* Web service was developed. This *early-stage* module enables users to conduct experiments and use the results as support for decision-making. The section also presents the results of applying the proposed model to real and synthesized datasets. Finally, the critical review and the possibilities for improvements are given in the *Conclusion* section.

Literature review

Artificial intelligence (AI) is used in almost all spheres of human life. One of the specific ways of using it is in education. In the last decades, many researchers in this area have tried to incorporate different techniques of AI into existing educational systems (Virtanen et al, 2017; Al-Theeb et al, 2024; Kosareva et al, 2023). More precisely, they have tried to improve e-learning systems to make them adaptive in accordance with the educational needs of individual students (Essa & Human-Hendricks, 2023). Such systems facilitate personalized learning through adaptation of content and navigation based on an actual student profile (Tsai et al, 2019).

In addition, there are e-learning systems designed for learning specific content (Mitrovic, 2016; Johns, 2022). These systems, commonly named Intelligent Tutoring Systems (Wang et al, 2023), significantly increase learning productivity due to AI technologies that enable them to learn about students' needs, interests, motivation, habits and behavior. All these data enrich the student model and provide sufficient information for delivering appropriate learning content.

The student model represents a common component for both general-purpose e-learning systems and intelligent tutoring systems. It has been recognized as a significant part of the intelligent behavior of e-learning system (Woolf, 2010). For that reason, many different standards have been designed for user modelling (Böck, 2024).

Over the last decade, there have been intentions to integrate different systems to collect data about students from different sources and to use the data for obtaining a better student profile and extending the information about their competences (Ocheja et al, 2018; Labba et al, 2020). Moreover, new standards have been developed for this purpose. The most cited ones are xAPI (Manso-Vázquez et al, 2018) and CMI5 (Bakhouyi et al, 2022). The former provides the collection of more detailed information about students' activities during their interactions with e-learning systems. The latter enables the exchange of this information among systems.

There are already developed and well-formed process models for data mining and data preparation for further processing in AI models. One of the frequently mentioned models is CRISP-DM (Dwivedi & Rawat, 2015). It is the d*e facto* industrial standard that proposes a process framework for data mining from any kind of data source. However, in the educational process, there is a variety of information that e-learning systems, as well as teachers, collect about students. Although the standards mentioned above enable automatization of information

exchange, teachers usually use their individual forms and formats for collecting student results and information about their activities and progress during the learning process. For that reason, the data preparation method presented in the research has a more detailed design than proposed by the standards found in the literature.

The selection of models for students' profile classification and results prediction represents another challenge in contemporary educational systems. The questions *How many students would pass from one school year to the next?* and *What are the predictions about students' results?* are commonly asked by the institutional management, who need this information for planning enrollment quotas and selecting the method of scholarship distribution. For a similar purpose, Benkhalfallah & Laouar (2023) propose linear and polynomial regression models, as well as models based on tree algorithms (e.g. random forest, tree ensemble, gradient boosted trees, and simple regression trees), emphasizing the high performance obtained. On the other hand, a review paper by Rastrollo-Guerrero, Gómez-Pulido & Durán-Domínguez (2020) focused on the general use of different machine learning (ML) techniques and algorithms highlights ANN and support vector machine (SVM) models for students' classification and results prediction. Another research that compares different ML models for students' classification (Ahammad et al, 2021) favors the feed-forward multilayer perceptron (hereafter MLP) as the basic ANN classification model compared with Naive Bayes, K-nearest neighbors, SVM and Gradient Boost Tree models. The presented results provide strong support for choosing ANN as a classification model.

Methods

For building reliable prediction models, it is important to consider available data and potential prediction models together. The resulting model should depend on the size, complexity and variance of the data. Further, the complexity of the data depends on the number of data sources as well as the number of features and their mutual correlation. On the other hand, there is a variety of models suitable for prediction purposes. The selection of appropriate models cannot be performed without experimenting with the data collected and prepared for prediction purposes. The method used in the research treats data preparation together with the design of the prediction model (Figure 1). A UML activity model (Ahmad et al, 2019) is used as a template for the design. The data preparation activities (presented in blue) are in accordance with the CRISP-DM process model (Schröer et al, 2021), while the activities of the

prediction model design (presented in yellow) are used to support the development and evaluation of the prediction model.

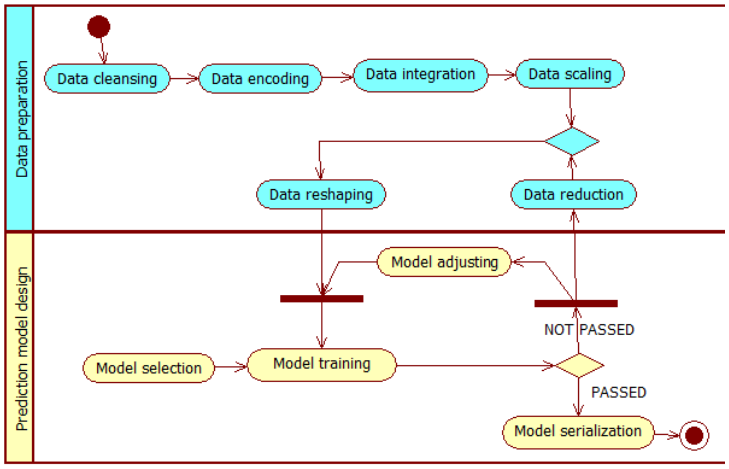
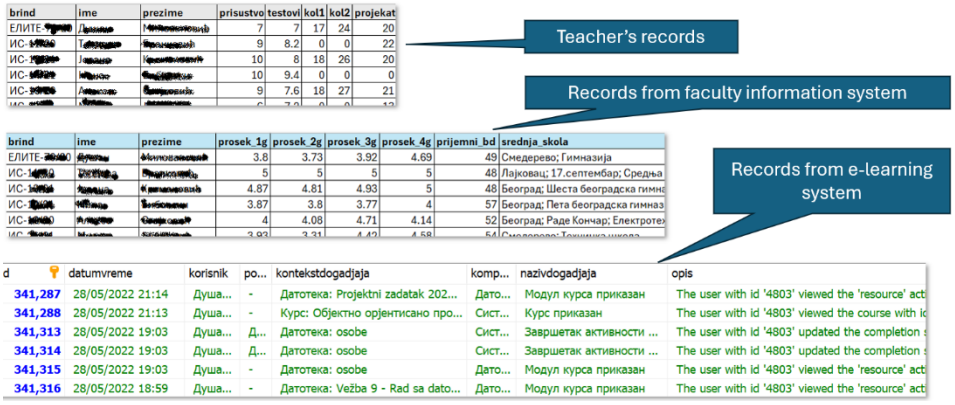


Figure 1 – Method used for data preparation and prediction model design

Data preparation activities

Firstly, the data preparation includes sequential stages: cleansing, encoding, integration and scaling. Data cleansing removes records from datasets that contain unreliable or incomplete data. For instance, the records of students that have paused or discontinued their studies are irrelevant and are therefore excluded from the dataset.



brind	ime	prezime	prisustvo	testovi	kol1	kol2	projekat
ЕЛИТЕ-			7	7	17	24	20
ИС-			9	8.2	0	0	22
ИС-			10	8	18	26	20
ИС-			10	9.4	0	0	0
ИС-			9	7.6	18	27	21

brind	ime	prezime	prosek_1g	prosek_2g	prosek_3g	prosek_4g	prijemni_bd	srednja_skola
ЕЛИТЕ-			3.8	3.73	3.92	4.69	49	Смедерево; Гимназија
ИС-			5	5	5	5	48	Лајковац; 17.септембар; Средња
ИС-			4.87	4.81	4.93	5	48	Београд; Шеста београдска гимна
ИС-			3.87	3.8	3.77	4	57	Београд; Пета београдска гимназ
ИС-			4	4.08	4.71	4.14	52	Београд; Раде Кончар; Електротех

d	datumvreme	korisnik	po...	kontekstdogadjaja	komp...	nazivdogadjaja	opis
341,287	28/05/2022 21:14	Душа...	-	Датотека: Projektni zadatak 202...	Дато...	Модул курса приказан	The user with id '4803' viewed the 'resource' act
341,288	28/05/2022 21:13	Душа...	-	Курс: Објектно оријентисано про...	Сист...	Курс приказан	The user with id '4803' viewed the course with i
341,313	28/05/2022 19:03	Душа...	Д...	Датотека: osobe	Сист...	Завршетак активности ...	The user with id '4803' updated the completion
341,314	28/05/2022 19:03	Душа...	Д...	Датотека: osobe	Сист...	Завршетак активности ...	The user with id '4803' updated the completion
341,315	28/05/2022 19:03	Душа...	-	Датотека: osobe	Дато...	Модул курса приказан	The user with id '4803' viewed the 'resource' act
341,316	28/05/2022 18:59	Душа...	-	Датотека: Vežba 9 - Rad sa dato...	Дато...	Модул курса приказан	The user with id '4803' viewed the 'resource' act

Figure 2 – Samples of students' data from different sources

Data encoding provides a common format for all data. For instance, there are names of students, schools, exam terms' names, as well as

descriptive results originally recorded in text format. The categories for prediction are also in textual format. Therefore, encoding them into numerical format is necessary for further processing. The target categories defined by management (with meanings adapted to the needs of decision-making) are encoded by integers. In this way, the categories (*critical, less_critical, in_the_middle, scholarship_candidate and best_candidate*) are encoded with number values (0,1, 2, 3 and 4).

Data integration provides the fusion of data from different sources. The raw data used in the research consists of thirty-six different features collected from three different sources: teachers' spreadsheets, e-learning platform and faculty information system (Figure 2). The teachers' spreadsheets contain information about students' attendance and results (e.g. from pretests, colloquiums, essays and projects). The data collected from the e-learning platform consists of records with a uniform structure. Each record contains information about the user, activity type, context of the activity, event description, and date and time of the student's interaction with the e-learning system. The information from the faculty information system consists of the name of the secondary school the student finished, the student's results from four years of high school, the entering exam results (before enrollment) and the subject's final exam results.

Table 1 – 36 features collected from three different sources

raw_id	average_HS1	file_downloads
student_id	average_HS2	access_url
first_name	average_HS3	exercise1
surname	average_HS4	exercise2
attendance	entering_exam	exercise3
pretest	high_school_id	exercise4
colloquium1	high_school_name	exercise5
colloquium1	final_exam_term	exercise6
project	course_attendance	exercise7
activity	forum_attendance	exercise8
num_of_final_exam_tries	task_attendance	exercise9
school_year	test_attendance	exercise10

The whole set of the collected features is presented in Table 1. Some features are eliminated as they hold irrelevant information: *row id*, *student id*, *first name, surname* and *URL address*. Other features are mostly

numerical, except for *high school name* and *final exam term* (e.g. *January term* or *June term*). As high schools are represented with an additional identifier (*high school id*), the feature named *high school name* is unnecessary, and it is also eliminated. Further, through (exploratory) analysis, three features with the information redundancy are found – *number of final exams tries* on the one hand, and *school year* and *final exam term* (mentioned above) on the other. The feature *number of final exams* is left in the candidate set, while *school year* and *final exam term* are eliminated.

After elimination of unnecessary features, there are still 28 features left in the candidate set. As the number of features is significantly high for an ANN classifier (and for most other classification models generally), the principal component analysis (PCA) is performed on the remaining feature set. The following diagram shows the distribution of variance among the components (Figure 3). Based on the Kaiser-Guttman rule (Kaiser, 1960) presented by *eigenvalues* (Frost, 2022), the most variance in the dataset is captured by six principal components (*eigenvalues* > 1). The diagram shows the components in descending order to emphasize the recommended number of candidates for further processing.

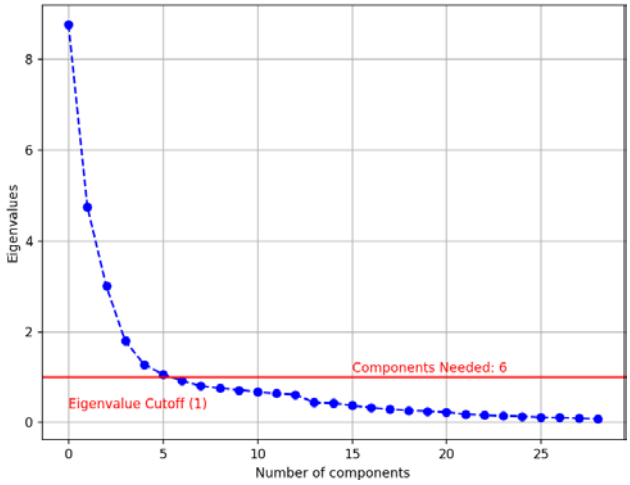


Figure 3 – PCA Eigen-values distribution

On the other hand, the cumulative variance plot (Figure 4) suggests 12 components for building a consistent prediction model in the case of 90% variance threshold. The suggested values should be between 80% and 95%, depending on the domain of use. Empirically, if *N* represents the full number of features, their optimal number for ML tasks (within the

limited dataset) should be between $\sqrt{N}$ and $2\sqrt{N}$ (Yongmin et al, 2025). In the concrete case, if the total number of features is 36, then the optimal number of features included in ML can vary from 6 to 12.

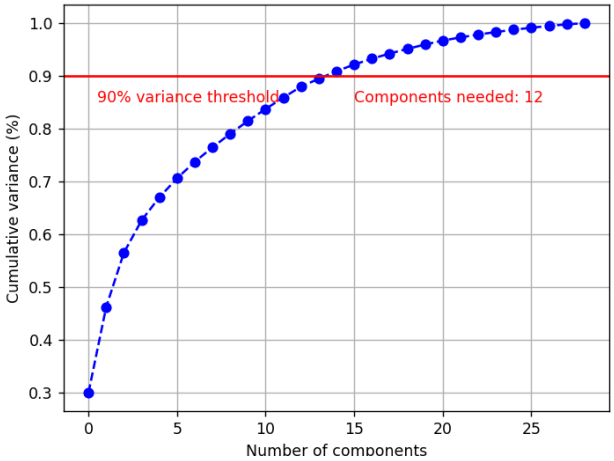


Figure 4 – PCA cumulative variance of components

To select the exact features for further processing, a supervised PCA that uses ANOVA F-value as a score function is performed. Seven subsets of features that represent the supervised PCA result are presented in three columns in Table 2. The parameter *k* defines the number of features to be selected, and *k*-selected features are on the right-hand side. For clarity, the subsets are presented in different colors. The most informative features (*attendance*, *pretest*, *colloquium1*, *colloquium2*, *project* and *num_of_final_exam_tries*) are common to all subsets and they represent the content of *k=6* subset. Other subsets are extended by one to six other features, as shown in the table.

Data scaling is necessary as different features have data in different ranges. The contemporary machine learning models expect standardized input datasets. Without scaling, the joint processing of different features' data will not be reliable. Moreover, the model can favor the features with greater number values and wider data ranges. For instance, students produce hundreds and thousands of records during interactions with the e-learning system. On the other hand, there are features encoded with small integer values from narrow intervals (for instance, descriptive students' ratings encoded by numbers from zero to four, as mentioned above). Therefore, data scaling transforms the features' data to be in the same ranges. This way, the datasets become more comparable and further processing becomes more reliable for prediction purposes. Since

property values vary within expected ranges, *StandardScaler* is used for this purpose (*sklearn.preprocessing* module).

Table 2 – Results of features selection by supervised PCA with ANOVA F-value as a score

k	features	*k*	features	*k*	features
6	attendance	9	attendance	11	attendance
	pretest		pretest		pretest
	colloquium1		colloquium1		colloquium1
	colloquium1		colloquium1		colloquium1
	project		project		project
	num_of_final_exam_tries		num_of_final_exam_tries		num_of_final_exam_tries
7	attendance		average_HS2		average_HS1
	pretest		average_HS3		average_HS2
	colloquium1		entering_exam		average_HS3
	colloquium1	10	attendance		entering_exam
	project		pretest		exercise10
	num_of_final_exam_tries		colloquium1	12	attendance
	average_HS3		colloquium1		pretest
8	attendance		project		colloquium1
	pretest		num_of_final_exam_tries		colloquium1
	colloquium1		average_HS1		project
	colloquium1		average_HS2		num_of_final_exam_tries
	project		average_HS3		average_HS1
	num_of_final_exam_tries		entering_exam		average_HS2
	average_HS3				average_HS3
	entering_exam				average_HS4
					entering_exam
					exercise10

Besides data preprocessing, the proposed method contains two additional activities in the data preparation process. Data reshaping is the first one in the sequence. As machine learning models support different data shapes, this activity adjusts the actual data shape to match the one expected by the model. Experimentation with different models needs reshaping of the input data. Consequently, this activity can be repeated.

Data reduction represents the second additional activity. If the prediction model is not satisfactory, before changing it (e.g. its type,

structure and/or parameters), one of the techniques to improve the model is to change the input dataset. This boils down to the reduction of feature data included in model training (already described in the previous section). As the used dataset consists of 159 records, the completion of missing data is performed instead of removing incomplete records. The *Pyhton* class *KNNImputer* (K-Nearest Neighbors Imputer) was used for this purpose (*sklearn.impute* module). It fills in missing data based on the similarity of neighboring samples in the dataset. *KNNImputer* selects the K nearest neighbors (samples that are most similar to the one to be completed). Further, it uses the mean value of the missing feature to fulfill the incomplete data.

Activities of prediction model design

Model preparation represents the other subprocess of the proposed method. It consists of four activities (the yellow part of Figure 1). The first one is model selection. As the prediction of students' performance based on heterogeneous and ambiguous data represents the research problem, it is essentially a classification problem type. The data complexity (a lot of uncorrelated features and data records from different sources) led to the selection of ANN as a prediction model.

Model training represents the next activity. The ANN model uses prepared datasets for the machine learning process. The training happens in epochs. An epoch consists of forward and backward passes. In the forward pass, ANN model processes the training dataset by propagating it through its structure (the layers). Then it uses the resulting (output) values and expected (test) values for loss calculation. Finally, it uses the loss function values for adjusting ANN parameters (weights of synapses between neurons of the neighboring layers) through the backward pass. If the loss function is sufficiently low and accuracy is sufficiently high, the ANN prediction model is trained and prepared for exploitation. The next activity is model serialization. It includes saving the model byte code in an appropriate file format that can be reloaded and reused.

Otherwise, if the model is not trained at a satisfactory level, this leads to loopback and changes to the model as well as to the data. This way, the next activities are model adjusting and data reduction. The model adjusting implies changes to the model parameters: number of epochs, types of layers' activity functions, number of neurons in the layers and number of layers. Empirically, minor changes are better than major ones. In experimentation, one should select one parameter at a time, slightly changing it and monitoring the consequential changes.

The design and implementation of the prediction model

The design and implementation of the overall system was done by using a Python environment. The *keras* library (*https://keras.io/*) is used for building an ANN prediction model and its serialization, while the *sklearn* library (*https://scikit-learn.org/*) is used for data preparation, and the *pandas* library (*https://pandas.pydata.org/*) is used for loading and formatting data from different sources. The resulting model for prediction is sequential and consists of an input layer of twelve neurons, a hidden layer of eight neurons, and an output layer of five neurons – one for each category/class (Figure 5). Generally, for a small number of features and records in the dataset, an empirical rule of thumb is to keep the number of neurons in the layers as small as possible. *Dense* class (*keras.layers* module) is used for constructing the layers. It provides full connectivity between neurons in adjacent layers. Initially, there were eight neurons in the input layer (same as the number of features). To avoid overfitting, the *Dropout* layer (*keras.layers* module) was added after the input layer. It is suitable for small-sized models. The *Dropout* layer drops out a fraction of neurons from the previous (input) layer in each training iteration. This way, the *Dropout* layer forces the model to learn more from the data patterns of consistent features than from noisy ones. For this reason, the number of neurons in the input layer increased to twelve.

Layer (type)	Output Shape	Param #
dense (Dense)	(None, 12)	108
dropout (Dropout)	(None, 12)	0
dense_1 (Dense)	(None, 8)	104
dense_2 (Dense)	(None, 5)	45

Figure 5 – Model of ANN used for prediction

Number of parameters for each layer can be calculated as presented in Equation 1. Each neuron has one parameter for each input neuron and one parameter for its *bias*. For instance, since the input layer consists of 12 neurons, each neuron has eight inputs (for each feature) and one bias. The full number is 108 parameters ($12 * 8 + 12 = 96 + 12 = 108$). This formula is not applicable to the *Dropout* layer as it doesn't have any parameters.

$$N_{params} = N_{neurons} * N_{inputs} + N_{bias} \quad (1)$$

Besides the dropout layer, another technique is implemented for avoiding overfitting problems of the model. This is L2 regularization that adds additional value to the loss function. It is calculated as a sum of squared weights of all synapses in the model. The resulting loss function (Equation 2) consists of two parts: categorical cross entropy (CCE) loss (left-hand side) and L2 regulator (right-hand side). In CCE (Mao et al, 2023), constant *N* represents the number of samples in the dataset (in the concrete case, it is 159 samples), *C* stands for the number of categories, factor y_{ij} determines if the i^{th} sample belongs to class *j* (its values can be only 1, or 0), while p_{ij} represents the probability of prediction that i^{th} sample belongs to class *j*. As probability values are in the [0,1] interval, the logarithm produces negative values. To make the loss function positive, CCE has the minus prefix. The right-hand side of the equation is the L2 regulator, where λ represents the hyperparameter for regularization strength. Constant *P* represents the full number of the model's parameters (in the concrete case, it is 257 parameters) and w_k represents the weight (parameter) of k^{th} synapse. The L2 regulator has negligibly small values if the weights are close to zero. In contrast, the L2 penalty value is significant if the model's weights are closer to one. Consequently, the L2 regulator gains the influence of new samples (with smaller weights) on the learning process.

$$F_{loss} = -\frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{C} y_{ij}\log(\widehat{p_{ij}}) + \lambda\sum_{k=1}^{P} w_k^2 \tag{2}$$

Except for the output layer, hyperbolic tangent (*tanh*) (Equation 3) represents the activation function for all neurons in the model (Apicella et al, 2021). Regarding linear activation functions (e.g. ReLU activation function), *tanh* has a greater sensitivity for smaller input values and a reduced sensitivity for greater input values, producing neuron output in the [-1, 1] interval. Empirically, *tanh* better fits shallow ANN.

$$\tanh(\mathrm{x}) = \frac{e^{x} - e^{-x}}{e^{x} + e^{-x}} \tag{3}$$

As the output layer consists of five neurons (one output for one category), the *softmax* function (Ren et al, 2023) represents the activation function for the model's output layer. This function (Equation 4) is the extension of the sigmoid (logistic) function, with the difference in additional parameter *K* that represents the number of output categories. Basically, sigmoidal functions produce probabilities for input values. Unlike the sigmoid function, the *softmax* function produces the probability distribution over the predicted categories.

$$\text{softmax(x)} = \frac{e^{x_j}}{\sum_{j=1}^{K} e^{x_j}} \quad (4)$$

The limitation of the sigmoid function is that it fits only for binary classification. On the other hand, the *softmax* function is suitable in the case of more than two categories. The outcome of prediction is a vector of *K* values that represents the probability of a sample belonging to a particular category. As a single value is expected as the result of the prediction, the *argmax* (*argument maxima*) function is used for this purpose. It simply returns the maximum value(s) from the input dataset. In other words, the predicted category will be the one with the highest probability.

Results

For training and evaluation purposes, the dataset was split into 127 records (80%) for training and 32 records (20%) for evaluation of the training process. The dataset was split by stratification to obtain the same category distribution in the training and evaluation subsets. The target labels (categories) were encoded automatically by using the *LabelEncoder* class (*sklearn.preprocessing* module). It results in an encoded categories vector, which is converted into an encoded categories matrix necessary for CCE loss calculations. For control of the training process, *EarlyStopping* class (*keras* module) was used with the purpose of stopping the training when the validation loss function stagnates (Figure 6).

Although the maximum number of epochs was set to 200, the diagram shows that the training was stopped earlier (after 114 epochs). During these iterations, both training and evaluation losses decreased steadily. The validation loss curve does not vary at all while the training loss curve has minor variations caused by small inconsistences in the dataset. Through experiments, the obtained training accuracy varies as expected – between 0.59 to 0.65 (due to the small dataset).

The confusion matrix (Figure 7a) of validation subset (32 records) points out satisfactory results obtained for labels 0 (*critical*), 1 (*less_critical*), 3 (*scholarship_candidate*) and 4 (*best_candidate*). The results for label 2 (*in_the_middle*) are not satisfactory, as the model failed to correctly predict this category for any sample in the validation dataset. For analysis, the confusion matrix of the ANN model is compared with the confusion matrices produced by other models: random forest classifier, logistic regression model and support vector machine model. The same pattern was found – the results are satisfactory for each label except for label 2. The conclusion is that the models cannot be well trained for this

category as there is just 14% of category *in_the_middle* samples in the whole dataset. The problem is resolved by using SMOTE (*Synthetic Minority Over-sampling Technique*) that slightly extends the original dataset with synthetic records (Elreedy et al, 2024). The confusion matrix after SMOTE processing of the dataset (Figure 7b) shows improvements in all categories.

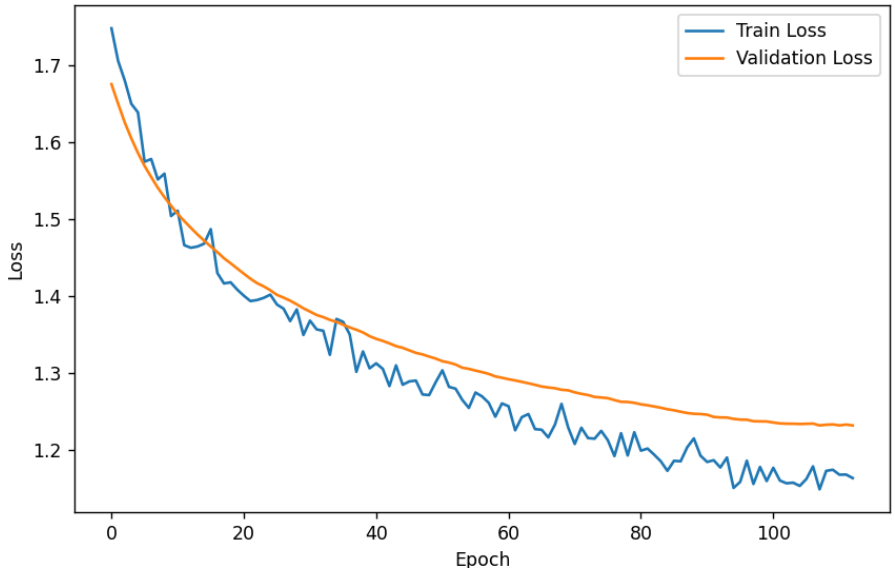


Figure 6 – Loss function descending during the training process

SMOTE technique is designed to reduce the imbalance of samples between categories. The original training set (consisting of 127 samples and category distribution 0: 27, 1: 26, 2: 18, 3: 30 and 4: 26), is extended with 23 new samples (the SMOTE class from *imblearn.over_sampling* module is used for this purpose) and the same category distribution among 150 samples (each category 30 samples). Consequently, the model accuracy is improved (~ 0.67).

Once the model is trained, it should be saved in a format appropriate for further use. Serialization into *keras* binary format (*https://keras.io/api/models/model_saving_apis/*) provides model reusability. Otherwise, if the prediction model with the same structure is trained with the different data sets (e.g. prediction models for different education subjects), the trained models should be serialized separately. This resulted in multiple *keras* files. This way, the prediction of students' performance for subject *x* needs both the subject *x* prediction model and subject *x* students' results. For exploitation purposes, the *Python HTTP*

server (embedded module *http.server*) is added as a frontend of the system (Figure 8).

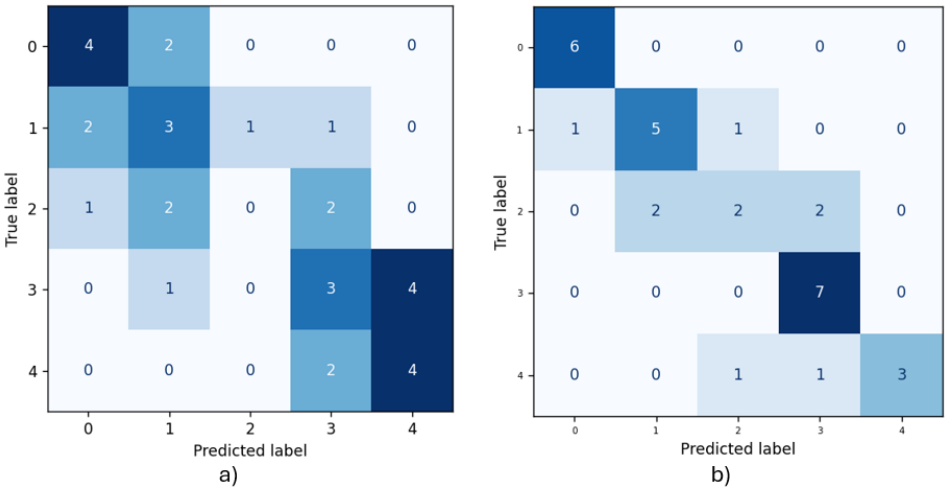


Figure 7 – Confusion matrix of validation subset of data before (a) and after SMOTE improvement (b)

During the server initialization, the system loads the *keras* models and *Python* scripts into the working memory and starts to listen on a specified server port, expecting Web client requests. The system design is flexible and scalable. The client request consists of one or more student records. For instance, it can be a dataset for one study program or dataset for first-year students, as well as an individual student record. The server responds with the category predictions.

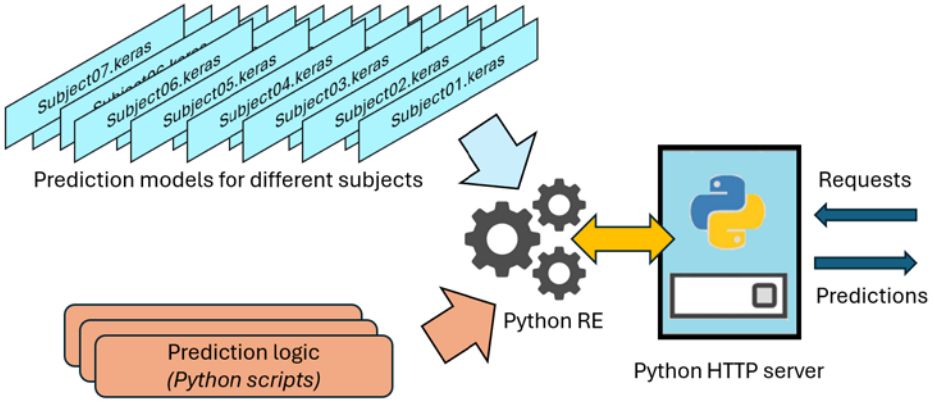


Figure 8 – Overall system architecture

Conclusion

The presented research proposes a solution based on artificial neural networks for predicting students' performance. Originally, the research dealt with solving the problem of classification. The nature of the data directed the way the problem was solved. The presented research covers the theoretical aspects, methods, design, implementation and achieved results in students' performance prediction based on heterogeneous data collected from different sources.

The proposed method for development insists on simultaneous consideration of data and prediction models. This method uses a UML activity diagram to describe complex relationships among the activities of data preparation and the activities involved in the design of prediction models. After the sequential activities of data preprocessing and initial setup of the prediction model, there is a loop of activities for fine-tuning of both the data and the model. In other words, the method proposes an iterative sub-process that will lead to the maximum fitting of the data with the prediction model. After its completion, the prediction model is ready for use.

There are three basic limitations of the research. One of them is the use of ANN as a prediction model due to its portability as easy integration based on Web services in the existing educational environment. There are other efficient models found appropriate for the research (e.g. logistic regression, support vector machine and random forest). These models are excluded from consideration as their serialization includes only basic predefined parameters and consequently, they need to be fitted each time after loading. The second limitation of the research is the dataset that consists of many features (originally 36) and a small number of records (159) due to only one subject (*OOD*) dataset used. As the raw data included numerous independent features, PCA with ANOVA F-value was performed for selection of principal components. Finally, eight features were selected for the training of the model. The third limitation is the dataset based on only one subject. The data should be prepared separately for each subject due to teachers' evidence that differ in structure and criteria.

Small number of samples made the training process difficult. Missing data completion was performed without teacher intervention and the *k-nearest neighbor imputer* was used instead. Overfitting problem represented the main difficulty (due to a small dataset). It was compensated by two approaches – adding a Dropout layer in the model and L2 regularization of the loss function. The Dropout layer forces the

model to learn more from the consistent features, while L2 regularization enables learning from new samples. Although stratification was performed, the confusion matrix pointed out another problem – an imbalanced number of samples among categories. SMOTE (*Synthetic Minority Over-sampling Technique*) is used for this purpose. SMOTE generates synthetic samples and adds them to the original dataset, changing its structure to be better balanced. The training process was controlled by monitoring the loss function over epochs. Finally, the obtained model accuracy is ~0.65, which represents a satisfactory result due to the previously mentioned problems with dataset.

For experimentation, the research proposed a Web framework based on the *Python* runtime environment and its modules. This framework integrates prediction models and the logic necessary for loading the models, on-demand prediction of students' performance and *request – response* interaction with Web clients.

The proposed solution gives many possibilities for making improvements. One of them should be to extend the research to more subjects – at least to subjects of one study program. Often, data preparation takes more time than other activities. Elimination of unnecessary features, derivation of features to reduce data dimensionality, and dealing with incomplete records are the most important activities during the data preparation stage. On the other hand, prediction models should be updated after data changes.

The proposed application framework offers lightweight components that provide reusability and changeability of prediction models. Moreover, some of the components enable easy integration of the prediction models into different application environments (e.g. Web services), giving engineers the opportunity to improve the systems they are responsible for.

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Predviđanje uspeha studenata na osnovu heterogenih i nejasnih podataka

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OBLAST: informacione tehnologije
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Predstavljeno istraživanje opisuje primenu veštačkih neuronskih mreža za predviđanje performansi studenata na osnovu heterogenih i nejasnih podataka.
Metode: Podaci studenata prikupljeni tokom tri školske godine na predmetu Objektno orijentisano projektovanje (OOD) na Elektrotehničkom i računarskom fakultetu (Akademija primenjenih studija tehnike i umetnosti u Beogradu), predstavljaju osnovu istraživanja. Veličina uzorka je sto učenika. Istraživanje obuhvata trideset šest različitih karakteristika iz tri različita izvora prikupljenih podataka. Prikazani podaci i rezultati su potpuno depersonalizovani. Istraživanje opisuje metode pripreme podataka kao i modelovanje, obuku, testiranje i evaluaciju veštačkih neuronskih mreža primenjenih za predviđanje performansi studenata.
Rezultati: Eksperimentisanje podacima i modelom predviđanja kao i tačnost modela predstavljaju glavne rezultate istraživanja. Pored toga, istraživanje uključuje diskusije o prethodnoj obradi podataka i tehnikama dubokog učenja koje se primenjuju na modelima predviđanja.
Zaključak: Metode razvoja, modeli predviđanja i rezultati predviđanja kao ishodi, njihov kritički pregled i mogućnosti poboljšanja predstavljaju glavne zaključke istraživanja.

Ključne reči: veštačke neuronske mreže, predviđanje uspeha studenata, arhitektura veb servisa, analiza podataka.

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BAB software framework and micro-service technology as the basis for cooperative process-aware information systems on the Java platform

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Abstract:

Introduction/purpose: The objective of this research is to investigate the viability of using the Business Application Builder (BAB) software framework and microservice technology for the development of cooperative process-aware information systems (CPAIS) tailored for smaller business organizations with limited expert resources. The central hypothesis is that the BAB framework, based on an ontological model, combined with a microservice architecture, can facilitate automatic code generation, ensure rigorous consistency within an individual system, and enable seamless cooperation between multiple information systems.

Methods: The research methodology utilized the BAB ontology, implemented with RDF and OWL, as the conceptual model for the information system. Microservice technology was employed for communication between distributed applications, while the CodeOntology, in conjunction with predefined templates, was used for automatic code generation in the Java programming language on the Jakarta EE platform. The research design was validated through the implementation of a proof-of-concept CPAIS for a group of companies in the transport logistics sector, where each company's information system acted as a BAB instance.

Results: The implementation of the proof-of-concept system yielded significant quantitative improvements. Development time was reduced by nearly 60%, from an estimated 120 days for a traditional approach to 50 days using the BAB framework. Integration testing revealed a 75% reduction in errors related to the persistence and communication layers. The framework demonstrated high flexibility, allowing a new system node to be integrated in a single working day. The system successfully automated core logistics processes and enabled real-time data synchronization between distributed actors via standardized REST APIs.

Conclusion: The findings confirm that the BAB framework is a highly effective platform for the accelerated development of scalable, interoperable, and flexible cooperative process-aware information systems. The research validates the initial hypothesis, demonstrating that this approach provides a distinct advantage for agile business environments, especially small- to medium-sized enterprises, by drastically reducing development effort, improving software quality, and enabling rapid adaptation to changing business requirements.

Keywords: business information systems, PAIS, cooperative information systems, microservice architecture.

Introduction

Today's competitive business environment consists of business organizations (ranging from large to medium and small) made up of business processes and resources characterized by high changeability, heterogeneity, distributedness and global connectivity.

The research presented in the paper belongs to the field of information systems, more precisely to the application of semantic modeling and microservice architecture for the development of process-aware cooperative information systems. The characteristics of distributedness and heterogeneity of process-aware cooperative information systems highlight interoperability, especially semantic interoperability, as one of the main challenges (Park & Ram, 2004), while the changeability of business processes in modern business environments results in the challenge of continuous software development and delivery (Chen, 2015).

The result is a heightened need for continuous development and delivery of information systems based on business process models while ensuring collaboration and communication with external entities. Therefore, the construction of cooperative process-aware information systems (CPAIS) (Eshuis et al., 2009) becomes a key to the efficient use of resources and faster decision-making with the aim of improving

operations for business organizations of all sizes, including small- and medium-sized enterprises. In this context, the process-aware information systems (PAIS) concept (Dumas et al., 2005) provides process awareness, and the cooperation concept (Brodie & Ceri, 1992) provides collaboration and communication with external entities.

The development of the Internet, artificial intelligence and related technologies provides technological prerequisites for the development and operation of such systems. Moreover, cooperative information systems have reached high level of maturity and wide application, with a rapid increase in the utilization of artificial intelligence and semantic models utilization. However, the development and operation of such systems require significant resources, especially expert human resources that are rarely available in smaller business organizations.

The subject of research in this work is the possibility of developing CPAIS for smaller business organizations based on the BAB framework (Bogdanović et al., 2023; 2024) and micro-service technology (dos Santos Krug et al., 2024).

The research hypothesis is that it is possible to automatically generate Java code for CPAIS, including a rigorous check of its consistency, based on an ontological conceptual model of the information system extended by the ontology of the target programming language and generic structures and interfaces for working with microservices.

The research methodology applied in this work is as follows.

- The BAB ontology (Bogdanović et al., 2023; 2024; 2025), implemented through standardized Semantic Web technologies (RDF, OWL) is used as a conceptual model of an information system with generalized common business processes.
- The ontology CodeOntology (Atzeni & Atzori, 2017)], which is an ontology of the Java programming language and is also implemented through RDF and OWL, in conjunction with templates aware of generalized common business processes in the BAB ontology and ontological reasoning techniques, is used for automatic Java code generation.
- Microservices technology is used for cross communication between different applications and systems.
- The MVP (Minimum Viable Product) of the real-world cooperative information system that supports the logistic functions of transport in a waste management company is implemented, where each individual information system is represented as a BAB instance.

The paper consists of five sections, the first being this introductory section. Section two provides a brief overview of the fundamental concepts and technologies on which the research relies and of previous research in the relevant fields (process-aware information systems and cooperative information systems). Section three provides a brief overview of the software architecture of the generated information system and the software architecture of the BAB framework, along with a detailed description of the part related to working with REST services. Section four describes the process of applying the BAB framework for the development of cooperative PAIS systems including development of the MVP of the real-world cooperative information system that supports the logistic functions of transport in a network of waste management companies, and evaluation of the results. The fifth section, which is the conclusion, discusses the advantages and limitations of the proposed solution compared to other comparable solutions and identifies directions for further research.

Related work

This section presents the fundamental concepts and technologies used in the research, as well as a brief overview of previous research relevant to the paper. It places previous research on cooperative information systems and microservice architecture in the CPAIS context.

Fundamental concepts and technologies

The PAIS concept definition is provided in Dumas et al. (2005): “Process-aware information system (PAIS) is a software system that manages and executes operational processes involving people, applications, and/or information sources on the basis of process models” together with a detailed analysis of the concept and a classification of PAISs according to four orthogonal dimensions: (1) orientation (design-oriented and implementation-oriented), (2) participants involved (humans and software applications), (3) structure and predictability of the process (unframed, ad hoc framed, loosely framed, and tightly framed), and (4) organization scope (intra-organizational, inter-organizational).

The fact that in modern business systems the business process often extends beyond the boundary of the business system imposes a requirement for the cooperation of different business information systems that "live" in a distributed environment. Within such systems, two concepts are especially important: cooperation and communication, as a prerequisite for cooperation.

In the existing literature relevant to our research, these two concepts appear in the context of cooperative systems and service-oriented architecture (SOA), more specifically micro-service architecture. Cooperative systems represent frameworks in which several autonomous entities (software systems, services or organizations) work together to achieve a common goal, sharing information and resources, while Service-Oriented Architecture (SOA) is a software design approach that structures applications as a collection of loosely coupled, interoperable services.

Finally, the concept that is also relevant to our research is ontological modelling. In computing, ontology enables the machine readable representation of knowledge about the domain of discourse, consistency checking, queries and reasoning over the representation. When it comes to business systems, ontologies facilitate the description of the structure and behavior of the system (model and model execution) by transformation of informal models into formal, machine-readable ontological representations. Due to limited space, we briefly present here only two sources that most directly influenced the development of the BAB framework. The main difference between these studies and the BAB framework is that the latter contains a conceptual ontological model of a business information system that is further adapted to the needs of the specific application domain and explicit support for checking the consistency of the generated code, which is not the case in any of these studies. Source Strmečki & Magdalenić (2019) defines five ontologies for generating Java code using tools from the Semantic Web stack. It has a significant similarity with the BAB framework in terms of the information system's model (ontology) and the technology stack used. It differs from the BAB framework in the level of abstraction of the information system and the absence of explicit support for code consistency checking. The research presented in Đurić & Devedžić (2012) internalizes the ontological paradigm into the Clojure programming language, thus enabling semantically rich domain-driven programming on two basic platforms, Java and .NET. In addition to the absence of a conceptual ontological model of an information system, it differs from the BAB framework in terms of the target programming language because the BAB framework integrates knowledge of the target programming language into the BAB ontology and enables automatic code generation in that target language.

Implementation of those fundamental concepts in our research is done through suitable technologies: standardized Semantic Web technologies (RDF, OWL, SPARQL), microservice technologies (standardized REST services), and object programming (Java language).

Cooperative information systems and micro-service architecture in CPAIS context

The idea of cooperative (collaborative) information systems appeared in the early 1990s. Back in 1992, Michael Brodie and Stefano Ceri (Brodie & Ceri, 1992) provided the initial definitions of the key concepts of such information systems, which include multiple heterogeneous intelligent agents distributed over large computer/communication networks. Moreover, in De Michelis et al. (1998a) the authors state: "...The paradigm for the next generation of information systems will involve large numbers of information systems distributed over large, complex computer/communication networks. …We call such next generation information systems cooperative information systems...".

Cooperative systems also have an organizational dimension, their components ("agents") relate to each other in the form of a social organization, share responsibilities and coordinate their participation in tasks (De Michelis et al., 1998b). In practice, this means that independent, federated information systems can operate autonomously, but also collaboratively execute processes to achieve common business goals. Typical examples of their application are inter-system and inter-organizational integrations e.g., the integration of multiple business applications within a company or the connection of information systems of different organizations to achieve an end-to-end supply process. Some examples of domains that strongly rely on such cooperative networks of systems are public administration (Rocheleau, 2005; Gacitúa et al., 2021; Chawviang & Kiattisin, 2022), health care systems (Marref et al., 2022; Rinty et al., 2022; Kamal et al., 2023), education (Sanz-Angulo et al., 2025; Miranda et al., 2021), modern production systems and smart factory environments (Wang et al., 2016) and especially supply chains (Kakhki & Gargeya, 2019; McLaren et al., 2004; Gunasekaran & Ngai, 2004; Pan et al., 2021; Kot et al., 2020).

A key advantage of cooperative systems is the ability to share resources and knowledge among components, resulting in greater efficiency and innovation. These indisputable advantages of cooperative information systems are followed by significant challenges in their implementation (De Michelis et al., 1998b). Firstly, there is the complexity of integration and the issue of interoperability (Hodapp & Hanelt, 2022). The necessity for different information systems (often heterogeneous in terms of technology and structure) to communicate and exchange data smoothly requires standardized protocols and data models. In addition, security and trust are critical (Logeshwaran, 2021) since the data and

transactions are shared among multiple entities requiring authentication, authorization and permission management in a distributed environment. Process coordination is also a challenge since a collaborative process management is needed to synchronize the activities of several participants, often in real time (Steinau et al., 2021). Finally, managing changes in such systems is difficult. Each cooperative agent can evolve, so maintaining the integrity of the entire system requires good organizational coordination and flexible software architecture.

Micro-service architecture is a modern style of software design in which an application is not built as a single entity (monolith), but as a set of small, independently executable services that communicate with each other via lightweight network protocols (Wang et al., 2021). Unlike a monolithic architecture, where all modules are part of a single application and share the same environment and database, microservices are executed as separate processes, often in containers, communicating via REST API calls, messages or other network interfaces (Wang et al., 2021). This architectural approach is inspired by the principles of service-oriented architecture (SOA), but with finer granularity and a focus on the independent management of the life cycle of each service. Microservice architecture brings many well-documented advantages over traditional monolithic systems. Some of the key ones are (dos Santos Krug et al., 2024; Kumar, 2020): independent development and delivery, scalability and performance, fault tolerance, technological agility, faster delivery and development in large teams. Despite the advantages, the transition to micro-services brings serious challenges in the implementation and operational management of the system such as distributed complexity, communication delays and performance, data consistency, security, operational management and costs (dos Santos Krug et al., 2024; Kumar, 2020).

Cooperative systems and microservice architecture share a common philosophy of modularity and collaboration aimed at achieving system goals. In the context of PAIS, both cooperative systems and microservices support process orientation, the former through connecting different organizational units into a single process flow, and the latter through breaking monolithic BPMS into a series of service components. In fact, microservice architecture is recognized as one of the technologies that can support the construction of cooperative (process-aware) information systems.

Despite their complementary goals, the concepts are different. Cooperative systems emphasize organizational aspects, while microservices are purely software entities under the control of a single

organization. In other words, a microservice is typically not a separate IS at the enterprise level, but rather part of a wider system, while units in a cooperative system are often complete ISs or service systems belonging to different owners. Cooperative systems deal with a heterogeneous environment, while microservices are most often a homogeneous environment under a single orchestrator. Also, the granularity is different: a microservice is fine-grained, while a cooperative system can be coarser-grained.

The consequence is a difference in challenges. With cooperative systems, the dominant problems are standardization, interoperability and management between subjects, while with microservices, the challenges are more technical within software engineering. However, both paradigms must address distributed communication and coordination, just at different scales.

Cooperative systems and microservice architecture are not mutually exclusive but are often complementary in modern PAIS solutions. Research shows that an approach where each business process activity is implemented as a microservice brings scalability at the activity level and naturally distributed process performance (Cocconi & Villarreal, 2020; Schulte et al., 2015). Thus, PAIS can use microservices for the technical implementation of process steps, while the concept of a cooperative system ensures that these steps flow across the boundaries of different systems or organizations.

In practice, BPM systems are evolving towards microservice architectures to facilitate easier integration into cooperative environments such as the cloud (Cocconi & Villarreal, 2020).

System architecture

The BAB framework (Bogdanović et al., 2023) is designed to support the collaboration and integration of multiple software components and organizational units in a distributed environment. Based on JAKARTA EE specifications (Figure 1), it represents a modular and easily extensible approach to the development of business applications, enabling rapid development, continuous integration and automatic code generation, thus responding to the demand for continuous development and delivery. Through the use of key components such as the AbstractEntity class, AbstractDTO and, especially, the AbstractHome class (Bogdanović et al., 2025), the framework provides a standardized way to manage data and processes, thus facilitating integration with other applications and systems within a cooperative network.

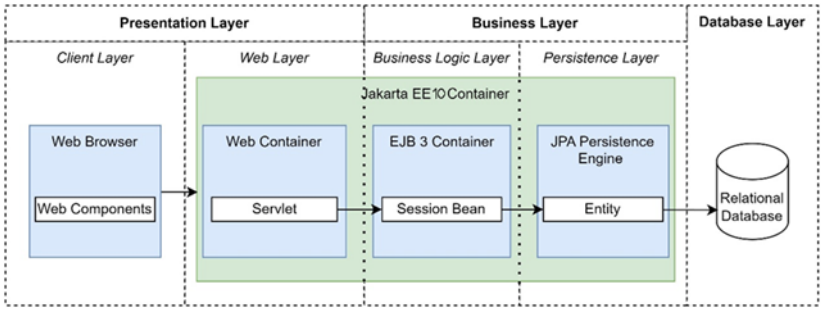

Figure 1 - Architecture of BAB based BPMS

By using ontologies and semantic technologies within the framework, BAB provides semantic interoperability, i.e., a mutual understanding of data and concepts between different systems. Standardized REST services further increase interoperability, enabling easy connection of different systems and organizational units.

Although initially developed as a monolithic application, the BAB framework fits naturally into microservice architecture concepts thanks to its clearly defined interfaces and modular internal structure. Each component of BAB can be isolated and implemented as an independent service, thus achieving easier scaling and maintenance.

In addition, BAB can be seen as the basis for a service in a microservice architecture if we define each service as a separate application instance based on the BAB framework. This approach allows the benefits of the BAB framework, such as automatic code generation, standardized operations, and rigorous validation, to be used directly within microservices.

The BAB core

At the center of the BAB framework lies a sophisticated core engineered to automate and streamline the creation of complex software by intelligently bridging the gap between the abstract concepts of business logic and the concrete implementation of source code. This is achieved through a synergistic interplay of three key components: the business-oriented BAB ontology, the foundational CodeOntology, and a powerful set of code generation templates. Together, these elements form a robust system that not only accelerates development but also enhances the consistency, correctness, and maintainability of the resulting software.

The code generation diagram (Figure 2) illustrates the following generation process:

1. First, the developer defines the application's structure and business logic by creating an ontology that imports and extends the BAB and CodeOntology. This ontology serves as a comprehensive model of the application to be built.
2. Next, the OwlBabGenerator tool parses this ontology and extracts all the relevant information about the classes, fields, relationships, and business rules that have been defined.
3. Finally, this information is fed into the FreeMarker templates, which use it to generate the complete and compilable Java source code for the application's entities, data transfer objects, session beans, and user interface views. These templates, which have the .ftl file extension, contain the boilerplate code for the various components of a BAB application. They are designed with placeholders that can be filled in with the specific details extracted from the ontologies.

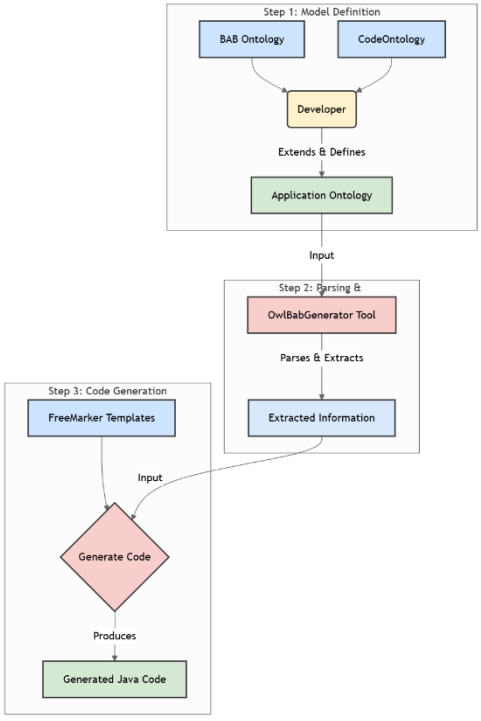

Figure 2 - Code generation diagram

The business-oriented BAB ontology is composed of several key components:

- Classes that represent the basis of an information system, i.e., atomic entities that are used in business processes. The most important ones, which can be extended by adding interface classes, are: AbstractEntity (represents the base for all subjects, later mapped to database tables and entities in Object-Relational Mapping (ORM)), AbstractDTO (principal concept for all different “looks” that one can have at data; used to define Domain Transfer Objects (DTO) and build SQL queries for populating views), AbstractHome (connects data from the former two classes by enabling transformation from entity to DTO and encapsulates business logic tasks).
- Classes that are a formal description of common web application elements: GenericMainView (used to represent the shell of the web app, responsible for navigation and security) and GenericView (an abstraction of one web page representing data and controls for a specific triplet of AbstractEntity, AbstractDTO and AbstractHome).
- Classes that are abstractions of entity properties, including their type, name, and access modifier. There are also classes that represent restrictions on those properties, like NotNull and NotEmpty. These properties are vital for enforcing business rules and data validation at the ontology level, which in turn influences the generated code's reliability and robustness.
- The fourth type of classes are relationship description classes. Ontology supports the four common types of relationships, one to one, one to many, many to one and many to many.
- Apart from classes there are object properties that describe relations between classes. We mainly use them to explain how classes compose together.
- The last part of the ontology is a Task concept, which is used to model business processes. It consists of three parts, subject, predicate, and object, just like RDF itself. It usually has a duration, can be combined with other tasks to form a complex process, knows which business subject has privileges to start it, can require some external data (Resource) and has a status of competition.

This template-based approach to code generation offers several significant advantages. It ensures that the generated code is consistent, adheres to established best practices, and is closely tailored to the specific requirements of the business application as defined in the ontology. This

not only accelerates the development process but also results in a final product that is more robust, maintainable, and aligned with the needs of the business.

Generic structures and interfaces for working with REST services

The concept of cooperative business information systems directly relates to the ability of systems to programmatically communicate, collaborate and share resources. The BAB (Business Application Builder) library, although primarily focused on the rapid development of business applications with a user interface based on the Vaadin technology, contains a dedicated package rs.co.bora5.programs.bab.session.rest. This package, together with a series of specialized interfaces, provides the fundamental architecture for transforming a BAB application from a monolithic, user-oriented system into an open platform that can function as a service within a wider digital ecosystem. Using the standard Java technology for web services, JAX-RS (Jakarta RESTful Web Services), BAB enables developers to expose business logic and data via REST APIs in an elegant and standardized way.

The core of this functionality relies on three key abstract classes within the rest package, which define a pattern for consistency, security, and proper data formatting. The central component is AbstractEndpoint, which represents the basis for each specific REST endpoint. Instead of each developer writing an endpoint from scratch, it inherits AbstractEndpoint<T>, where T is the entity type being managed. The class is annotated with @Produces(MediaType.APPLICATION_JSON), ensuring that all endpoints will return data in JSON format by default. Its most important aspect is the direct connection with AbstractHome beans, which encapsulate business logic and base operations. Through dependency injection (@Inject), the endpoint obtains an instance of the corresponding Home bean, making the API layer a thin facade that only exposes pre-existing, well-defined business logic.

Security is handled through AbstractApiKeyRequestFilter. This class, which implements JAX-RS ContainerRequestFilter and is annotated with @Provider, automatically intercepts all incoming REST requests. Its task is to check whether the request contains a valid API key in HTTP. If the key does not exist or is not valid, the request is rejected with the status 401 Unauthorized. Only validated requests are forwarded to the appropriate endpoint, thus protecting the data and business logic of the system.

The third key component is AbstractObjectMapperContextResolver, which controls the conversion of Java objects to JSON and vice versa. By implementing ContextResolver<ObjectMapper>, this class allows the developer to create and configure an ObjectMapper instance (from the Jackson library) for the entire application. Custom serializers, such as LocalDateSerializer, are registered here. This ensures that the JSON produced by the API is consistent, predictable, and easy to understand by client applications.

The success of the Rest package lies in its deep integration with other parts of the BAB architecture, which is additionally formalized through specific interfaces that contain the word "Rest" in their name. These interfaces define the contracts that the Entity and Home classes must fulfill to fit properly into the REST architecture.

At the data model level (AbstractEntity), interfaces such as RestPublicIdEntityInterface and RestResourceEntityInterface define basic requirements. The entity implementing RestPublicIdEntityInterface undertakes to have a getPublicId() method, providing a stable, publicly exposed identifier that is not directly tied to a primary key in the database. Similarly, RestResourceEntityInterface defines through inheritance and extension additional methods for monitoring the state of synchronization. Interface RestResourceLocationInterface additionally specifies how to form the complete URL of the resource with the getRestResourceLocation method.

At the level of business logic (AbstractHome), the corresponding interfaces ensure that Home beans provide the necessary methods for working with REST endpoints. RestPublicIdHomeInterface defines the contract for the Home bean that it must have a method findByPublicId (String publicId), allowing an endpoint to easily find an entity based on its public identifier. On the other hand, RestResourceHomeInterface specifies methods for sending resources, such as the send method. This strict division of responsibilities, formalized through interfaces, guarantees that the system is predictable and easy to maintain.

When all the components come together, the flow of an API request is clear and robust. The client sends an HTTP request with an API key. AbstractApiKeyRequestFilter validates it. JAX-RS routes it to the appropriate endpoint it inherits from AbstractEndpoint. The endpoint, using an injected Home bean that implements e.g. RestPublicIdHomeInterface calls business logic (e.g. findByPublicId(...)). The home bean finds the entity in the database. An entity, which implements e.g. RestPublicIdEntityInterface, returns to the endpoint. In the end,

AbstractObjectMapperContextResolver ensures that the entity is properly serialized to JSON before sending the response to the client.

In conclusion, the rest package and associated rest interfaces are not just an add-on, but a key architectural element that makes the BAB library truly cooperative. They provide a robust, secure and standardized framework for creating REST APIs, promoting code reuse and clean design principles. In this way, the BAB application becomes not only a tool for internal users, but also a valuable resource that can communicate and collaborate with other systems, opening the door to more complex and powerful business integrations.

The BAB based implementation of cooperative PAIS systems

This paper investigates the application of the BAB software framework in the implementation of cooperative PAIS systems, with a special emphasis on practical implementation in Java.

Methodology

The methodology consists of several interconnected phases that ensure a comprehensive understanding of how the BAB framework is used to build distributed and cooperative information systems.

The first phase involves a detailed analysis of business and technical requirements for developing cooperative PAIS systems. In this phase, key challenges, such as the need for rapid development, scalability, interoperability and continuous integration, are identified. Based on literature analysis and case studies, the need for automation of the code generation process and business logic validation is particularly emphasized.

The second phase, preparing the development infrastructure, is a key step in the BAB framework development process, as it provides a stable basis for further implementation. It includes the following activities:

Configuration of development tools and environment: In this phase, a development environment based on the JAKARTA EE platform is initially set up, which provides a rich set of standard tools for business application development. An SQL database is integrated for reliable data storage and processing, as well as the Vaadin framework for developing modern, interactive web applications.

Installation and configuration of the BAB library: Since the BAB framework already exists as a complete, pre-prepared solution, proper integration of the BAB library into the development project in question

requires special attention. Within this activity, detailed adjustments of basic classes and structures such as AbstractEntity, AbstractDTO and especially AbstractHome should take place as well as adjustments of generic structures and interfaces definitions for working with REST services, which enables the automation of data exchange processes and integration with external systems.

Implementation

The implementation of a real process-aware business information system (PAIS) using the BAB framework took place through the following key activities:

Detail domain model creation: Based on defined business needs and goals, a detailed domain model was first created that includes entities, their mutual relationships and attributes necessary for business processes. The BAB framework provides tools for easy and efficient mapping of these entities to the persistence layer using JPA technology, thus ensuring data consistency, integrity and easier system implementation. This mapping enables efficient entity lifecycle management and optimized execution of data operations.

Implementation of business logic: To implement business logic, EJB components and JPA technology were used, which ensured high performance, scalability and transaction management of applications. The AbstractHome class of the BAB framework offers generic and optimized methods for performing CRUD operations. It supports lazy loading, automatic management of transactions and validations, which significantly simplifies application development and reduces the chance of errors. This component enables consistent implementation of business rules and facilitates future changes to business logic.

User interface development: The Vaadin framework[1] was used to create the user interface. The developed interface provides the ability to view, enter, modify and delete data in a clear and structured way. In addition to the basic functions, the Vaadin framework provides a real-time synchronization, which instantly shows all users the changes made in the system, thus achieving better interactivity and communication between users and contributing to more efficient development of business processes.

Verification and validation: The verification and validation of the system implemented using the BAB framework was carried out through a multi-layered testing strategy, designed to confirm the correctness of both

[1] vaadin.com

individual components in isolation, and of their mutual interactions within the overall architecture. The approach included unit tests, integration tests and performance tests, each tailored to the specifics of the BAB architecture.

The focus of unit testing is on isolating and verifying the key building blocks of the application: the business logic class (Home) and the API layer class (Endpoint). For this purpose, industry standards were used, JUnit 5[2] as an executive framework, Mockito[3] for simulation (mock-up) of dependencies and Java Microbenchmark Harness (JMH)[4] to test query performance.

Methods within the inheriting classes AbstractHome are tested in isolation from the database. Dependencies, such as EntityManager, are simulated to verify the correctness of business rules, validation logic and data transformations (e.g. from entity to DTO), without the need to establish an actual connection to the database.

The abstract nature of the class AbstractEndpoint required the creation of test-specific, concrete implementations. Through these implementations, and with the help of the Mockito framework, the operation of Home beans was simulated. This approach enabled the verification of key scenarios.

Creating Resources (POST): Using the Mockito.verify() construct, it is verified that the endpoint, after receiving the request, calls the save() method on the Home bean with the correct data and returns a 201 Created status.

Get a resource (GET): It was checked whether the endpoint returns a status of 200 OK when the simulated Home bean returns an entity, or 404 Not Found when it returns null.

Integration tests are designed to verify the entire flow of information, from the interface to the database, with special emphasis on cooperative functionalities.

The default send method from the interface RestResourceHomeInterface has been verified. These tests involved running a method on a real Home component that communicates with a test database (e.g. H2) and sends an HTTP request to a mock external server (e.g. WireMock). The test confirmed that after receiving a successful response (HTTP 200) from the fake server, the status fields on

[2] https://junit.org/junit5/

[3] https://site.mockito.org/

[4] https://www.geeksforgeeks.org/advance-java/java-microbenchmark-harness-jmh/

the entity (isSync, syncAt) are correctly updated and persisted in the database.

Using the Arquillian tool[5] to run the application in a controlled container, the complete incoming flow is tested. The external HTTP client sent requests to the running application, which verifies the entire chain:

1. Correct functioning of AbstractApiKeyRequestFilter authentication components.
2. Proper deserialization of the JSON body of the request, guided by the configuration from AbstractObjectMapperContextResolver.
3. Successful running of business logic in Home bean and writing data into the database.
4. Sending the correct HTTP response back to the client.

To analyze the performance and scalability of the loaded system, the tools Java Microbenchmark Harness (JMH) and JUnit 5 were used. Scenarios were defined that simulate the work of a large number of competing users and systems, with a focus on:

- API Endpoint responsiveness: Measured response time for read and write operations at different load levels.
- Database efficiency: Analyzed the efficiency of JPQL queries, with special reference to the lazy loading mechanisms that AbstractHome uses by default, to ensure that N+1 problems do not occur when loading complex datasets.

This comprehensive, multi-layered testing strategy ensures that all aspects of the architecture implemented using the BAB framework, from the logic of individual methods to complex, transactional flows between systems, are thoroughly verified, which guarantees high quality, reliability and performance of the final PAIS solution.

MVP development and evaluation of results

The proof of concept is the implementation of a process- PAIS serving a group of companies dealing with transport logistics, where the roles of each actor (company) are clearly defined. The major business challenge of the group was ineffective communication within individual companies and difficult coordination when planning and executing joint actions, which led to delays, manual errors and a lack of transparency in work.

The implemented network of PAIS, based on the BAB framework, aimed to automate key processes and enable seamless cooperation between distributed systems, as well as the integration of legacy

[5] https://arquillian.org/

applications that already function within companies (e.g., a material bookkeeping program).

Based on previously defined architectural and technical concepts, a system was implemented in which ready-made classes and services from the BAB library are used for processing business processes.

The implementation of the system is a multi-layered application (Figure 1), which includes:

- Persistent layer: Using JPA (Java Persistence API) and ORM tools (e.g. Hibernate), domain entities (such as *Announcement* and *TravelOrder*) are mapped to database tables. The BAB framework enables standardized management of these entities across classes *AbstractEntity*.
- Business layer: The implementation of basic operations (CRUD) and business logic is conducted through EJB components. Class *AbstractHome serves* as a central mechanism for managing entities and their DTO (Data Transfer Object) representations, thus enabling logic encapsulation and facilitating further integration.
- Web layer: Using the Vaadin framework, an interface was developed that allows users to view, enter, modify and delete data. This layer ensures user interaction and real-time synchronization between distributed system instances.
- REST communication: Class *AbstractEndpoint* implements RESTful operations, providing a unique interface for accessing services. By integrating REST principles, the system achieves stateless interaction, which contributes to scalability and interoperability.

The BAB framework, as part of its modular architecture, enables the integration of REST services through the abstraction of the AbstractEndpoint class. This class, using generic parameters, provides uniform processing of REST requests for creating, retrieving, updating, and deleting data. Thanks to the methods create, findById, listAll and deleteById, a consistent and easily maintainable approach to handling data within the system is provided.

AbstractEndpoint is the basis of the entire REST infrastructure, providing abstraction over CRUD operations, which in turn rely on AbstractHome methods. This class allows for easy extension of the system to new entities without the need for major changes to the existing infrastructure, which leads to a reduction in technical debt and easier code maintenance.

The RestResourceHomeInterface interface is used for dynamic synchronization. This interface allows sending data between different nodes of the system or external services. It defines the send method, which enables automatic forwarding of data to remote services, including the additional Transformations method for data customization before distribution, thus achieving greater interoperability between different components or external systems.

The key aspect of REST service implementation in the BAB framework is the configuration of data serialization and deserialization. For this, the Jackson library is used, whose configuration is implemented through the AbstractObjectMapperContextResolver class.

Managing the authentication and authorization of REST requests is another critical component of REST service integration in the BAB framework. The AbstractApiKeyRequestFilter class is used for this. This class checks the validity of API keys through cooperation with EJB components that implement the OperatorHomeInterface interface. The authentication process itself takes place by extracting the API key from the HTTP request header, then by checking its validity, and finally by allowing access to resources only to users with appropriate permissions. This ensures a high level of security and prevents unauthorized access to data and operations within the system.

RestPublicIdHomeInterface and RestPublicIdEntityInterface are used to identify entities, which define access to entities through their unique public identifier (publicId). This enables clear identification of each individual entity, thus facilitating work with data and increasing transparency in the operation of the system. RestResourceEntityInterface further extends these basic interfaces with attributes such as external entity status, synchronization information, and the time of the last successful synchronization, thereby providing additional information about the state and behavior of entities within distributed systems.

The combination of the above classes and interfaces results in a comprehensive solution for the implementation of REST services within the BAB environment. This integration enables not only standardized and simple access to data, but also high efficiency in the operation of cooperative applications. In addition, it provides flexibility for future extensions, and high data security.

Example implementation: Announcement and Travel Order

In this section, the application of the BAB framework is presented in detail through real-life examples of logistics and waste transportation, focusing on the entities Announcement and Travel Order.

The Announcement entity is a key part of the logistics system that serves to announce the place, time and method of waste collection. Its objective is to provide timely and accurate information to logistics operations regarding planned waste collection activities. As a specialization of the AbstractEntity class, Announcement uses the interface RestResourceEntityInterface, enabling automatic synchronization with external systems. This ensures consistency and up-to-date information shared between different applications or distributed system instances.

Class AnnouncementEndpoint extends AbstractEndpoint and provides REST API access to basic CRUD operations, and additional specialized validation (Listing 1) and invalidation (Listing 2) functions for announcements.

```
@POST
@Path("/validate")
public Response validateAnnouncement(@Context
HttpServletRequest request, AnnouncementDTO entity) {
      // Checking the validity of the carrier and order
      // Create or update the Announcement entity
      // Propagation of changes through the system using
      //the updateTables method
}
```

Listing 1 - Announcement validation method

```
@POST
@Path("/invalidate")
public Response invalidateAnnouncement(@Context
HttpServletRequest request, AnnouncementDTO entity) {
      // Checking the carrier and order
      // Remove invalid announcement
      // Update and synchronize data
}
```

Listing 2 - Method invalidate announcement

The validation process includes checking the carrier's data via PIB and checking the existence of the related Travel Order. If the validation is completed successfully, the Announcement entity is created or updated, and the change is propagated to all other instances of the system using

the updateTables method. In case of unsuccessful validation or identified data inconsistency, the invalidation method enables the announcement to be removed and the resulting changes to be synchronized.

TravelOrder is a central entity that aggregates transport information for a series of announcements, providing a consolidated view of all transport activities. It implements the interfaces RestResourceEntityInterface, CheckPayoutEntityInterface and LocationInterface, which enables not only external communication but also detailed tracking of operations and locations. This way, logistics operators can more easily manage and monitor transport activities.

The TravelOrderEndpoint class defines specialized REST operations for validating and invalidating travel orders. Validation checks the correctness of information about the carrier, driver, vehicle and all related announcements. If the validation is successful, the entity Travel Order is updated or created, and the changes are propagated through the system. If there are errors or inconsistencies, invalidation allows operations to be reversed, thereby maintaining data integrity across the distributed system.

An important aspect of the implementation is the close connection between the Announcement and Travel Order entities. When a travel order is created or validated, all related entities, announcements, are automatically updated. This integration ensures that all data is synchronized, which allows logistics personnel to have centralized access to all the necessary information about individual transport operations.

Real-time synchronization, enabled by methods like updateTables, is a key functionality of the BAB framework. Any change made on one node of the system is instantly propagated to all connected instances, thus achieving high interoperability. This approach is particularly useful in dynamic logistics environments where timeliness of information is critical to the efficiency of operations.

In the implementation of the examples of Announcement and Travel Order, the validation of business rules is of particular importance. Before any changes are forwarded to the system, a detailed check of the validity of the data is performed, including checks such as the identification of the carrier, the connection with the appropriate entities and the correctness of the transport details. This approach ensures high reliability of the entire logistics system and minimizes operational errors.

Finally, the implementation through the BAB framework enables easy extension and adaptation of these entities to specific business needs. This flexibility additionally contributes to the efficiency of the system and enables quick adaptation to market requirements or regulatory changes.

Evaluation of results

The benefits of the BAB framework were quantified through a direct, sequential comparative study designed to measure its impact on development efficiency, code quality, and system flexibility.

Evaluation methodology

The evaluation was conducted by a dedicated team of two developers who implemented the same PAIS handling business processes of a company in the waste management sector, in two consecutive phases:

1. Baseline Development (Traditional Approach): The team first built the complete system using a traditional development approach. This involved using the standard Jakarta EE platform without the BAB framework, requiring manual implementation of the persistence layer, communication logic, and other common business application features. The metrics collected during this phase, most notably development time, served as the baseline for our comparison.
2. Framework-based Development (BAB Approach): After completing the baseline system, the same team then redeveloped the exact same system with the same functional requirements. However, in this phase, they utilized the BAB framework. This allowed for a direct comparison of the development effort and outcomes when leveraging the framework's abstractions, code generation, and built-in functionalities.

This sequential approach ensures that the comparison is not based on estimates, but on real-world, measured data, while keeping the developer skill level constant across both phases.

Results and analysis

The comparative study revealed significant quantitative and qualitative advantages of using the BAB framework. The key findings are summarized in Table 1.

The data clearly demonstrates that applying the BAB framework reduced the total development effort from 120 working days to just 50, a time-saving of almost 60%. This acceleration is attributed to the framework's automation of repetitive tasks and the provision of standardized, pre-built components.

Furthermore, the quality of the final product was substantially improved. Quantitative analysis during the integration testing phase

showed that the standardization imposed by the BAB framework reduced the number of errors, mostly related to the persistence and communication layers, by over 75% compared to the baseline implementation. This highlights the framework's role in producing more robust and reliable code.

Table 1 - Comparative analysis of development metrics

Metric	Traditional Approach (Phase 1)	BAB Framework (Phase 2)	Improvement
Number of tables	133	133	None, same model
Number of classes	856	684	~20% reduction
Number of lines of code	136632	54799	~60% reduction
Development Time (person-days)	120	50	~60% reduction
Total number of reported errors (QA)	52	13	~75% less
New Node Integration Time	Not Applicable / Complex	1 working day	High Flexibility

The evaluation also confirmed the system's flexibility. The time required to integrate an entirely new node (e.g., a new company) into the cooperative system was just one working day. This rapid integration is a direct result of the framework's modular architecture and standardized REST interfaces. This capability was inherent in the BAB design, whereas achieving it with the traditional approach would have required significant additional, complex development.

These quantitative improvements are supported by the framework's rich, out-of-the-box feature set, which eliminated the need to develop or integrate third-party solutions for the following:

- User-specific app personalization;
- Notification services (SMS, email, and browser push notifications);
- Advanced security with support for authenticator applications;
- Real-time data synchronization using web socket technology;
- Application localization and standardized PWA APIs for hardware access.

Finally, the framework's reliance on stateless EJB components ensures the business layer is inherently scalable and ready for clustered environments, guaranteeing high performance from the ground up.

Conclusion

This paper presents the BAB framework intended for accelerating the development of business information systems that are process-aware and adaptable to changes. The key aspects of the BAB framework, its modular architecture, generic structures and REST service integration possibilities are analyzed. The advantages of using abstract models and ontological approaches, which enable automatic generation of program code and faster implementation of applications, are highlighted.

Evaluation results and comparisons with other popular frameworks such as Spring, Quarkus, and Jakarta EE show that the BAB framework offers a clear advantage for organizations that strive for simplicity, flexibility, and rapid adaptation to change. Although there are certain limitations, primarily poor available documentation and the size of the user community, the BAB framework provides a strong basis for further improvements.

Recommendations for future research include the development of more detailed and comprehensive documentation of the BAB framework, which would enable easier adoption, implementation and maintenance of this system.

In addition, integrating more advanced features to manage business processes and enhance security is recommended. The implementation of tools for automatic monitoring and optimization of business processes would enable more efficient management of resources. Improving security features, such as authentication, authorization and protection against common attacks, would increase the reliability and resilience of systems based on the BAB framework.

One of the concrete plans for further development is the creation of a new version of the BAB library called BAB-Q, which would be based on the Quarkus framework. This version would be an extension of the existing Jakarta EE specifications, allowing easier integration into modern microservice architectures and containers, with significantly better support for running in Docker-based environments and Kubernetes technologies.

Finally, as a long-term direction of the BAB development, the authors consider the inclusion of artificial intelligence methods and techniques, more specifically the application of large language models for generating OWL code.

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Softverski okvir BAB i tehnologija mikro-servisa kao osnove za kooperativne procesno-svesne informacione sisteme na Java platformi

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Sažetak:

Uvod/cilj: Cilj ovog istraživanja je da se ispita izvodljivost korišćenja softverskog okvira „Business Application Builder“ (BAB) i mikro-servisne tehnologije za razvoj kooperativnih procesno-svesnih informacionih sistema (CPAIS) prilagođenih manjim poslovnim organizacijama sa ograničenim stručnim resursima. Centralna hipoteza je da BAB okvir, zasnovan na ontološkom modelu, u kombinaciji sa mikro-servisnom arhitekturom, može olakšati automatsko generisanje koda, obezbediti rigoroznu doslednost unutar pojedinačnog sistema i saradnju između više informacionih sistema.

Metode: Metodologija istraživanja koristila je BAB ontologiju, implementiranu pomoću RDF-a i OWL-a, kao konceptualni model informacionog sistema. Mikro-servisna tehnologija je korišćena za komunikaciju između distribuiranih aplikacija, dok je CodeOntology, u sprezi sa unapred definisanim šablonima, korišćena za automatsko generisanje koda u programskom jeziku Java na Jakarta EE platformi. Dizajn istraživanja je validiran kroz implementaciju bazičnog (MVP) CPAIS-a za grupu kompanija u sektoru transportne logistike, gde je informacioni sistem svake kompanije delovao kao BAB instanca.

Rezultati: Implementacija sistema za dokaz koncepta donela je značajna kvantitativna poboljšanja. Vreme razvoja je smanjeno za skoro 60%, sa procenjenih 120 dana za tradicionalni pristup na 50 dana korišćenjem BAB okvira. Integraciono testiranje je utvrdilo smanjenje grešaka u vezi sa slojevima za perzistenciju i komunikaciju za 75%. Okvir je pokazao visoku

fleksibilnost, omogućavajući integraciju novog čvora sistema u roku od jednog radnog dana. Sistem je uspešno automatizovao ključne logističke procese i omogućio sinhronizaciju podataka u realnom vremenu između distribuiranih aktera putem standardizovanih REST API-ja.

Zaključak: Nalazi potvrđuju da je BAB okvir efikasna platforma za ubrzani razvoj skalabilnih, interoperabilnih i fleksibilnih kooperativnih procesno-svesnih informacionih sistema. Istraživanje potvrđuje početnu hipotezu, pokazujući da ovaj pristup pruža izrazitu prednost za agilna poslovna okruženja, posebno za mala i srednja preduzeća, drastičnim smanjenjem napora u razvoju, poboljšanjem kvaliteta softvera i omogućavanjem brzog prilagođavanja promenljivim poslovnim zahtevima.

Ključne reči: poslovni informacioni sistemi, procesno-svesni informacioni sistemi, kooperativni informacioni sistemi, mikroservisna arhitektura.

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Structural types of terrains in the ophiolite belt of the Dinarides, Central Bosnia

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Abstract:

Introduction: The ophiolite belt of the Dinarides in the Central Bosnia region represents a specific formation, both in lithological and engineering-geological terms. From an engineering-geological perspective, this formation is characterized by anisotropic and heterogeneous geotechnical properties, with all the specific features typical of an ophiolitic mélange. It consists of a series of intrusions and extrusions of basic and ultrabasic magmas, partially of intermediate composition. A distinctive feature of this formation is the presence of a volcanogenic-sedimentary sequence that locally separates magmatic rocks from Paleogene, Neogene, and Quaternary clastic sediments. Additionally, magmatic activity during later stages led to the metamorphosis of basic and ultrabasic rocks, resulting in the formation of serpentinites.

Methods: Terrain instability phenomena, primarily represented by landslides, are predominantly associated with areas where direct contact exists between sedimentary formations and magmatic rocks. Rockfalls, as geodynamic processes, are linked to steep rocky slopes or road cuts and,

occasionally, riverbeds. By applying geological and geotechnical investigation methods, six terrain types within the ophiolite belt of the Dinarides in Central Bosnia were identified and analyzed. This classification is of critical importance for the design, construction, and maintenance of artificial structures, particularly in view of the the alignment of the Vc motorway through this region of Bosnia and Herzegovina.

Results: The paper presents research findings related to the age of individual lithological units and their stratigraphic positions. Furthermore, the study provides significant insights into the physical and mechanical properties of specific lithological members, their hydrogeological characteristics, and their broader functional role within the terrain system of Central Bosnia.

Conclusion: Based on the conducted investigations, terrain types within the ophiolite belt of the Dinarides have been defined and analyzed. The study concludes that the causes of terrain instability during construction, particularly the activation of landslide processes, can be classified into four main categories: geological, geomorphological, physical (climatic), and anthropogenic factors, all of which are clearly defined and addressed in this paper.

Key words: ophiolite belt of the Dinarides, sediment, magmatites, landslides.

Introduction

The area of Central Bosnia, located within the triangle formed by Žepče, Zavidovići, and Tešanj, is part of the central sections of the ophiolitic belt of the Dinarides. It is primarily composed of clastic rocks from the Jurassic and Cretaceous periods. Within the Jurassic period, the volcanogenic-sedimentary formation stands out in particular. In this formation, clastic rocks dominate, mainly represented by various types of sandstones, which often show signs of epigenetic changes. They most commonly contain interlayers of siltstone and, more rarely, breccias formed from fragments of volcanic rocks. Hornfels are present in thicker sequences south of Zavidovići. The sedimentary rocks are distinguished as separate lithological units, including sandstones, breccias, hornfels, siltstones, and clays (Golijanin & Malbašić, 2019; Grujić et al., 2025; Ahmed Bilal Benjahia et al., 2025).

Within the volcanogenic-sedimentary formation, two groups of magmatic rocks can be identified. The first group includes spilites, diabases, dolerites, gabbros, and granites, while the second group consists of ultrabasic rocks, represented by peridotites, which most likely formed during the final phase of magmatic activity. As such, these rocks

were intruded and cooled, along with amphiboles, within pre-existing formations.

Spilites are mainly products of submarine eruptions, while diabases appear in the form of layers within the sediments of the volcanogenic-sedimentary formation. Dolerites are more widespread than diabases and spilites. They most often occur at contact zones between ultramafic rocks and the sediments of the volcanogenic-sedimentary formation. Gabbroid rocks are also widely distributed within the volcanogenic-sedimentary formation. Granites appear as smaller masses along fault zones in ultramafic rocks or in their marginal areas. Amphibolitic schists and amphibolites generally occur as narrow or broader zones along the contact between ultramafic rocks and the volcanogenic-sedimentary formation.

Peridotites form a large ultramafic massif in the Ozren region and the northern part of the Krivaja massif. Peridotites are typically serpentinized to varying degrees, typically between 30% and 50%. Serpentinites, which are subordinate to peridotites, appear in several forms: as small masses within the sediments of the Jurassic volcanogenic-sedimentary formation, along the edges of large ultramafic massifs, and within them along fault zones. Serpentinites are typically highly tectonized.

The ophiolitic massif of the Dinarides in Central Bosnia is divided into several structural or tectonic units. These include:

1. The Krivaja-Mračaj syncline, predominantly composed of rocks from the Jurassic volcanogenic-sedimentary formation;
2. The Klečka anticline, which is located north of and adjacent to the Krivaja-Mračaj syncline;
3. The Maglaj-Zavidovići syncline, composed of rocks from the volcanogenic-sedimentary formation and representing the most prominent structural unit in this area;
4. The Paklenica syncline, a smaller structural unit located in the extreme northwestern part.

These tectonic units are outlined on the Geological Map of the Former Yugoslavia, Zavidovići sheet (Sunarić et al., 1973; 1974), Figure 1.

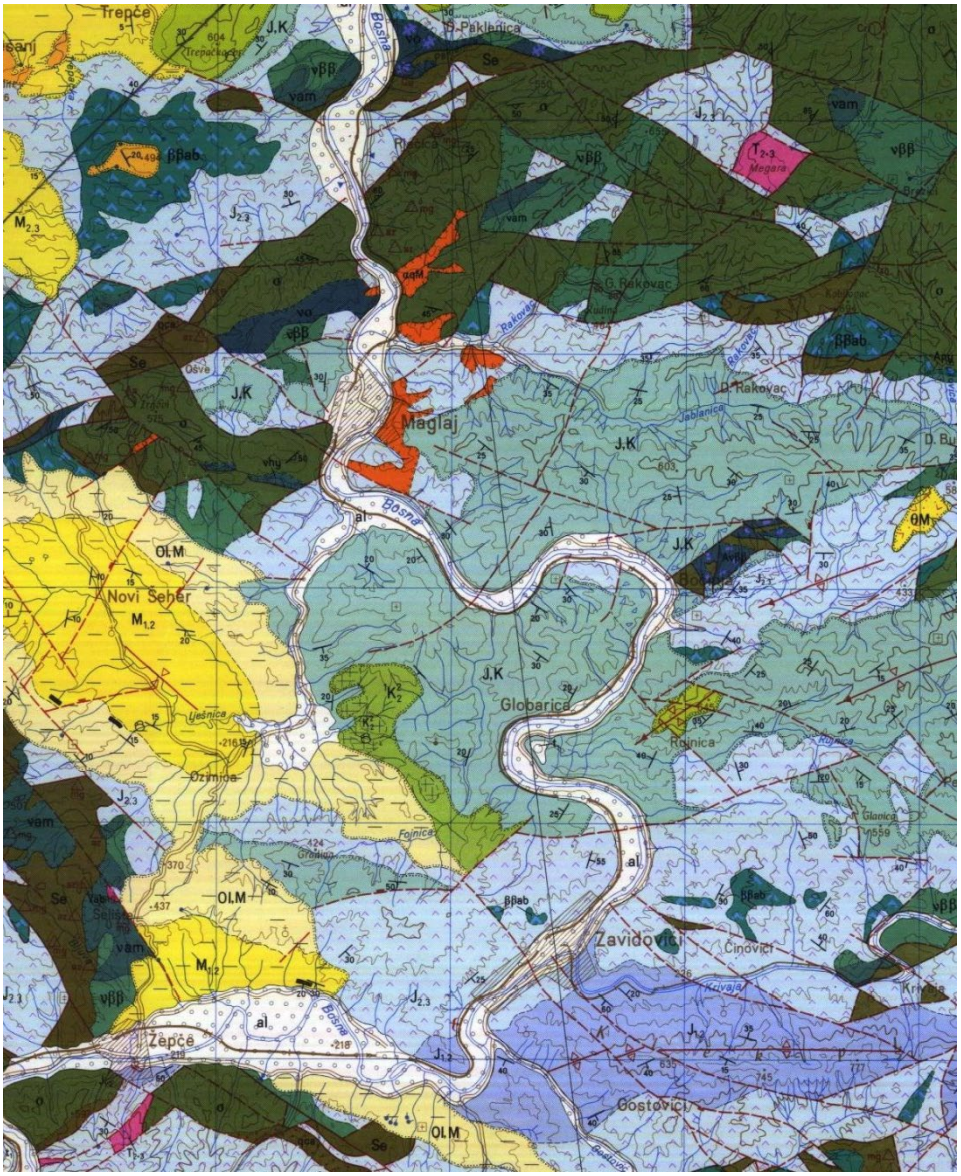

Figure 1 - A detail of the basic geological map of Zavidovići, R 1:100,000

Methodology of terrain research

For the construction of the highway section on Corridor Vc through Bosnia and Herzegovina, the most advanced research methods were

applied, both in the field and in laboratory conditions. Based on the results of field and laboratory geological investigations, a synthesis was made, and characteristic types of terrain in the ophiolite belt of the Dinarides in Central Bosnia were identified.

The research included detailed engineering-geological mapping of the terrain, based on which numerous exploration works were located, both during the design phase and additional works during the construction phase of the highway section. The research also involved a series of shallow boreholes, exploration trenches, and test pits. Geophysical investigations were applied, along with a significant number of laboratory geomechanical, mineralogical, and petrological tests, as well as several engineering-geological and hydrogeological maps for specific areas of the terrain. All of this was done depending on the construction challenges of certain structures along the highway section, such as bridges, tunnels, and retaining structures, with the goal of defining the conditions for the construction of specific objects or resolving the stability conditions of certain slopes whose natural stability was disrupted by the construction of the roadway in question.

During the 1970s and 1980s, extensive regional geological surveys were conducted, resulting in the Zavidovići and Teslić sheets of the Basic Geological Map of the former Yugoslavia (Sunarić et al., 1973; 1974), Figure 1.

This paper presents scientific solutions regarding the age of specific lithological formations and their position in the geological column. It also defines the physical-mechanical characteristics of individual lithological members as well as their hydrogeological properties.

Research results

Chronological overview of the geological composition of the Central Bosnia terrain

The Middle and Upper Triassic formations ($T_{2,3}$) have a very limited distribution and are represented exclusively by carbonate rocks, including limestones and dolomites. These formations are not fully differentiated on the geological column and are considered a single lithological unit. The older Jurassic ($J_{1,2}$) includes a series of rocks composed of claystones, marl limestones, limestones, and hornfels. These formations appear in narrow and wide zones along the tectonic contact between peridotites and the volcanogenic-sedimentary formation (Cvetkovic et al., 2016).

The younger Jurassic ($J_{2,3}$), or the Jurassic volcanogenic-sedimentary formation, also known as the "diabase-hornfels formation," has the largest

extent in the ophiolitic zone of Central Bosnia. It is most widespread in the southern parts of this zone, where it forms the Krivaja-Mračaj syncline. This volcanogenic-sedimentary formation also extends into the large Maglaj-Zavidovići syncline and the Bočinja anticline. A narrow zone of the volcanogenic-sedimentary formation is also present in the southern part of the Paklenica syncline. The Jurassic volcanogenic-sedimentary formation is a very thick complex of rocks with a highly varied composition. In addition to numerous sedimentary rocks, it contains large masses of ultrabasic rocks, amphibolites, and both effusive and intrusive basic and acidic magmatic rocks (Cvetkovic et al., 2016).

The Late to Early Cretaceous (J,K_1) includes a thick series of coarse clastic sediments that form the large Maglaj-Zavidovići syncline. Consequently, the sediments of the Late Jurassic and Early Cretaceous, along with the Jurassic volcanogenic-sedimentary formation, have the greatest distribution.

Upper Cretaceous sediments (K_{22}), predominantly carbonates, are much less widespread than the Jurassic and Late to Early Cretaceous formations. Their greatest distribution is in the Paklenica syncline, located in the extreme northwestern part of the ophiolitic zone. These sediments are represented by layered limestones and limestone conglomerates.

The Paleogene (Pc, E) is developed exclusively in the extreme northwestern parts of the ophiolitic zone, where it forms the central parts of the Paklenica syncline. It is represented solely by limestones, which are typically massive and rarely layered.

Neogene sediments (Ng) have a wide distribution in the ophiolitic zone, particularly in the northern parts of the terrain. They are represented by lacustrine-lagoonal (Oligo-Miocene, Lower and partly Middle Miocene) and marine (Tortonian, Sarmatian, and Pliocene) facies. This also includes the so-called "red series," which represents the oldest sediments in the superposed Neogene sequence. It consists of alternating conglomerates and sandstones, with subordinated claystones and mudstones. The conglomerates are poorly to moderately sorted and very heterogeneous (containing clasts of hornfels, diabase, grauwacke sandstones, clays, limestones, and serpentinites). The cement is primarily carbonate, sometimes mixed with limonite. In this zone, sandstones are poorly sorted and poorly cemented.

Lithological composition

In the area of Central Bosnia, within the so-called Ophiolitic Zone of the Dinarides, specifically in the "diabase-hornfels" formation, we can identify all types of rock masses, differentiated by their origin. These

include: igneous (both intrusive and effusive), sedimentary, and metamorphic rocks (Božović et al., 2013).

Sedimentary rocks dominate the volcanogenic-sedimentary formation and are represented as follows:

- Sandstones, which are the most prevalent rocks in this formation.
- Siltstone clays, which are somewhat less common than sandstones.
- Breccias**,** with a variable granulometric composition; their fragments vary in size.
- Hornfels, which occur rarely, usually in the form of chalcedony and opal.
- Limestones, which are also a rare component of this complex, and are generally marly.

Volcanic rocks in the volcanogenic-sedimentary formation are significantly represented and form a large part of the terrain in the area under consideration in this study. These are predominantly effusive rocks of medium acidity, including spilites**,** diabases, and dolerites**.**

Intrusive rocks are of basic and ultrabasic character and are represented by gabbros of various types, as well as peridotites.

- Spilites (ββab, $J_{2,3}$) are a very important and common eruptive member of the volcanogenic-sedimentary formation. The size of spilitic masses varies considerably. Sometimes, they form small bodies that are not clearly distinguished within the sediments, while at other times, they cover areas of several tens of square kilometers.
- Diabases (ββ, $J_{2,3}$) are also an important member of the volcanogenic-sedimentary formation. It is often difficult to distinguish diabases from spilites in the field. They differ from dolerites in their granulometric composition. The grains of diabases are not visible to the naked eye, unlike in dolerites.
- Dolerite rocks (υββ, $J_{2,3}$) are widely distributed, much more so than the described diabases and spilites. They typically appear in the contact zones between ultramafic masses and the sediments of the volcanogenic-sedimentary formation, in larger or smaller bodies.
- Gabbros (υ, $J_{2,3}$) are intrusive, basic igneous rocks that are noticeable on the surface. Depending on their composition and occurrence, they can be divided into: amphibolic gabbros, gabbros, troctolites, microgabbros, and gabbro-peridotites.
- Peridotites ($J_{2,3}$) are by far the most widespread igneous rocks in the Jurassic volcanogenic-sedimentary formation. These are ultrabasic igneous rocks. Peridotitic massifs are in clear tectonic

contact with the sediments of the volcanogenic-sedimentary formation. As a result, the peripheral parts of this formation are subject to intense metamorphic processes, specifically serpentinization.

Metamorphic rocks in this area are represented by serpentinites and amphibolitic schists (Božović et al., 2013).

- Serpentinites (Se, $J_{2,3}$) are commonly found within larger ultramafic massifs, occurring as narrow zones along faults. Large masses of serpentinites are also frequent and typically form parts of larger peridotitic massifs that border younger, usually Tertiary sediments. Serpentinites are often intensely tectonized.
- Amphibolitic schists (A, $J_{2,3}$) frequently appear as narrower zones along the contact between ultramafic rocks and the Jurassic volcanogenic-sedimentary formation. They are much rarer within the lithological formations themselves.

Marine development is represented by Tortonian sediments of the Upper Miocene (M_{22}). This formation is subdivided into two horizons:

- Limestone conglomerates ($^1M_{22}$), which lie transgressively over the "red series". These are composed exclusively of limestone clasts, poorly sorted, and well cemented by carbonate and marl binders.
- Sandstones, conglomerates, and clays ($^2M_{22}$), which lie normally over the conglomerates.

Tectonic properties of the terrain

The central ophiolitic zone of the Dinarides is characterized by the presence of large ultramafic bodies. There is considerable debate in the literature regarding the age of the peridotite masses, but it is generally accepted that they date back to the Jurassic period ($J_{2,3}$). Based on the analysis of the sheets from the Basic Geological Map of the former Yugoslavia that cover this area, six structural units can be identified (J. Sunarić et al., 1973; 1974).

- Krivajsko-Mracaj Syncline
- Klecka Anticline
- Maglaj-Zavidovici Syncline
- Paklenica Syncline
- Freshwater Neogene Basins
- Marine Neogene Basins

Hydrogeological properties of the terrain

In hydrogeological terms, the Quaternary eluvial-deluvial deposits, degraded siltstone, clays, sandstones, and thin-bedded marls, during

periods of heavy precipitation, represent a water-saturated environment in the ophiolitic area of Central Bosnia. Under such conditions, physically bound water reduces shear strength parameters, adds additional load to slopes, and consequently contributes to the activation of sliding processes. Free groundwater in fractured rock aggregates, with its pressure and circulation, contributes to the physical-chemical weathering and degradation of the primary rock mass.

Magmatic and metamorphic rocks in the ophiolitic zone of Central Bosnia are characterized by highly developed fracture porosity. Based on porosity type, hydrogeological function, and position within the terrain, as well as the hydrogeological conditions of formation, the following categories of rock masses can be distinguished by their hydrogeological function:

• Hydrogeological aquifers: These are rocks with prominent fracture porosity and are predominantly of magmatic origin. They are represented by diabases (ββ), spilites (ββab), dolerites (uββ), gabbros (u), peridotites, and metamorphic rocks represented by serpentinites (Se).
• Relative hydrogeological modifiers: These are siltstones, aleuritic sandstones, breccias, sandstones, and limestones, which are the dominant rocks in the volcanogenic-sedimentary formation of Neogene age (Ng).

Types of terrain construction

From a mechanical perspective, rock masses, as real bodies, exhibit very complex behavior. This is due not only to their specific structure but also to the different stress conditions they have experienced throughout geological history. As a result, all rock masses- even the youngest ones- are fractured, both with primary and secondary fractures, which are the result of various stresses that exceed the strength of the rock masses.

The terrain formed by the ophiolite formation, specifically the diabase – chert formation, is of heterogeneous composition, consisting of Neogene sediments, volcanogenic-sedimentary formations, and various types of magmatic rocks, including both eruptive and plutonic, as well as metamorphic rocks. These magmatic rocks collide with each other but also intrude into one another. These lithological components have different physical and mechanical properties. As a result, the terrain is formed by complex geological structures with the following characteristics (Sunarić, 2017; Golijanin et al., 2024):

1. Plastic environments – Deluvial clayey
2. Plastic to quasi-plastic environments – Neogene sediments
3. Quasi-plastic environments – Volcanogenic-sedimentary

4. Brittle environments – Magmatics (Eruptives and Plutonics) and Serpentinites

In the ophiolite belt of the Dinarides in Central Bosnia, the diabase-chert formation consists of six distinct types of terrain construction, which the authors illustrate in the following images, from Figure 2 to Figure 7.

Based on the types of terrain construction in the ophiolite zone, specifically the diabase-corneal formation of the Dinarides in Central Bosnia, as well as the overall complex tectonic relationships throughout the region, it can be concluded that the forms of deformation are highly intricate. Depending on the spatial arrangement of the geotechnical environments (lithological units) that interact in this area—sometimes colliding, sometimes intruding through one another, and at other times overlying each other—each with distinct physical and mechanical properties, their behavior in nature varies under the influence of specific forces and stresses.

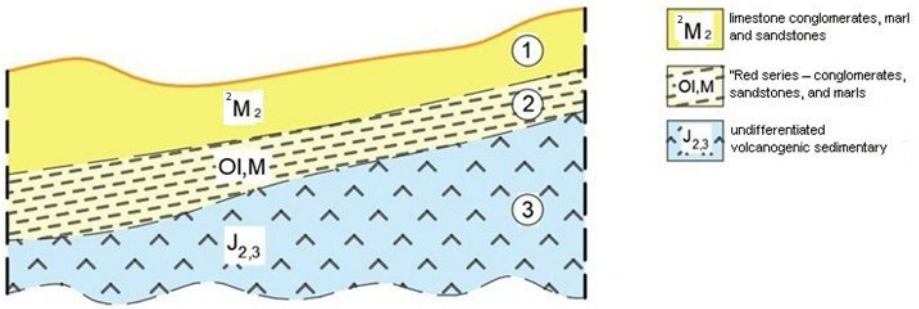

Figure 2 - Terrain construction type 1

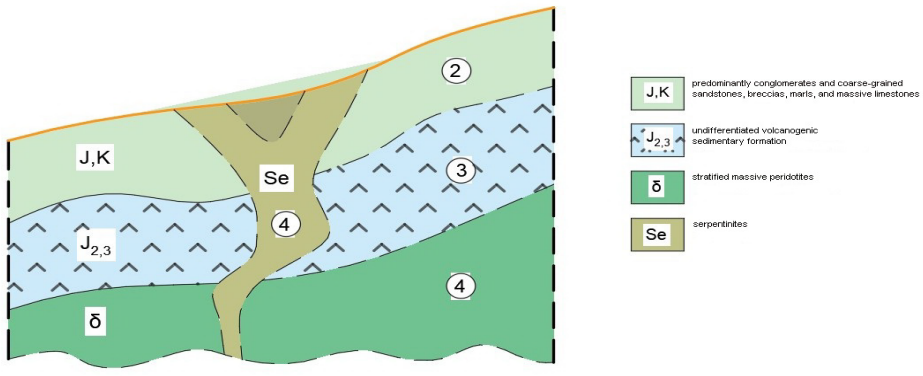

Figure 3 - Terrain construction type *2*

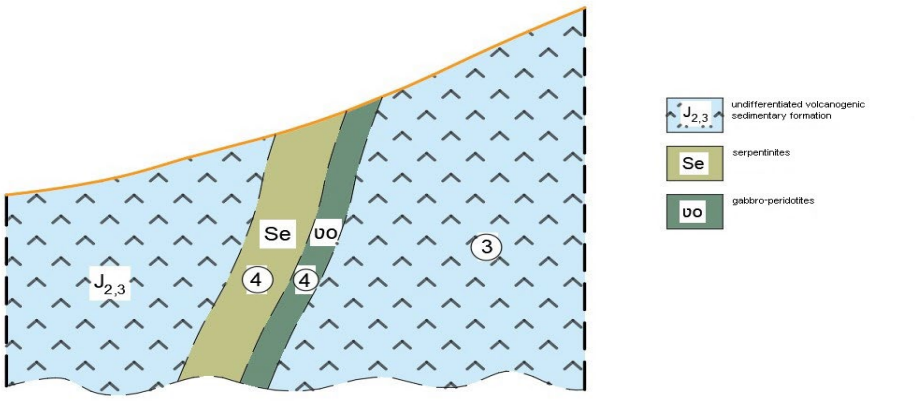

Figure 4 - Terrain construction type 3

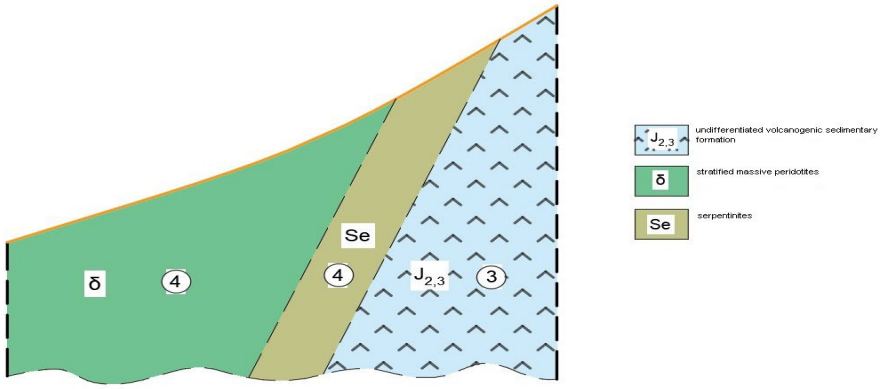

Figure 5 - Terrain construction type 4

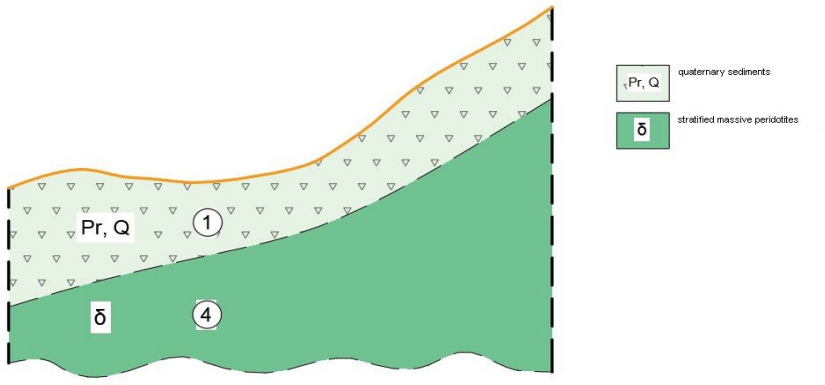

Figure 6 - Terrain construction type 5

Figure 7 - Terrain construction type 6

Modern processes in the ophiolite zone of the Dinarides in Central Bosnia

A generalized classification of contemporary exodynamic processes in our region has been in use since 1960 (Janjić, 1982). According to this classification, contemporary exodynamic processes are categorized as follows:

- Rockfalls
- Landslides
- Soil creep
- Earth flows

Rockfalls within the ophiolite belt of the Dinarides in Central Bosnia are not characterized by significant areal distribution or large volumes. They are predominantly associated with steep man-made road cuts and steep valley flanks incised by river channels. The formation of rockfalls is primarily attributed to significant annual temperature fluctuations and substantial precipitation. Large rock blocks are rarely observed, occurring mainly along transportation corridors in excavated or cut sections. Rockfalls may also be triggered by seismic activity (Sunarić et al., 2008).
Landslides, as a form of contemporary geodynamic activity, involve the downslope movement of soil and rock masses along a well-defined shear surface, without detachment from the basal material. Within terrains underlain by these geological formations, landslides of various scales are commonly observed. In areas where sedimentary deposits directly overlie magmatic rocks and where favorable morphological conditions exist, such zones may be considered naturally predisposed to slope instability.

The causative factors of landslide formation are diverse and often interdependent. The primary factor is the lithological contact between the underlying magmatic rocks and the overlying sedimentary sequences, along which displacement typically occurs. Additional contributing factors include slope gradient, saturation of sedimentary masses with water, and proximity to hydrological features, including major and minor fluvial systems - most notably the Bosna and Krivaja Rivers, among others.

Figure 8 - "Strupina" landslide near Maglaj city

In the explored area, the landslides predominantly fall within the category of consequent landslides, specifically those exhibiting a block-structured morphology with preconditioned slip surfaces (Zolotarev, 1990). The slip surface typically develops at the interface between the bedrock—comprising magmatic rocks—and the overlying Neogene and Quaternary sediments. In addition to this inherent lithological relationship, several other factors critically influence the initiation and development of landslides, including terrain saturation, thermal fluctuations, topographic configuration, and the spatial disposition of the bedrock within the landscape.

In portions of the terrain where a distinct geological unit—designated on the Basic Geological Map as volcanogenic-sedimentary—intervenes between the magmatic bedrock and the sedimentary cover, it may be inferred that this formation contributes significantly to slope stability. Notably, landslides have not been observed in these zones, nor have any displacements been recorded in excavated sections. By way of illustration, the authors refer to the excavated slopes adjacent to the approach portals of the “Crni Vrh” tunnel along Corridor Vc. Remarkably, the near-vertical

cuts within this geological context remained stable over six months, exhibiting no visible deformation despite substantial exposure to both rainfall and snow accumulation between December 2023 and April 2024 (Divel d.o.o., 2024).

Figure 9 - Terrain cut near the southern portal of the "Crni Vrh" tunnel on Vc Corridor, Bosnia and Herzegovina

Discussion of research results

This paper presents six characteristic types of terrain structure within the specific lithological formation under study, with clearly defined conditions of their formation. The identified types of terrain configuration are of significant importance for analyzing the stability of specific terrain sections during the construction of artificial engineering structures, such as motorways, as well as during slope excavation in tunnel portal zones on steep slopes or when constructing bridge foundations.

The causes of instability during construction, i.e., the triggering of landslide processes, can generally be categorized as geological, geomorphological, physical (climatic), and anthropogenic.

Geological conditions contributing to instability are inherent in the rock masses themselves — their origin, formation conditions, and physico-mechanical properties, which reflect their capacity to respond more or less rapidly to external weathering agents. The contact between the magmatic bedrock and overlying sedimentary formations, when combined with favorable contact morphology, can lead to the activation of landslide processes under anthropogenic influence (Jevremović & Golijanin, 2025). Interestingly, the presence of re-deposited volcanogenic-sedimentary formations — representing a combination of terrigenous and volcanogenic materials located between the bedrock and sedimentary units — acts as a

stabilizing factor regardless of terrain morphology or the geometry of the lithological contact (Figure 8).

Geomorphological conditions relate to the morphogenetic development of slopes and the shaping of the terrain under the influence of contemporary exogenous processes.

Physical or climatic conditions refer to the amount of precipitation and the rapid freezing and thawing of snow.

Anthropogenic activity, or human-induced impact, is the most common cause of instability. These instabilities — such as landslides and rockfalls — are not only frequent but also characterized by rapid and uncontrolled development, often resulting in severe consequences for residential and infrastructure facilities (Figure 7).

Conclusion

The ophiolitic or diabase-hornblende formation in Central Bosnia represents a complex lithological unit formed during the Middle and Upper Jurassic periods — Dogger and Malm (J2,3). Following the emplacement of magma during the Dogger and Malm, the area was initially subjected to intense disintegration processes, resulting in the degradation of magmatic and volcanic rocks. In the final stages of the Jurassic and into the Lower Cretaceous, the terrain experienced partial lacustrine sedimentation and the redeposition of disintegrated surface material. This led to the formation of a volcanogenic-sedimentary unit, which acts as a kind of "buffer" or damping layer between the magmatic rocks and subsequently deposited sediments. This interaction enables terrain stability even under conditions of vertically excavated slopes.

The extruded magma was of neutral, basic, and ultrabasic composition. In certain parts of the terrain, additional magmatic activity occurred during the Neogene period, resulting in dacitic magma intrusions and the deposition of tuff layers. Partial metamorphism of the surrounding ultrabasic magmatic rocks-specifically peridotites - also took place during this process, leading to the formation of serpentinites.

In areas where sedimentary deposits of Paleogene (Pg), Neogene (Ng), and Quaternary (Q) age directly overlie the magmatic basement in a discordant contact, and where the volcanogenic-sedimentary unit is absent, such zones are considered unstable from a slope stability perspective - particularly when morphological conditions are favorable for instability. In these cases, the likelihood of landslide occurrence is significantly increased. Landslides are especially likely to be triggered if the primary geostatic conditions are disturbed, such as through terrain

water saturation, anthropogenic activities, or the occurrence of seismic movements.

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Vrste terena u ofiolitskoj zoni Dinarida na području srednje Bosne

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OBLAST: geologija
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Ofiolitski pojas Dinarida na području centralne Bosne predstavlja specifičnu formaciju, kako u litološkom, tako i u inženjergeološkom pogledu. U inženjergeološkom pogledu, ova formacija se odlikuje anizotropnim i heterogenim geotehničkim svojstvima, sa svim specifičnostima koje karakterišu dijabazno-rožnačku formaciju. Ova formacija se sastoji od niza proboja i izliva bazne i ultrabazne magme, delimično intermedijarnog karaktera. Posebnost ove formacije je prisustvo vulkanogeno-sedimentnog paketa koji mestimično odvaja magmatite od klasičnih sedimenata paleogena, neogena i kvartara. Takođe, pod uticajem magmatskih procesa u kasnijoj fazi, došlo je do metamorfizma baznih i ultrabaznih stena i njihove transformacije u serpentinite.

Metode: Fenomeni nestabilnosti terena, uglavnom predstavljeni klizištima, povezani su sa područjima gde postoji direktan kontakt između sedimenata i magmatita. Klizišta, kao geodinamički fenomeni, povezana su sa strmim usecima ili urezima stena i, mestimično, sa rečnim koritima. Primenom geoloških i geotehničkih metoda, u radu je predstavljeno šest tipova terena u ofilolitskom pojasu Dinarida centralne Bosne, što je od izuzetnog značaja za izgradnju i održavanje veštačkih objekata, s obzirom na to da trasa autoputa Vc kroz Bosnu i Hercegovinu prolazi kroz ovo područje.

Rezultati: U ovom radu predstavljena su istraživanja o starosti pojedinačnih litoloških formacija, njihov položaj u geološkom stubu i u značajnoj meri definisana su fizičko-mehanička svojstva pojedinačnih litoloških članova,

njihova hidrogeološka svojstva i njihova funkcija u širem smislu, sve na području centralne Bosne.

Zaključak: Na osnovu sprovedenih istraživanja dobijeni su i analizirani tipovi terena u ofiolitskom pojasu Dinarida, gde je zaključeno da se uzroci nestabilnosti tokom izgradnje veštačkih objekata, odnosno aktiviranja procesa klizanja, mogu svesti na geološke, geomorfološke, fizičke i tehnogene uzroke koji su jasno definisani u ovom radu.

Ključne reči: ofiolitski pojas Dinarida, sedimenti, magmatiti, klizišta.

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Shear behavior of sandy soil reinforced with plastic waste fibers

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FIELD: civil engineering, materials
ARTICLE TYPE: original scientific paper

Abstract:

Introduction/purpose: The issue of plastic pollution represents a significant global challenge that demands urgent action. Current initiatives focus on employing technical solutions to incorporate non-biodegradable plastics into the construction of buildings and road pavements.

Methods: This paper presents a series of direct shear tests aimed at highlighting the benefits of using recycled fibers, specifically in terms of shear strength performance. The tests examined reinforced sand with varying fiber contents of 0.2, 0.4, 0.6 and 0.8%, applied to both low- and medium-density sand.

Results: The results indicate that samples prepared through dry deposition exhibited significantly higher shear strength compared to those prepared using wet deposition. Additionally, the increase in shear strength was closely related to the quantity of fiber content used.

Conclusion: In conclusion, utilizing plastic waste as reinforcement offers two solutions to pressing environmental issues: it enhances soil reinforcement and helps reduce the impact of waste.

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Key words: shear test, sandy soil, plastic waste, cohesion, friction angle, sustainability.

Introduction

The north of Algeria is known for significant geological and geomorphological risks induced by earthquakes, including phenomena such as soil erosion, ground rupture, liquefaction, and landslides. Soil liquefaction is among the leading causes of structural damage in saturated loose sand deposits during earthquakes. During the Zemmouri earthquake (Mw = 6.8) of May 21, 2003, the city of Boumerdes, located in northern Algeria, was severely affected, and significant liquefaction was observed in the region (Bourenane et al., 2018).

Several solutions have been proposed in order to overcome this problem. Various soil improvement techniques, such as soil reinforcement and stabilization, have brought very satisfactory results in many cases (Arasan et al., 2015). Soil reinforcement is provided using different processes and materials, such as geosynthetics and fibers (Bader and Szilagyi, 2023; Zhou et al., 2024). The reinforcement of soils with fibers has undergone considerable development in recent years (Kumar et al., 2015; Szypcio et al., 2023). The fibers are generally introduced into the soil in a random way. There are at least two advantages to using randomly distributed fiber as reinforcement. First, discrete fibers are simply added and mixed randomly with soil as cement, lime, or other additives. Second, the distributed fibers overcome the problem of potential weakness that can develop parallel to the oriented reinforcement (Prabakar & Sridhar, 2002). Implementing the recycling process is necessary to make this achievable, provided that the material is ready to be effectively reused (Shukla et al., 2009; Horodytska et al., 2020). From an ecological point of view, the use of these wastes in civil engineering projects could avoid burying or burning them while avoiding the use of other expensive materials (Maurya and Kumar, 2014; Jigheh and Rasulifard, 2016; Abbaspour et al., 2018; Al-Ghazawi and Zboon, 2021; Ahmed, 2023).

Reinforcing the soil using strips of raw waste plastic bottles is an alternative method to improve the geotechnical properties of the subgrade road and the stability of the constructed embankment (Kanwar and Shukla, 2020; Hameed et al., 2021; Festugato et al., 2022). This new soil-reinforcing technology can actually be used to reduce the amount of plastic waste, which helps protect the environment (Jalal and Hassan, 2021). There are low-cost plastic recycling methods that provide aggregates and fibers for use in concrete and flexible pavements

(Belmokaddem et al., 2020). In recent years, polymers have been used in the form of fibers for various geotechnical engineering applications, including soil improvement (Kurniawan & Anouzla, 2025).

Polymer-based fibers are usually added to soil to improve its strength parameters. These fibers are coating agents capable of filling the voids between the soil grains and reinforcing the soil fabric (Monkul, 2021). In addition, these fibers can be mixed with other binding materials in the soil, such as fly ash, lime, or cement, to increase the shear and compressive strength of the soil (Tingle et al., 2007). Several earlier research studies were carried out by adding synthetic polymer-based fibers to soils and soil-cement mixtures and subjecting those materials to strength tests such as unconfined compression and direct and triaxial shear tests (Javani et al., 2019; Kholghifard and Amini Behbahani, 2022; Lv et al., 2021; Hamza et al., 2022).

Gray and Ohashi (1983) showed that the incoporation of fibers into the tested soil improved the soil shear resistance and compression significantly. In recent years, this area has seen significant advances in civil engineering practice and geotechnical engineering in particular. For example, Souadeuk and Boudaoud (2021) studied the effect of mixed soil-sand-cement columns with or without polypropylene (PP) fibers. The experimental results of consolidated drained (CD) tests proved that the fibers mixed with the soft soil are effective in improving the mechanical properties of the studied soil. Yasmine and Zeineddine (2022) indicated that 1% of polypropylene fibers (12mm and 18mm) mixed with cement content (0, 3, and 6%) and sand through the consolidated drained triaxial test increased both the cohesion and friction angle of sands. A study by Correia and Rocha (2021) showed the effects of recycled polypropylene (R-PP) fibers on compacted clayey lateritic soil at different compaction degrees. The results of the tests indicated that using fibers improved the shear stress-strain behavior of the composites and soils compacted at different degrees of compaction.

This research focuses on studying the shear behavior of sandy soil from the Zemmouri region reinforced with waste plastic fibers recovered from plastic packaging for application in embankment reinforcement or foundations. A series of direct shear tests were carried out to assess the optimum content of plastic waste fibers to improve the mechanical properties of the sand. Several parameters related to the mechanical properties, including dry density and water content, were also examined and discussed.

Materials and methods

To investigate the effect of fiber content on shear strength, a direct shear testing program was conducted. This type of testing was chosen due to its simplicity and suitability for testing. The direct shear testing was carried out according to the NF EN ISO 17892-10 standard (2018). Several specimens with varying fiber content and relative density for the dry and wet states were prepared for testing, as shown in Table 1.

Table 1 – Summary of the table tests

Groups	Normal stress (kPa)	Relative Density	Fibre content (%)	Water Content (%)
A1	50, 100, 200	25%	0, 0.2, 0.4, 0.6, 0.8	0
A2	50, 100, 200	25%	0, 0.2, 0.4, 0.6, 0.8	4
B1	50, 100, 200	49%	0, 0.2, 0.4, 0.6, 0.8	0
B2	50, 100, 200	49%	0, 0.2, 0.4, 0.6, 0.8	4

Materials

- *Sand*

The soil used in this investigation was collected from Zemmouri City, northern Algeria. Quartz is mainly present in this sand, along with carbonate materials. According to the USCS, the sand is classified as poorly graded with little or no fines (SP). The sand particles are sub-rounded and generally anisometric, ranging from 0.08 to 2 mm. The samples were taken from the bank-liquefied layer in the deposit areas at a depth of 3.00m. The grain size distribution and physical properties of the tested sand are presented in Figure 1 and Table 2, and the minimum and maximum void ratios presented in Table 2 were determined according to ISO 14688-1 specifications.

Figure 1 illustrates the particle-size distribution of the studied soil, indicating significant variability in grain size across the sample.

Table 2 – Physical properties of the used sand

Sand properties	Standard test specifications	Value
Mean grain size, D_{50} (mm)	ISO 14688 1	0.51
Maximum diameter, D_{max} (mm)	ISO 14688 1	2
Uniformity coefficient, C_u	ISO 14688 1	2.21
Coefficient of curvature, C_c	ISO 14688 1	0.83
Classification	USCS	SP
Mean specific gravity, G_s	ISO 14688 1	2.64
Maximum void ratio, e_{max}	ISO 14688 1	0.51
Minimum void ratio, e_{min}	ISO 14688 1	0.79

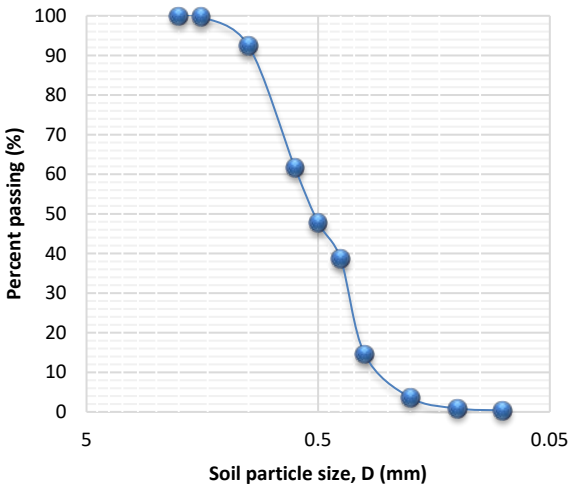


Figure 1 – Grain size distribution of Zemmouri sand

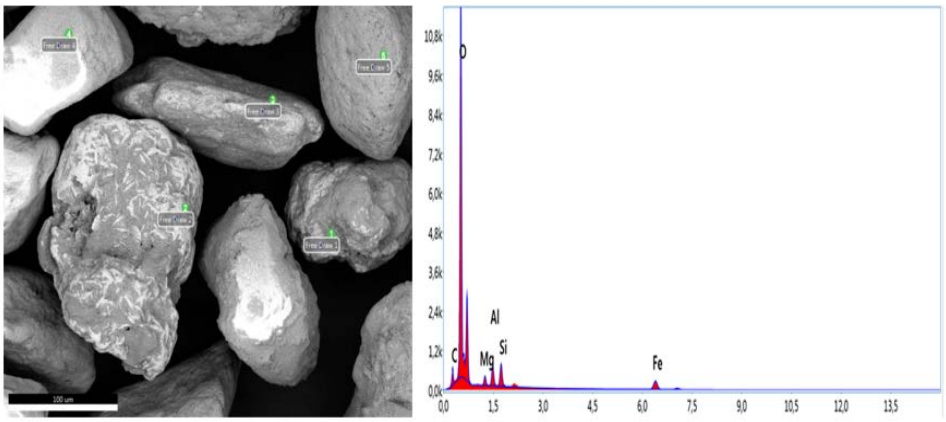


Figure 2 – (a) SEM images of sandy soil; (b) EDX spectrum of sand

Scanning Electron Microscopy (SEM) was employed to characterize the microstructure of dried sand samples. As shown in Figure 2 (a), the particles are predominantly angular to sub-angular, exhibiting rough and irregular surfaces.

An Energy Dispersive X-ray (EDX) system coupled with the SEM was employed to determine the elemental composition at various distinct

points. As illustrated in Figure 2 (b), the EDX spectrum is dominated by Si and O peaks, confirming a silica-rich composition. The presence of Al, Mg, Ca, and Fe is likely associated with aluminosilicates and accessory mineral phases.

- *Fiber*

The study utilized recycled yoghurt pots fiber with an average length of 10 to 18 mm and a diameter of 1 to 3 mm as shown in Figure 3. The fiber was composed of a polypropylene-based polymer with an average density of 1.02 g/cm^3. For the experiment, the weight of the fiber content was varied between 0% and 0.8%, with 0.2% increments. This range was selected based on previous studies demonstrating that the optimum fibre content for reinforced soils was between 0.5% and 1%. These earlier studies include (Consoli et al., 2005; Eldesouky et al., 2015; Peddaiah et al., 2018).

(a) Yoghurt pots (b) Yoghurt pots fiber

Figure 3 – Recycling fibers

Sample preparation and test procedure

Twelve unreinforced samples and forty-eight reinforced samples incorporating recycled fibers were used in this study, totaling sixty samples for the Direct Shear Test (DST).

Figures 4 (a) and 4 (b) show the Zemmouri sand and the recycled yogurt pot fibers, respectively, prior to the mixing procedures. Two types

of sample preparation have been used in Figure 5: dry specimens and wet specimens characterized by a water content of 4%. All tests were done on loose and medium relative densities. A small direct shear test apparatus with dimensions of 60×60 mm was used with a sample thickness of 25mm. Sample preparation was first conducted by determining the mixture's required mass of sand and fiber.

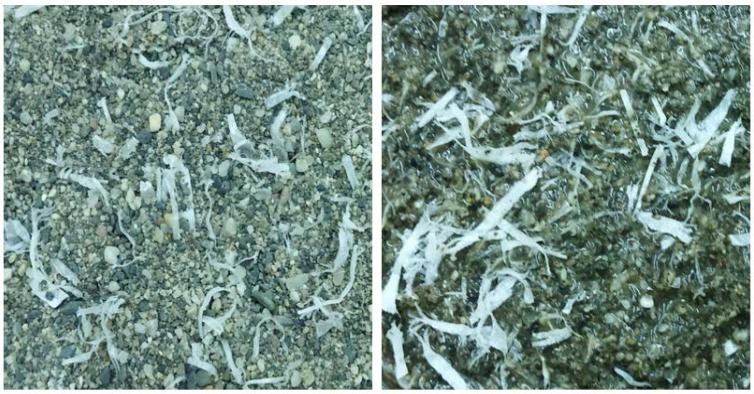
The concentration of fibers (Fc) included in a composite is defined as a percentage of the dry mass of sand. Based on the hypothetical equations assumptions, we assume the weight and content of sand used to obtain a fiber reinforced with a volume (V) and a void ratio (e0) equal to those for an unreinforced specimen (Anagnosopoulos et al., 2013). In this case, a particular soil mixture is changed by replacing a portion of a total solid with another component with a lower density, such that the entire solid mass remains unchanged (Michalowski, 2002; Özkul and Baykal, 2007).

$$F_c\,(\%) = \frac{Wf}{Ws} \times 100 \qquad (1)$$

Where Wf and Ws are fiber and dry sand masses, respectively. The samples were manually prepared by adding and mixing the oven-dried sand with fibers as shown in Figure 5. Special attention was paid during sample preparation to ensure a similar level of mixture for all the samples tested.

(a) (b)

Figure 4 – Materials used in this study: (a) Zemmouri sand; (b) recycled fiber



(a) (b)

Figure 5 – Samples preparation for (a) dry specimens; (b) wet specimens

Results and discussions

Sixty conventional shear box tests were conducted for wet and dry sand at different fiber contents. We assume here that the fibers are uniformly distributed and randomly oriented in the sand. The fibers are considered one-dimensional elements, and they can be deformed or slipped into the matrix (sand).

Effect of fiber content

Through a series of direct shear tests, this study examines the impact of fiber content on the mechanical behavior of Zemmouri sand. Parameters including dry density, normal stress, and water content were evaluated to determine how fiber reinforcement influences the sand's shear response. The results for fiber contents ranging from 0% to 0.8% are presented and compared against findings for unreinforced, dry sand.

- *Loose sample (Dr=25%)*

Test results for loose samples (Dr=25%) distinctively illustrate the impact of fiber content on both the shear strength evolution and the intrinsic failure envelope. In Figure 6a, the variation of shear strength-displacement relationship of a sand-fiber mixture under different normal stresses is shown. A proportional increase in shear strength was observed during the test period until it was constant after 5 mm of horizontal displacement. It can be seen that the initial tangential stiffness of the matrix fiber-sand was the same for all tests, indicative of a stiffer sand-fiber matrix, while the final stable value of shear strength increased

proportionally with fiber content. It is evident that the addition of fiber has accelerated the development of shear strength. For volumetric fiber contents of 0.2 and 0.4%, peak strength was reached after 2.5 mm of horizontal displacement; this event is significant at the 0.4% fiber content. Additionally, an increase in residual shear strength was observed for samples reinforced by fibers in this case of relative density and specimen preparation (dry samples).

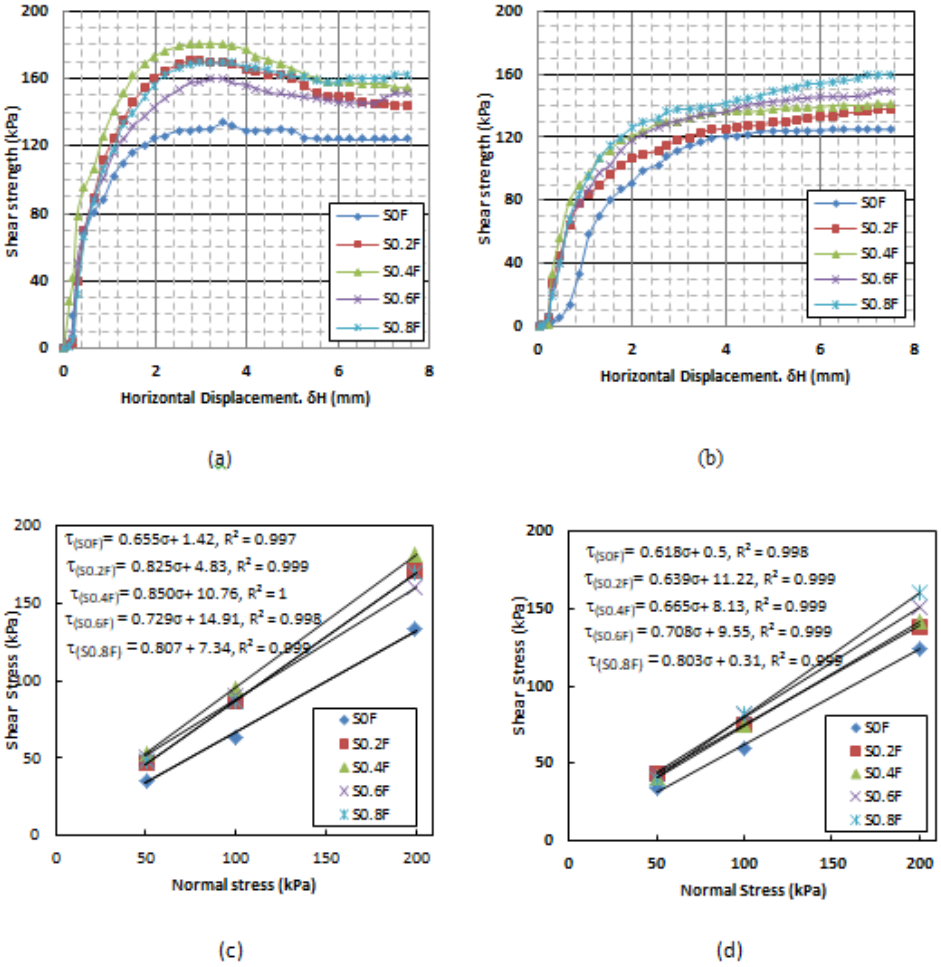


Figure 6 – Effect of fiber content on shear strength, normal stress of 200KPa and average density Dr=25%: (a) variation of shear strength of dry sand versus horizontal displacement δH (mm); (b) variation of the shear strength versus horizontal displacement δH (mm) with a water content W= 4%; (c) intrinsic curves of dry sand; (d) intrinsic curves of wet sand with (w=4%)

The two figures showed a significant difference (Figures 6a and 6b). Figure 6b illustrates the variation of shear strength of wet sand versus horizontal displacement; the shear stress increases with increasing fiber content at the same applied normal stress, showing practically the same behavior. The results indicate that the reinforcement with recycled fiber improved the interlocking force of sand particles while increasing the shear stress. Moreover, shear strength improvement is essentially governed by the movement of fibers and their interaction with sand particles. The intrinsic curves shown in Figures 6c and 6d reveal that all reinforced specimens exhibit higher shear strength than the unreinforced sand. For dry sand, the friction angle slope values for varied fiber contents, specifically 0.2%, 0.4%, 0.6%, and 0.8%, were 0.82, 0.85, 0.72, and 0.80. Compared to Figure 6d, the friction angle slope varied to 0.63, 0.66, 0.70, and 0.80, respectively, for sand with 4% water content.

The interlocking force of fibers with sand particles produces the mobilization of tensile strength at higher strains in the shear plane. Several studies have demonstrated that increasing volumetric fiber content improves shear strength (Michalowski, 2002; Özkul and Baykal, 2007; Sadek et al., 2010; Yu et al., 2021; Hasanzadeh and Shooshpasha, 2023). In the mechanics of stress transfer in composites reinforced with short fibers, the applied stresses are first transferred to the matrix material (the shape of sand supported the applied stress afterwards), then to the fibers through the fiber ends and the surfaces of the fibers near the fiber ends. Figure 7 explains the mechanism of fiber-reinforced sand. As a result of a normal stress application on the fiber-reinforced sand, the soil particles at the sand-fiber interface may have a heading of rotation, and the fiber in tension may undergo plastic deformation at the sharp angles or boundaries of the particles.

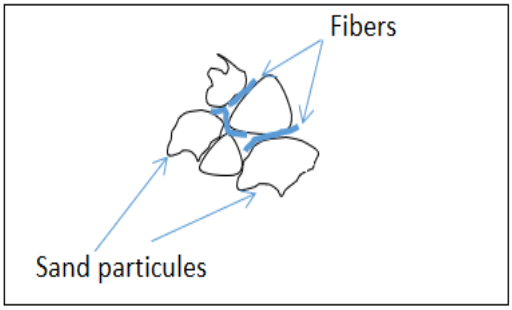


Figure 7 – Incorporating fiber reinforcement mechanisms into sandy soil materials

- *Medium dense sample (Dr=49%)*

In the shear stress versus horizontal displacement curves shown in Figures 8a and 8b, for a normal stress of 200 kPa in medium density, the specimens without reinforcement exhibit slightly higher initial stiffness compared to those with reinforcement. Additionally, shear strength increases across all fiber contents for dry sand, as the fibers create voids within the matrix. The shear peak resistance of fiber-reinforced sand is greater than that of unreinforced sand due to enhanced interaction between the fibers and the sand. This finding is consistent with previous studies on sandy soil reinforced with polypropylene fibers, as reported byBenziane et al. (2019) and Berkane et al. (2023).

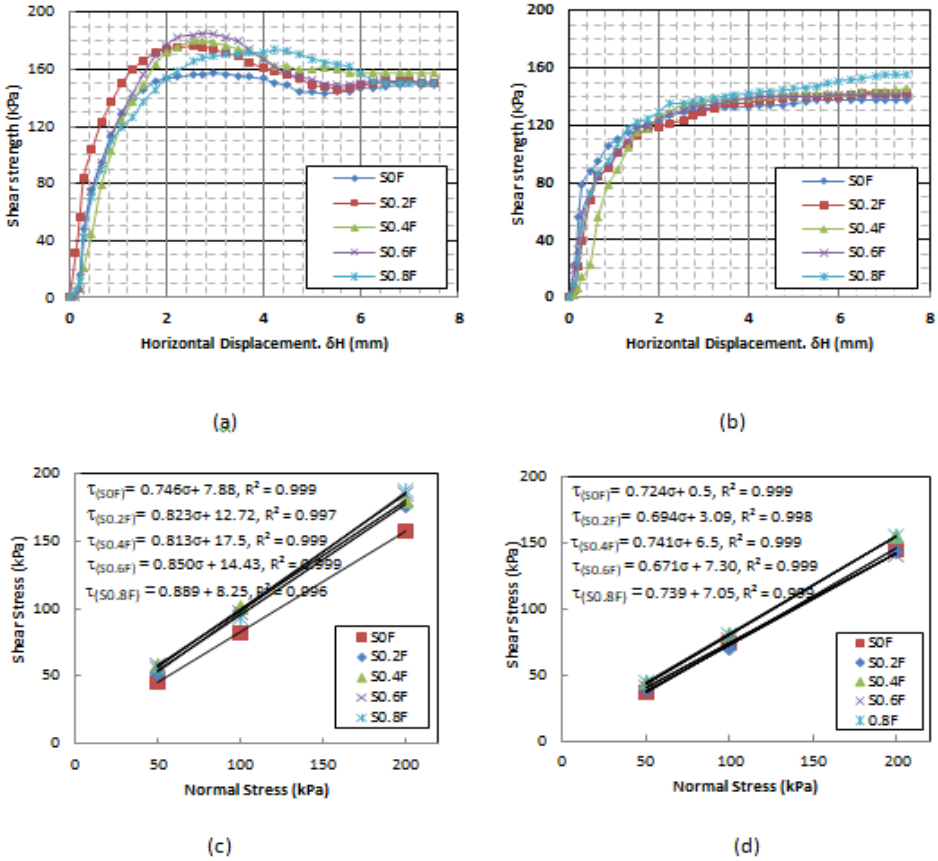


Figure 8 –Effect of fiber content on shear strength, normal stress of 200kPa and average density Dr=49% : (a) variation of shear strength of dry sand versus horizontal displacement δH (mm), (b) variation of the shear strength versus horizontal displacement δH (mm) with a water content W= 4%, (c) intrinsic curves of dry sand, (d) intrinsic curves of wet sand with (w=4%)

Effect of fiber content on cohesion and friction angle

- *Loose samples*

For the loose samples, the shear strength envelopes corresponding to each level of normally applied stress are presented in Figures 6c, 6d, 9a, and 9b. In the case of a dry sand-fiber mixture, the cohesion and the friction angle increase proportionally with fiber content. However, a slight decrease in the angle of internal friction and an increase in cohesion are observed at 0.6% fiber content, a decrease in cohesion at 0.8% fiber content, and an increase in the angle of internal friction. In general, the amount of incorporated recycled fibers directly affects the reinforced soil's cohesion and internal friction angle. The enhanced cohesion results from a binding effect in which the fibers carry tensile loads and create bridging forces. Concurrently, the increase in internal friction angle is attributed to the interfacial shear resistance and the physical restraint that the fibers impose on particle rearrangement during shearing. This finding was also reported by Alhassani (2021) and Manuel et al. (2021).

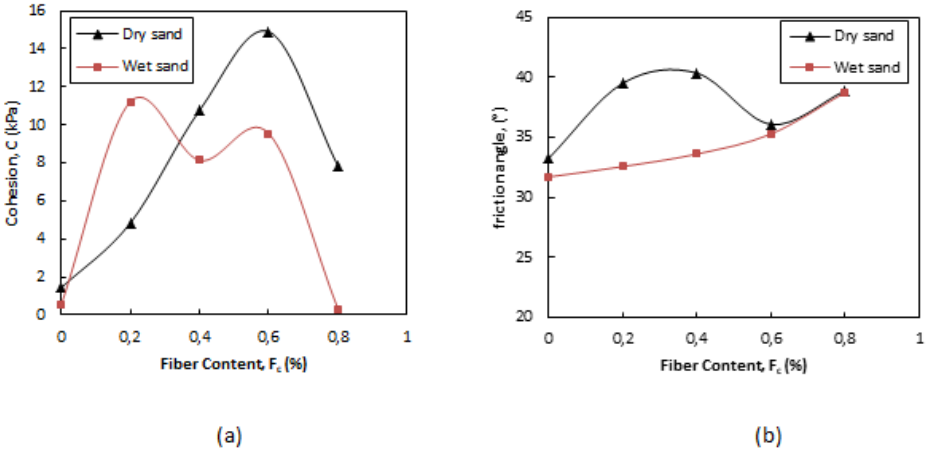


Figure 9 – Effect of fiber content of dry and wet loose sand as function of (a) cohesion, (b) friction angle

- *Medium density samples*

In the case of medium density samples, as shown in Figures 10a and 10b, for dry sand, an increase in cohesion and the angle of internal friction is observed up to a fiber content of 0.4%. From this value, the cohesion decreases, and the angle of internal friction increases to 41.36°. This increase in the angle of internal friction is due to the

development of the fibers network and their mobilization with the sand particles. Figures 10a and 10b show a slight increase in cohesion in wet sand due to the improvement in soil shear strength induced by the fibers in the soil, with the same behaviour observed by Benziane et al. (2019). Furthermore, a distinct variation in the internal friction angle (ϕ) was observed. Consistent with the findings of Isazadeh-Khiav et al. (2022), the internal friction angle exhibited an increasing trend as the fiber content increased. Water content and density affected cohesion and internal friction angle.

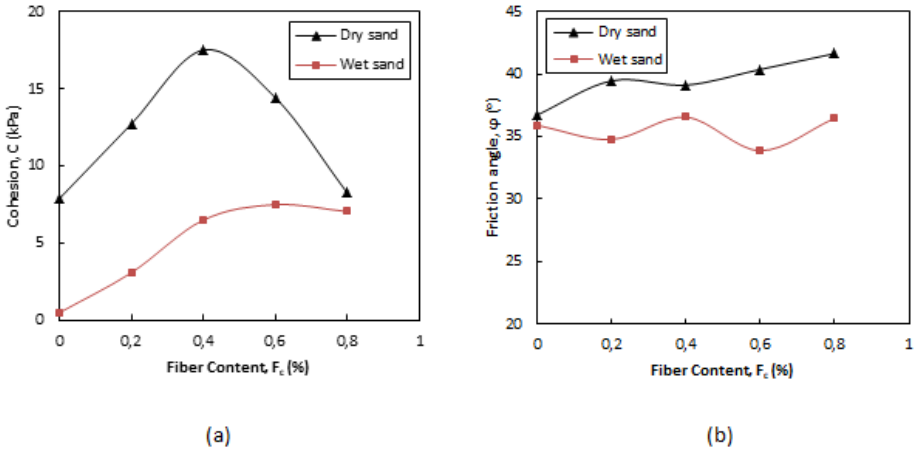


Figure 10 – Effect of fiber content on cohesion and the frictional angle of reinforced dry and wet medium density sand specimens: (a) cohesion, (b) frictional angle

Effect of fibers on contracting-dilatancy

Based on the vertical displacement-horizontal displacement curves, Figure 11a indicates an increase in volume variation for the sandy soil during shearing (dilatancy). Compared to soils without fiber, soils with fiber showed a slightly higher variation. Figure 11b displays a tendency for volume variation to decrease (contracting) for wet sand in the case of unreinforced sand. Additionally, an increase in fiber content increases the volume. The inclusion of strips altered the behavior of the soil at the maximum applied stress levels. Volumetric variation indicates that the soil exhibited a brittle rupture (with dilation), and the material began to display ductile behavior. Similar findings were reported by Eldesouky et al. (2015).

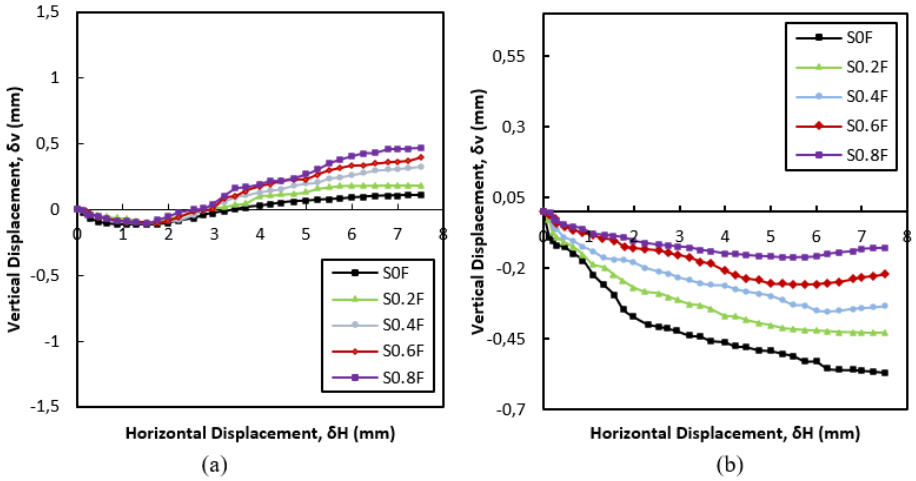


Figure 11 – Vertical displacement versus horizontal displacement curves for loose sand specimens sheared at 200 kPa, (a) dry sand, (b) wet sand

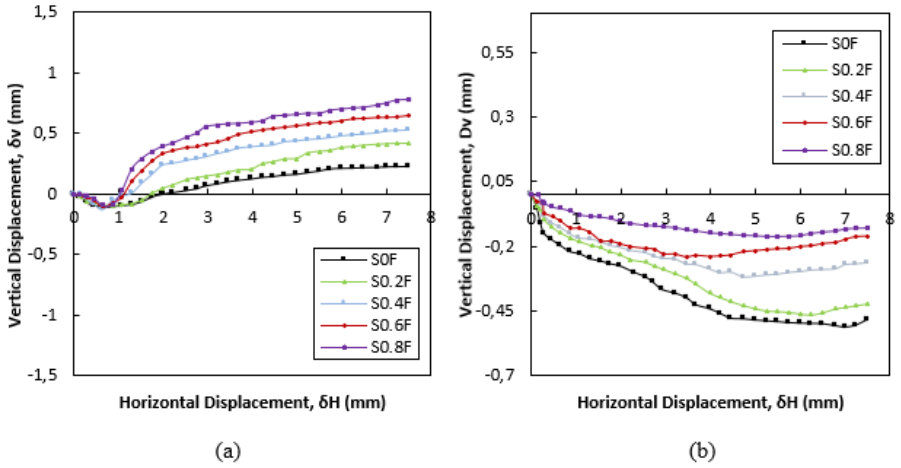


Figure 12 – Vertical displacement versus horizontal displacement curves for medium sand specimens sheared at 200 kPa, (a) dry sand, (b) wet sand.

Figure 12a illustrates the case of dry medium-density sand, where the volume increased with increased fiber content (dilatancy). Figure 12b shows that a greater density of the wet sand increases the contractiveness of the samples, which results in the effect of the relative density and fiber content on the development of the vertical displacement. Similar results indicate the same behavior (Falorca & Pinto, 2011; Aouali et al., 2019; Benziane et al., 2019; Berkane et al., 2023).

Conclusion

A laboratory investigation was carried out to study the effect of the inclusion of recycling fibers on the shear behavior of Zemmouri sand from the Boumerdes region, northern Algeria. Based on the results obtained through this investigation, the following conclusions can be reached:

- Reinforcing sandy soil with discrete recycling fibers can reduce the impact of solid plastic waste on the environment, and ensure sustainability.
- The incorporation of recycled fiber reinforcement reduces soil dilatancy in samples prepared at loose density, while adding fibers increases the dilation tendency in dense samples. This phenomenon can be attributed to the characteristics of the fiber-sand matrix, which exhibits a strong dependence on both relative density and the contribution of fiber reinforcement. Randomly distributed fibers offer strength isotropy and limit the potential planes of weakness that can develop parallel to oriented reinforcement.
- The test results show that the mechanical properties of fiber-reinforced soil are significantly influenced by the presence of recycled fibers, leading to an increase in maximum cohesion and friction angle values at all densities studied.
- The most effective amount of recycling fiber content to achieve the maximum shear strength of Zemmouri sand is 0.4% and 0.6% for a relative density of 25% and 49%, respectively, in dry conditions.

Nomenclature

PP		Polypropylene
R-PP		Recycled Polypropylene fiber
DST		Direct shear test
Fc	(%)	Fiber content
W_f	(g)	Weight of fiber
W_s	(g)	Weight of dry sand
Dr	(%)	Relative Density
τ	(kPa)	Shear strength
σ_n	(kPa)	Normal stress
δ_h	(mm)	Horizontal displacement
δ_v	(mm)	Vertical displacement
ϕ	(°)	Friction angle
C	(kPa)	Cohesion

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Ponašanje peščanog tla ojačanog vlaknima od plastičnog otpada pri smicanju

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OBLAST: građevinarstvo, materijali
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Zagađenje plastikom predstavlja značajan globalni problem koji zahteva hitno delovanje. Savremene inicijative su usmerene na tehnička rešenja za upotrebu nerazgradive plastike u izgradnji objekata i kolovoza.

Metode: Ovaj rad predstavlja seriju ispitivanja direktnog smicanja u cilju isticanja prednosti upotrebe recikliranih vlakana, posebno u pogledu čvrstoće na smicanje tla. Analiziran je pesak male i srednje gustine ojačan različitim sadržajem vlakana od 0,2, 0,4, 0,6 i 0,8%.

Rezultati: Rezultati pokazuju da su uzorci pripremljeni suvim taloženjem ispoljili značajno veću čvrstoću na smicanje u poređenju sa uzorcima pripremljenim mokrim postupkom. Takođe, povećanje čvrstoće na smicanje je usko povezano sa količinom dodatih vlakana.

Zaključak: Upotreba plastičnog otpada za ojačanje nudi dva rešenja za aktuelne probleme životne sredine: poboljšava ojačanje tla i doprinosi smanjenju uticaja otpada.

Ključne reči: ispitivanje smicanja, peščano tlo, plastični otpad, kohezija, ugao trenja, održivost.

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Multi-criteria evaluation of pavement quality based on the fuzzy AHP methodology: an integrated approach for optimizing road performance

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FIELD: civil engineering, decision sciences
ARTICLE TYPE: original scientific paper

Abstract:

Introduction/purpose: In this paper, a multi-criteria evaluation framework for pavement condition assessment using the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) is proposed, integrating technical, economic, and environmental considerations. Road infrastructure is a key component of transportation systems, and its sustainability depends on effective management and maintenance. This study aims to provide a scientific basis for optimizing road maintenance planning by identifying and prioritizing the key factors affecting pavement quality. The framework considers technical,

economic, and environmental dimensions to ensure a comprehensive evaluation.

Methods: A hierarchical structure of evaluation criteria was developed, including technical sub-criteria such as surface roughness, bearing capacity, traffic characteristics, and environmental conditions, alongside economic and material-related factors. Weights were assigned using the Fuzzy AHP method, with consistency checks validating the reliability of the results. A case study was applied to National Road RN101, linking Sidi Bel Abbès to Aïn Témouchent.

Results: The analysis revealed significant deficiencies in certain segments, including excessive roughness and insufficient structural strength. Sections subject to high traffic loads and severe environmental conditions showed the most deterioration. Technical aspects, particularly bearing capacity and material quality, were found to exert the strongest influence on pavement performance and durability.

Conclusion: The findings demonstrate the relevance and applicability of the proposed Fuzzy AHP-based evaluation model in supporting decision-making for road maintenance prioritization. The methodology can be extended to other road networks requiring a structured, reliable approach to pavement quality assessment.

Key words: pavement quality, fuzzy analytical hierarchy process (FAHP), maintenance strategy, multi-criteria management.

Introduction

Road infrastructure, particularly pavements, constitutes a fundamental component of modern transport systems. It facilitates the movement of people and goods while playing a crucial role in economic growth (Simões et al., 2017). By providing effective connections between urban, industrial and rural areas, these infrastructures facilitate trade, reduce travel time, and increase the efficiency of supply chains (Yang et al., 2014). Pavement quality directly influences user comfort and security, as well as economic drivers like fuel consumption and vehicle deterioration (Pérez-Acebo et al., 2020). For this reason, road infrastructure is a strategic economic and territorial resource (Taylor and Philp, 2015; Oulha and Derras, 2023).

In order to guarantee pavement lifespan and minimize maintenance expenses, optimized management is unavoidable (Gong et al., 2022). Subject to permanent stress from heavy traffic and climatic changes, pavements need intensive condition surveys and selective preventive treatments (Titus-Glover, 2019). Proactive management not only minimizes the cost of long-term repairs but also ensures continuous

service (Derras et al., 2022). In this context, multi-criteria decision-making methods, such as Fuzzy AHP, have been increasingly applied in infrastructure management. Recent applications include: the assessment of unmanned maintenance strategies using a hybrid fuzzy-AHP evaluation framework (Hu et al., 2024), benefit-cost analyses integrating fuzzy concepts for pavement testing track planning (Fosu-Saah et al., 2023), and expressway renewal prioritization through a fuzzy Delphi–Fuzzy AHP–TOPSIS model (Zhu et al., 2023). These studies underscore Fuzzy AHP's strength in handling uncertainty and integrating technical, economic, and environmental criteria. Building on this foundation, the present study develops an integrated framework for pavement condition assessment and applies it to a real case study, thereby contributing to both methodological advancement and decision-support practice.

Road infrastructure managers are faced with paramount challenges in terms of pavement quality and lifespan. The rapid deterioration of such pavements, which is driven by the increasing movement of heavy freight, is a major constraint. Heavy vehicles exert repetitive loads that accelerate the wear of infrastructure, leading to cracking, rutting, and reducing the load-carrying capacity (Gong et al., 2022). Additionally, extreme climatic conditions such as heavy rainfall, freeze-thaw, and high temperatures subject pavements to additional stress, contributing to increased material degradation and higher erosion and cracking hazards (Titus-Glover, 2019).

In this context, a case study was conducted on the national road between Sidi Bel Abbès and Aïn Témouchent. This regional strategic corridor is particularly susceptible to accelerated degradation due to high transport flows and harsh environmental conditions. The study identified the most significant issues, such as a high percentage of cracks and high roughness on certain sections. Based on the Fuzzy AHP approach, priority was assigned to critical sections for urgent intervention, which made possible the optimal resource allocation.

To this end, a systematic and uniform evaluation of pavement condition is required to develop optimal maintenance plans. A correct evaluation system enables managers to choose interventions based on specific needs, levels of deterioration, and available resources. The integration of tools such as Fuzzy AHP enables the development of a multi-criteria hierarchy taking into account technical, economic, and environmental factors, thereby enabling optimal maintenance decisions. Through the identification of the most significant causes of pavement deterioration, such evaluations ensure preventive maintenance,

conserving long-term costs in the form of avoiding more expensive reactive actions.

Enhancing pavement management practices is therefore critical in upholding the integrity and safety of road infrastructure. The current paper suggests providing a robust scientific foundation for optimizing pavement management practice through the identification of the most vital criteria for the durability of the latter. Close scrutiny of those criteria will avail a well-defined hierarchy such that decision-making and targeted intervention can be conducted (Titus-Glover, 2019).

The new contribution of the study is the step-by-step prioritization of factors influencing pavement life and quality and the establishment of priorities for efficient road management. Utilizing an integrated framework based on Fuzzy AHP, this study intends to provide enhanced knowledge of the significant factors in pavement maintenance, thereby driving road management policy (Gong et al., 2022, 2024; Galdiani et al., 2022). The findings claim not only to extend existing scientific evidence but also to provide road infrastructure managers with valuable resources with which to optimize their actions and maximize pavement lifespan.

Methodology

This study applies Fuzzy AHP to quantify the pavement's condition through hierarchical ranking of contributing factors by pair-wise comparison and multi-factor weightings.

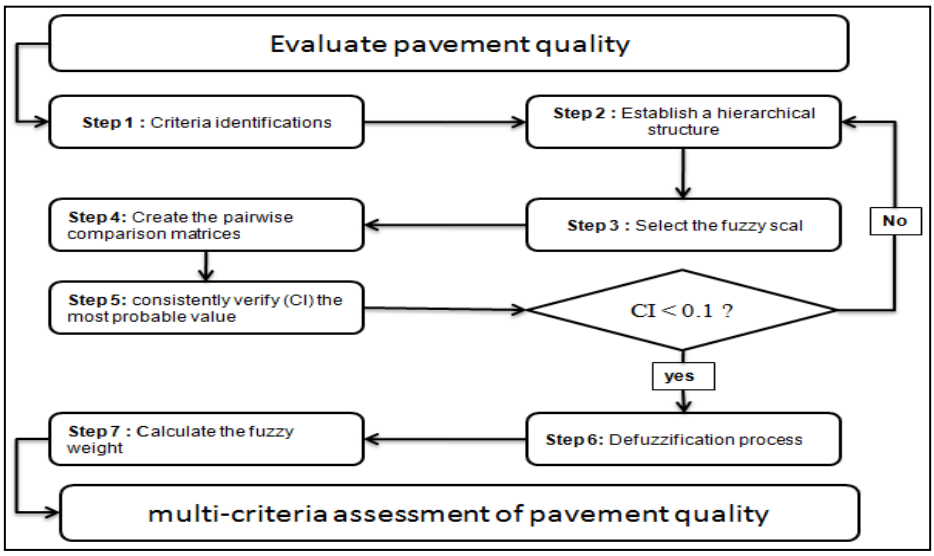

Figure 1 – The methodology used to evaluate pavement quality

The technique supplies a systematic weighing of factors amenable to influence in dealing with the attendant uncertainties of vague human judgment in qualitative rankings. The most important steps are the determination of the most significant factors that affect pavement quality, structuring the hierarchy of the criteria and sub-criteria, and application of the fuzzy analytic hierarchy process to make the prioritization more accurate at different levels of criteria (Figure 1).

Identification and pair-wise criteria comparison

The first step of this study is to identify the criteria affecting pavement quality. The criteria and sub-criteria for assessing the performance of pavements are based on the study of Sirin et al. (2019) and the various cited studies therein. This synthesis identifies 29 factors influencing pavement performance that are grouped into six general categories: surface conditions, infrastructure design, asphalt mixture properties, construction and maintenance quality, traffic loading, and environmental conditions. Every category is supported by research that demonstrates the noteworthy contribution of these criteria to pavement deterioration and optimization.

In the literature examined, there are some studies that bring out the immediate impact of surface conditions — roughness, cracking, and rutting — on the safety and comfort of users. For instance, Zhang et al. (2015) and Wang et al. (2016) present longitudinal and transverse cracks as having an exponential cost of maintenance if not taken care of in a timely manner. Also, Wayne Lee et al. (2017) cite rut depth as a major degradation indicator due to repeated heavy loading.

Asphalt mix properties and construction quality are also recognized as determining criteria. Behl et al. (2013) discuss the effect of additives in asphalt mixtures for enhancing thermal resistance and freeze-thaw cycle resistance, while Haiyan et al. (2017) discuss the effect of initial compaction on pavement life. These findings justify the inclusion of sub-criteria related to materials and processes, such as asphalt content, aggregate quality, and compaction procedures.

Traffic loads, particularly the heaviness of heavy traffic, become a recurring deterioration factor. Studies by Chen and Bai (2018) indicate that heavy vehicle traffic severity encourages cracking and rutting and is thus relevant as a technical sub-criterion.

Finally, the environmental factors, as considered by Tawalare and Raju (2016) and Wayne Lee et al. (2017), emphasize the significance of severe climatic conditions such as freeze-thaw cycles and excessive temperature variations in the rapid deterioration of materials.

A hierarchical structure

A hierarchical model has been established to categorize the criteria and sub-criteria that affect pavement quality. This model is comprised of a number of levels (see Figure 2). The first level consists of the three broad categories that have a considerable effect on pavement quality: technical, economic, and environmental. Each category is then subdivided into particular sub-criteria (level 2), which are recognized as key factors for pavement performance. The bottom of the hierarchy is the sub-sub-criteria, breaking the evaluation factors down into detailed specifics. The hierarchical structure facilitates multi-criteria analysis by establishing the different levels of factors and their interrelations.

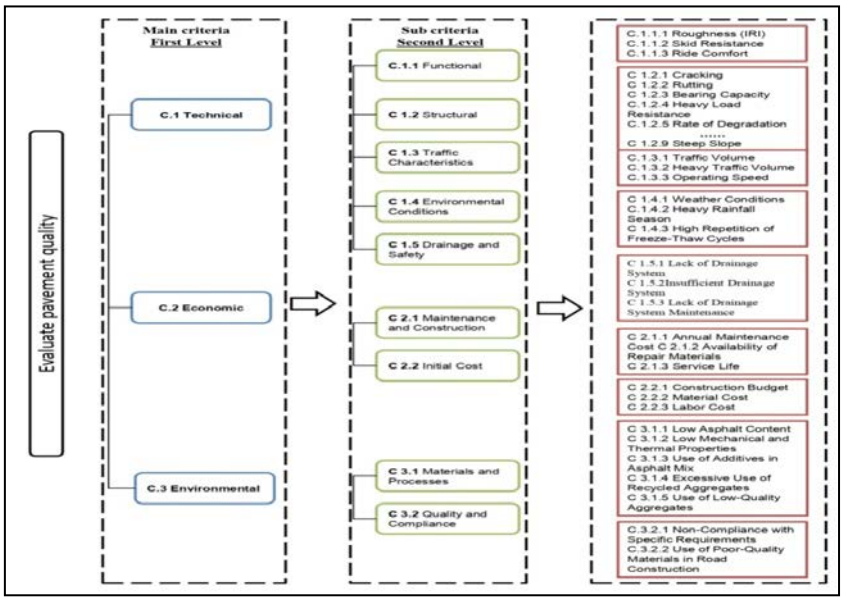

Figure 2 – Hierarchical structure (Source: authors)

For this analysis, the Triangular Fuzzy Number (TFN) is preferred for its simplicity and efficiency. A triangular fuzzy number $\breve{A} = (l, m, u)$ is defined by a triplet of values: l (the minimum value), m (the most likely value), and u (the maximum value), with a membership function $\mu_A(x)$ given by equation (1):

$$\mu_A(x) = \begin{cases} 0 \text{ for } x < 1 \\ \dfrac{x-l}{m-l} \text{ for } l \le x \le m \\ \dfrac{u-x}{u-m} \text{ for } m \le x \le u \\ 0 \text{ for } x > u \end{cases} \quad (1)$$

The algebraic operations between two triangular fuzzy numbers, denoted as $\breve{A}_1 = (l_1, m_1, u_1)\breve{A}_2 = (l_2, m_2, u_2)$, are formalized as follows:

Addition : $\breve{A}_1 + \breve{A}_2 = (l_1 + l_{2,} m_1 + m_{2,} u_1 + u_{2,})$ (2)

Subtraction: $\breve{A}_1 - \breve{A}_2 = (l_1 - l_{2,} m_1 - m_{2,} u_1 - u_{2,})$ (3)

Multiplication : $\breve{A}_1 \times \breve{A}_2 = (l_1 \times l_{2,} m_1 \times m_{2,} u_1 \times u_{2,})$ (4)

Division : $\breve{A}_1 \div \breve{A}_2 = (l_1 \div l_{2,} m_1 \div m_{2,} u_1 \div u_{2,})$ (5)

Reciprocal: $\breve{A}_1^{-1} = (\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1})$ (6)

In this study, the computational approach relies on the use of fuzzy numbers, with specific values presented in Table 1.

Table 1 – The scale for evaluation of criteria using fuzzy AHP

Linguistic	The scale of fuzzy number	Inverse expression
Equally important	(1, 1,1)	(1, 1,1)
Intermediate preference	(1, 2,3)	(1/3.1/2.1)
Moderately more important	(2, 3,4)	(1/4.1/3.1/2)
Intermediate preference	(3, 4,5)	(1/5.1/4.1/3)
Strongly more important	(4, 5,6)	(1/6.1/5.1/4)
Intermediate preference	(5, 6,7)	(1/7.1/6.1/5)
Very Strong more important	(6, 7,8)	(1/8.1/7.1/6)
Intermediate preference	(7, 8,9)	(1/9.1/8.1/7)
Extremely more important	(8, 9,9)	(1/9.1/9.1/8)

Source: (Buckley, 1985)

Pair-wise comparison matrices are constructed by comparing the relative importance of the criteria at the same level in the hierarchy using the pairwise comparison method (Appendix 1).

$$[\tilde{A}] = \begin{bmatrix} (1,1,1) & (l_{12}, m_{12}, u_{12}) & \dots & (l_{1n}, m_{1n}, u_{1n}) \\ (\frac{1}{u_{12}}, \frac{1}{m_{12}}, \frac{1}{l_{12}}) & (1,1,1) & \cdots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & & \ddots \quad \vdots \\ (\frac{1}{u_{1n}}, \frac{1}{m_{1n}}, \frac{1}{l_{1n}}) & (\frac{1}{u_{2n}}, \frac{1}{m_{2n}}, \frac{1}{l_{2n}}) & \dots & (1,1,1) \end{bmatrix} \quad (7)$$

The consistency of each comparison matrix is then verified by calculating the consistency index (CI) and the consistency ratio (CR), according to the following formulas:

$$IC = \frac{\lambda_{max} - n}{n - 1} \quad (8)$$

$$CR = \frac{IC}{RI} \quad (9)$$

where λ_{max} is the largest eigenvalue of the matrix, n is the dimension of the matrix, and RI represents the random consistency index, with its values provided in Table 2 (Galdiani et al., 2022).

Table 2 – Random consistency index value

N	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI	0.53	0.88	1.11	1.25	1.34	1.41	1.45

If the consistency ratio (CR) is less than 10% (CR < 10%), the matrix is considered consistent; conversely, a CR greater than 10% indicates inconsistency, requiring a reassessment of the judgments in the comparison matrix. The final weights are determined by the fuzzy averaging method, which involves calculating the fuzzy geometric mean of the TFN values for each factor (Equation 10). The obtained fuzzy weights are then calculated using the formula in Equation 11 (Gherbi et al., 2024):

$$\breve{r}_i = (\prod_{j=1}^{n} \breve{a}_{ij})^{1/n}, \quad i = 1,2,3, \dots, n \quad (10)$$

$$w_i = \breve{r}_i \otimes (\breve{r}_1 \oplus \breve{r}_2 \oplus \dots \dots \breve{r}_n)^{-1} \quad (11)$$

The fuzzy weights are then defuzzified using the center of area method, as shown in Equation 12. Subsequently, they are normalized to obtain interpretable values, as demonstrated in Equation 13:

$$w_i = \frac{l+m+u}{3} \quad (12)$$

$$nw_i = \frac{w_i}{\sum_{i=1}^{n} w_i},\ i = 1,2,\dots,n \quad (13)$$

Pavement degradation classification

In this study, a widely used assessment system to score pavement conditions has been employed to classify the level of road infrastructure deterioration. The Pavement Condition Index (PCI), which has been widely reported in the literature, is an index that measures pavement deterioration on a scale ranging from 0 (critical) to 100 (excellent).

Table 3 shows the structural and functional classification of pavement condition based on the dominant factors of cracking, rutting, potholes, and drainage efficiency. This follows from the systems that have been utilised by civil engineering structures in the past for scoring purposes in evaluating their structure, e.g., the French IQOA (quality assessment of engineering structures) scoring system (Orcesi et al., 2011).

Table 3 – Pavement condition classification based on degradation levels

Class	Pavement Condition	PCI Range (0-100)	Observed Distress Types
Excellent	Pavement in perfect condition	85 - 100	Smooth surface, minimal or no cracks, effective drainage
Good	Minor surface deterioration	70 – 85	Hairline cracks, slight surface wear, good drainage
Fair	Moderate deterioration	50 – 70	Medium cracks, slight rutting, early-stage ravelling
Poor	Advanced deterioration	25 - 50	Potholes, severe cracks, localized subsidence
Very Poor	Severely deteriorated pavement	0 – 25	Extensive deformation, weakened structure, severe drainage issues

Results and discussion

Analysis of final criterion weights

The decomposition of the results highlights the predominance of the technical criterion for pavement quality assessment, occupying 72.4% of the total weight (Figure 3). This predominance is caused by the technical parameters' immediate effect on road infrastructure lifespan, according to Garraín and Lechón (2019). In particular, properties such as bearing capacity and roughness play a crucial role in affecting pavement performance and its mechanical resistance to stress, as well as traffic load-carrying capacity. Therefore, the best practice and materials come as a strategic approach to increasing these inherent attributes, reducing costly maintenance procedures, and obtaining the maximum road structure durability.

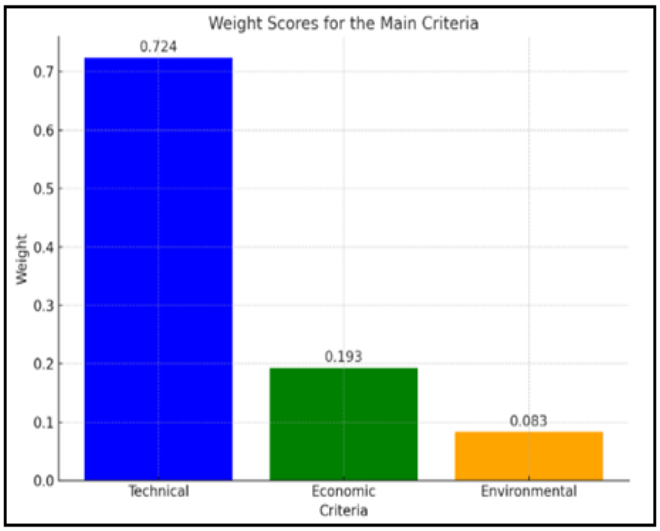

Figure 3 – Weight scores for the main criteria

The most significant of the technical criteria analysis (Table 4) are the functional sub-criteria, which have a combined weight of 48.1%. This preeminence is an indication of the central role played by surface condition attributes in optimizing the performance and life expectancy of road infrastructures. Of these, roughness, with a weight of 0.634, is the most critical factor because it has a direct impact on user comfort and pavement resistance, as seen from Saeed et al. (2017). Maintaining a correct surface

condition minimizes premature degradation and enhances maintenance efficiency strategies.

Table 4 – Weight scores for the technical sub-criteria

Level 1		Level 2		Level 3	
Criteria	**Weight (%)**		**Weight (%)**		**Weight (%)**
C.1 Technical	72.4	C.1.1 Functional	48.1	C.1.1.1 Roughness (IRI)	63.4
				C.1.1.2 Skid Resistance	26
				C.1.1.3 Ride Comfort	10.6
		C 1.2 Structural	25.8	C.1.2.1 Cracking	30.23
				C 1.2.2 Rutting	21.63
				C 1.2.3 Bearing Capacity	10.58
				C 1.2.4 Heavy Load Resistance	6.21
				C 1.2.5 Rate of Degradation	6.82
				C 1.2.6 Weather Resistance	11.17
				C 1.2.7 Thin Asphalt Layers	7.54
				C 1.2.8 Extremely Rough Road	3.72
				C 1.2.9 Steep Slope	2.1
		C 1.3 Traffic Characteristics	11.6	C 1.3.1 Traffic Volume	62.3
				C 1.3.2 Heavy Traffic Volume	24
				C 1.3.3 Operating Speed	13.7
		C 1.4 Environmental Conditions	7.8	C 1.4.1 Weather Conditions	63.3
				C 1.4.2 Heavy Rainfall Season	25.9
				C 1.4.3 High Repetition of Freeze-Thaw Cycles	10.8
		C 1.5 Drainage and Safety	6.7	C 1.5.1 Lack of Drainage System	55.7
				C 1.5.2 Insufficient Drainage System	32,4
				C 1.5.3 Lack of Drainage System Maintenance	11.9

As far as structural sub-criteria are concerned, they also have a considerable impact, with a weighting of 25.8%. Cracking and rutting are some of the parameters that act as important indicators of pavement deterioration, which calls for serious consideration in infrastructural design and maintenance. The determinants of paramount importance in this context are bearing capacity and resistance to heavy loads, which verify that dynamic stresses, particularly those due to heavy transport traffic, significantly accelerate structural layer degradation (Yang et al., 2016). Optimized sub-grade design and high-performance materials are thus a

necessity in order to reduce the number of interventions and enhance the service life of road infrastructures.

Traffic conditions, although less important than functional and structural issues (11.6%), also contribute significantly towards pavement degradation. Traffic volume (62.3%) and heavy traffic (24%), in specific terms, subject the pavement surface to repetitive loading, accelerating its deterioration. These findings are in agreement with the research of Meegoda and Gao (2015), in which the authors note that pavements should be designed to withstand anticipated load limitations to prevent premature deterioration.

Concerning environmental conditions (7.8% weight), the results indicate that meteorological conditions (63.3%) are the dominant influence, surpassing other influences such as the rainy season (25.9%) and freeze-thaw (10.8%). Climatic conditions' influence has been corroborated by Tawalare and Raju (2016) and Premkumar and Vavrik (2016), who state that severe thermal fluctuations expedite material degradation and compromise its mechanical strength. Furthermore, Zhang et al. (2018) demonstrated that long-term thermal exposure, with traffic loading, accelerates premature cracking and, thus, reduces pavement service life. While less important, the rainy season with high rainfall is nonetheless a major degradation factor as stated by Brown and Tawalare (2016). Heavy volumes of precipitation can cause settlement and erosion of the surface, especially in the absence of good drainage systems. Finally, the recurrence of freeze-thaw cycles (10.8%) calls for investment in thermally fluctuation-resistant materials to prevent cracking and loss of load-carrying ability (Tian et al., 2017).

The drainage sub-criterion (6.7%) once more indicates the major function of water management in ensuring pavement durability. No adequate drainage system is found to be the most important consideration in this category, carrying a weight of 55.7%. This is attested by Premkumar and Vavrik (2016), who state that water pooling on the surface accelerates degradation, particularly in asphalt pavements, which are most susceptible to water penetration. Inadequate drainage, with a weighting of 32.4%, can result in localized settlements as well as structural distortions, a fact reported by Yang et al. (2016) and Wayne Lee et al. (2017), who discovered rutting issues due to inadequate water runoff. Finally, poor maintenance of drainage networks (11.9%) is also a significant aggravating factor that increases the susceptibility of pavement erosion. It has been stated by Haiyan et al. (2017) that proper maintenance of drainage infrastructure is very important in order to attain long-term efficiency and prevent structural damage caused by water accumulation.

Economic factors (Table 5), contributing a combined weight of 19.3%, highlight the significance of embracing an optimized budget control method in road infrastructure maintenance strategies. Here, the maintenance and construction cost criterion as a sub-criterion is the leading determinant, having a weight of 0.751, highlighting the powerful impact of budgetary decisions on pavement lifespan. More importantly, the yearly maintenance cost, weighted at 0.685, is a determining factor in infrastructure durability. The findings are in agreement with the principles proposed by Tawalare and Raju (2016), who advocate for prioritizing preventive maintenance approaches to minimize reactive interventions, which tend to be more expensive and less efficient in the long run.

Table 5 – Weight scores for the economic sub-criteria

Level 1		Level 2		Level 3	
Criteria	**Weight (%)**		**Weight (%)**		**Weight (%)**
C.2 Economic	19.3	C.2.1 Maintenance and Construction	75.1	C.2.1.1 Annual Maintenance Cost	68.5
				C.2.1.2 Availability of Repair Materials	21.8
				C.2.1.3 Service Life	9.7
				C.2.2.2 Material Cost	24.9

Furthermore, although the initial cost has a lesser effect, with a weight of 0.249, it is nonetheless an important variable in the economic viability of road works. The high influence put on the construction budget (0.75) emphasizes the necessity for adequate allocation of funds between initial and recurring maintenance costs. This result concurs with the results of Abtahi et al. (2011), who stress the importance of proper budgeting to provide maximum lifespan with the least overall lifecycle cost of pavements.

Environmental conditions account for 8.3% of the overall evaluation (Table 6), which indicates their contributory role towards road infrastructure longevity. Construction materials and practices are examples of such factors, particularly in climates with high variations. Specifically, low asphalt content and material thermal properties have a direct bearing on pavement resilience to unfavorable environmental conditions (Tawalare and Raju, 2016; Onoyan-Usina et al., 2013). Therefore, selecting materials that have high thermal change resistance and severe climatic cycles is essential to counteract early degradation.

Whereas concerns over compliance standards, although low in weight of 0.0249 and moderately low, have to do with non-compliance with

standards, rigorous monitoring of compliance during construction is therefore invaluable in the avoidance of early deterioration of pavements. Herein, the provision of high-standard materials is elementary in the elimination of remedial actions and assuring infrastructure stability for the long run.

These findings corroborate the imperative of pre-emptive technical parameter control to restrain premature aging of pavements. The prevalence of bearing capacity and roughness emphasizes the key function of pre-emptive action to achieve optimum infrastructure lifecycle performance. Through restraining maintenance operation frequency and expenses, this practice supports the research findings of Derras et al. (2022) and Oulha and Derras (2023), who propose active maintenance techniques. Thus, adopting an active pavement management approach is the best solution to optimize resources and achieve the longest life for the infrastructure.

Table 6 – Weight scores for the environmental sub-criteria

Level 1		**Level 2**		**Level 3**	
Criteria	**Weight** (%)		**Weight** (%)		**Weight** (%)
C.3 Environmental	8.3	**C.3.1**Materials and Processes	75.1	**C.3.1.1** Low Asphalt Content	48.3
				C.3.1.2 Poor Mechanical and Thermal Properties	26.5
				C.3.1.3 Use of Additives in Asphalt Mixtures	14.4
				C.3.1.4 Use of Low-Quality Aggregates	10.8
		C.3.2 Quality and Compliance	24.9	**C.3.2.1** Non-Compliance with Specific Requirements	75.1
				C.3.2.2 Use of Poor-Quality Materials in Constructed Roads	24.9

Table 7 provides a comprehensive summary of the final weight results, detailing the local and global weight distributions assigned to the criteria, sub-criteria, and sub-sub-criteria. The analysis of these tables reveals significant variations in weight values, demonstrating the distinct influence of each factor on pavement quality. These discrepancies underscore the relative importance of the evaluated parameters, enabling the identification of the most critical elements for the assessment and optimization of road maintenance strategies.

Table 7 – Summary of final weights for criteria, sub-criteria, and sub-sub-criteria in pavement quality assessment

Level 1		Level 2			Level 3		
Criteria	**Weight** (%)		**Weight** (%)	**Wi**		**Weight** (%)	**Wi**
C.1	72.4	**C.1.1**	48.1	0.3482	**C.1.1.1**	63.4	0.2208
					C.1.1.2	26	0.0705
					C.1.1.3	10.6	0.0369
		C 1.2	25.8	0.1816	**C.1.2.1**	30.23	0.0565
					C 1.2.2	21.63	0.0404
					C 1.2.3	10.58	0.0198
					C 1.2.4	6.21	0.0115
					C 1.2.5	6.82	0.0127
					C 1.2.6	11.17	0.0209
					C 1.2.7	7.54	0.0140
					C 1.2.8	3.72	0.0069
					C 1.2.9	2.1	0.0039
		C 1.3	11.6	0.0840	**C 1.3.1**	62.3	0.0523
					C 1.3.2	24	0.0202
					C 1.3.3	13.7	0.0115
		C 1.4	7.8	0.0565	**C 1.4.1**	63.3	0.0357
					C 1.4.2	25.9	0.0146
					C 1.4.3	10.8	0.0061
		C 1.5	6.7	0.0486	**C 1.5.1**	55.7	0.0270
					C 1.5.2	32,4	0.0157
					C 1.5.3	11.9	0.0058
C.2	19.3	**C.2.1**	75.1	0.1449	**C.2.1.1**	68.5	0.0992
					C.2.1.2	21.8	0.0316
					C.2.1.3	9.7	0.0141
		C.2.2	24.9	0.0481	**C.2.2.1**	75.1	0.0361
					C.2.2.2	24.9	0.0120
C.3	8.3	**C.3.1**	75.1	0.0623	**C.3.1.1**	48.3	0.0301
					C.3.1.2	26.5	0.0165
					C.3.1.3	14.4	0.0090
					C.3.1.4	10.8	0.0073
		C.3.2	24.9	0.0207	**C.3.2.1**	75.1	0.0155
					C.3.2.2	24.9	0.0051

Application of the methodology to a case study

The present case study focuses on National Road No. 101 (RN101), which connects Sidi Bel Abbès to Aïn Témouchent. This road represents a strategic component of the national highway network, serving as a major corridor between the inland areas and the Témouchent coastal region, and thus plays a vital role in regional mobility and economic exchanges. The average daily traffic volume is estimated at 24,508 vehicles/day, indicating a considerable loading on the pavement. Traffic pressure is further intensified during the summer season due to the touristic attractiveness of

the coastal zone and the strategic position of Sidi Bel Abbès as a regional crossroads in Western Algeria. These characteristics place RN101 among the most heavily trafficked routes, making it particularly vulnerable to the combined effects of high traffic loads and local climatic conditions.

In terms of traffic composition, the road supports a medium level of heavy vehicle traffic, estimated between 500 and 1000 trucks/day, which significantly contributes to the structural deterioration of the pavement. The operating speed ranges from 70 to 90 km/h, reflecting fluid traffic conditions along most sections. However, the climatic conditions are characterized by an alternation of dry and humid seasons, which exacerbates pavement distress mechanisms such as cracking and rutting. Furthermore, the drainage system is limited, with recurrent stagnation zones and an irregular maintenance regime, leading to water infiltration and weakening of the pavement layers. From a structural standpoint, the bearing capacity measured by FWD testing indicates a deflection between 0.4 and 0.6 mm, which corresponds to a medium level of performance in terms of load-carrying capacity.

The pavement assessment reveals a Condition Score (CS) of 5.0081 (PCI range: 50–70), classifying the road in the "Fair" category with moderate deterioration, characterized by medium cracks, slight rutting, and early-stage ravelling (see Table 8 and Figures 4 and 5). The primary contributing factors to this condition include pavement roughness (0.6624), annual maintenance cost (0.7944), and the availability of repair materials (0.2844), highlighting significant maintenance and material management issues.

Structural criteria indicate a high vulnerability to traffic loads and climatic conditions, particularly cracking (0.1695), rutting (0.202), and the impact of heavy rainfall (0.1022). Furthermore, climatic conditions significantly influence pavement degradation, as evidenced by "Weather Conditions" (C.1.4.1) with a score of 0.1785 and "Heavy Rainfall Season" (C.1.4.2) at 0.1022, suggesting that adverse weather accelerates pavement distress. Additionally, the lack of an adequate drainage system (C.1.5.1) with a weight of 0.135 is a critical issue, exacerbating crack propagation and structural weakening due to moisture infiltration.

Figure 4 – Longitudinal and transverse medium cracking observed on the pavement surface

Figure 5 – Slight rutting indicating initial surface deformation

To enhance the condition of this road linking Sidi Bel Abbès to Aïn Témouchent, a major rehabilitation strategy is required, combining structural reinforcement and the implementation of an appropriate overlay system. The choice of this treatment is supported by the Fuzzy AHP results, which emphasized structural weaknesses and environmental stresses as the primary causes of deterioration. In this context, structural reinforcement involves strengthening the existing pavement layers through the use of high-performance bituminous mixtures with superior rutting resistance and durability under freeze–thaw cycles. The overlay system refers to the application of an additional asphalt layer that restores surface quality, increases load-bearing capacity, and prolongs service life. Considering the high traffic volume on RN101 (24,508 vehicles/day) and its exposure to seasonal rainfall and thermal variations, such measures are necessary to ensure the long-term durability of the pavement. Furthermore, optimizing the drainage system remains essential to limit water infiltration, reduce crack propagation, and maintain structural integrity over time.

Table 8 – Final weighting and condition score calculation for the case study pavement (Sidi Bel Abbès – Aïn Témouchent)

	Factor	Score (ASC_i)	overall weight (Wi)	PCI = ASCi × W_i
1	C.1.1.1	3	0.2208	0.6624
2	C.1.1.2	5	0.0705	0.3525
3	C.1.1.3	3	0.0369	0.1107
4	C.1.2.1	3	0.0565	0.1695

5	C 1.2.2 Factor	5 Score (ASC_i)	0.0404 overall weight (Wi)	0.202 PCI = ASCi × W_i
6	C 1.2.3	5	0.0198	0.099
7	C 1.2.4	5	0.0115	0.0575
8	C 1.2.5	3	0.0127	0.0381
9	C 1.2.6	3	0.0209	0.0627
10	C 1.2.7	3	0.0140	0.042
11	C 1.2.8	5	0.0069	0.0207
12	C 1.2.9	5	0.0039	0.0195
13	C 1.3.1	5	0.0523	0.2615
14	C 1.3.2	5	0.0202	0.101
15	C 1.3.3	7	0.0115	0.0805
16	C 1.4.1	5	0.0357	0.1785
17	C 1.4.2	7	0.0146	0.1022
18	C 1.4.3	9	0.0061	0.0549
19	C 1.5.1	5	0.0270	0.135
20	C 1.5.2	3	0.0157	0.0471
21	C 1.5.3	5	0.0058	0.029
22	C.2.1.1	7	0.0992	0.7944
23	C.2.1.2	9	0.0316	0.2844
24	C.2.1.3	5	0.0141	0.0705
25	**C.2.2.1**	3	0.0361	0.1083
26	C.2.2.2	3	0.0120	0.036
27	C.3.1.1	5	0.0301	0.1505
28	C.3.1.2	5	0.0165	0.0825
29	C.3.1.3	7	0.0090	0.511
30	C.3.1.4	7	0.0073	0.1085
31	C.3.2.1	5	0.0155	0.0357
32	C.3.2.2	3	0.0051	0.6624

$cs = \sum Wi26i=1 \times ASCi$ =5.0081, Class Fair, Moderate deterioration, Medium cracks, slight rutting, early-stage ravelling

Conclusion

This study set out to explore the potential of a structured multi-criteria decision-making approach to assess pavement quality more objectively and comprehensively. By applying the Analytic Hierarchy Process (AHP) enhanced with expert judgment, the complexity of pavement degradation was captured through a hierarchical model encompassing technical, economic, and environmental factors.

The evaluation framework proved effective in identifying the most critical elements influencing road performance, such as surface roughness, maintenance costs, and the availability of repair materials. These findings reflect the challenges faced in real-world pavement management, where degradation often results from a combination of insufficient maintenance, environmental exposure, and traffic-related stresses.

Applied to a real case study on the Sidi Bel Abbès – Témouchent road segment, the method delivered a clear diagnosis of the pavement's condition, which was classified as fair and in need of major rehabilitation. This practical outcome illustrates the value of the approach not only as an academic tool but also as a decision-support system for infrastructure managers and engineers.

Ultimately, this methodology contributes to more transparent and evidence-based maintenance planning. Further refinement of the model, such as the integration of GIS data or real-time monitoring, could expand its applicability and precision in future assessments.

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Višekriterijumska procena kvaliteta kolovoza zasnovana na fazi AHP metodologiji: integrisani pristup za optimizaciju performansi puteva

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OBLAST: građevinarstvo, nauke o odlučivanju

KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: U radu se predlaže višekriterijumski okvir za procenu stanja kolovoza primenom fazi analitičkog hijerarhijskog procesa (eng. Fuzzy AHP) koji objedinjuje tehničke, ekonomske i ekološke aspekte. Putna infrastruktura predstavlja ključnu komponentu transportnih sistema, a njena održivost zavisi od efikasnog upravljanja i održavanja. Cilj ovog istraživanja je da pruži naučne osnove za optimizaciju planiranja održavanja puteva kroz prepoznavanje i rangiranje ključnih faktora koji utiču na kvalitet kolovoza. Okvir uzima u obzir tehničke, ekonomske i ekološke dimenzije kako bi se obezbedila sveobuhvatna procena.

Metode: Razvijena je hijerarhijska struktura kriterijuma za evaluaciju koja obuhvata tehničke podkriterijume kao što su hrapavost površine, nosivost,

karakteristike saobraćaja i uslovi životne sredine, kao i ekonomske faktore i faktore povezane sa materijalima. Težinski koeficijenti su određeni primenom metode fazi analitičkog hijerarhijskog procesa, uz proveru konzistentnosti radi potvrđivanja pouzdanosti rezultata. Studija slučaja primenjena je na državni put RN101 koji povezuje Sidi Bel Abes i Ajn Temušent.

Rezultati: Analiza je pokazala značajne nedostatke na određenim deonicama, uključujući prekomernu hrapavost i nedovoljnu konstruktivnu čvrstoću. Deonice izložene visokim saobraćajnim opterećenjima i nepovoljnim uslovima životne sredine pokazale su najveći stepen degradacije. Utvrđeno je da tehnički aspekti, pogotovo nosivost i kvalitet materijala, najviše utiču na performanse i dugovečnost kolovoza.

Zaključak: Rezultati pokazuju relevantnost i primenljivost predloženog evaluacionog modela zasnovanog na metodi fazi analitičkog hijerarhijskog procesa pri određivanju prioriteta u procesu održavanja puteva. Metodologija se može proširiti na druge putne mreže koje zahtevaju strukturisan i pouzdan pristup proceni kvaliteta kolovoza.

Ključne reči: kvalitet kolovoza, fazi analitički hijerarhijski proces (FAHP), strategija održavanja, višekriterijumsko upravljanje.

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Monitoring steel bridge degradation with multi-criteria approaches

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FIELD: civil engineering
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Abstract:

Introduction/purpose: The objective of this work is to formulate a Fuzzy Analytical Hierarchy Process (FAHP) method that can assist specialists in conducting inspections of steel bridges. Fuzzy logic approaches are preferred due to their ability to handle uncertain information in ways that mirror human reasoning processes, making them particularly suitable for structural damage assessment applications.

Methods: The procedure is organized in a hierarchical framework consisting of 35 criteria and sub-criteria. This structure is designed to assist the project's inspection stakeholders in making decisions. The weights Wi of these criteria are established by utilization of the FAHP, supplemented by expert evaluations, in order to compute the comprehensive performance indicator CPI score that represents the extent of damage to the bridge being examined. The structure is categorized based on its overall CPI score using the IQOA notation.

Results: To rigorously evaluate the practical applicability and accuracy of the developed FAHP methodology, a real-world case study was undertaken. The methodology was applied to assess the health condition of the steel bridge situated in Oued Taria, located within the Mascara region. The application of this comprehensive approach yielded results that demonstrated remarkable consistency and strong alignment with previous, independently conducted expert assessments of the same structure.

Conclusion: The successful application and validated results unequivocally affirm the scientific efficacy and practical utility of this FAHP-based tool. It

serves as a robust and reliable decision-support system, significantly enhancing the capabilities of experts in accurately assessing the complex and often subjective aspects of damage in steel bridges. This methodology not only streamlines the inspection process but also contributes to more objective and consistent evaluations, ultimately leading to improved maintenance planning and enhanced safety of critical bridge infrastructure.

Key words: steel bridges, Fuzzy Analytical Hierarchy Process (FAHP), comprehensive performance indicator (CPI).

Introduction

Throughout their lifespan, steel bridges are subjected to a multitude of loads that progressively compromise their initial structural integrity. These loads can be of various types: permanent loads exerted by the self-weight of the structure and the elements it supports, dynamic loads induced by traffic, accidental loads such as impacts or exceptional overloads, and natural loads related to meteorological phenomena. The accumulation of damage due to traffic loads, especially from overweight trucks, significantly affects the durability of steel bridge components, necessitating detailed studies to assess these impacts (Cha et al., 2016; Wang, Deng & Shao, 2016). Additionally, the randomness of traffic loads can lead to increased fatigue in bridge elements, particularly in wide bridges with high vehicle velocity (Wysokowski, 2020). Environmental factors, including corrosion and climate change, further exacerbate the degradation of steel bridges, impacting their load-carrying capacity and structural integrity (Gocal & Odrobinak, 2020; Palu & Mahmoud, 2019). Extreme events, such as blasts, also pose significant risks, potentially leading to local damage or progressive collapse of the structure (Olmati et al., 2013; Tetougueni, Zampieri & Pellegrino, 2020). Therefore, it is crucial to consider these various load types and their cumulative effects when evaluating the structural performance and longevity of steel bridges. In light of these limitations, the Fuzzy Hierarchy Analysis Process (FAHP) is a robust method for efficiently assessing and classifying the overall damage level of bridges. This approach integrates the traditional Analytic Hierarchy Process (AHP) with fuzzy logic to handle the inherent uncertainties and subjective judgments involved in evaluating complex structures. For instance, the FAHP method has been successfully applied to assess corrosion damage in reinforced concrete bridges by combining various factors such as the Corrosion Damage Index, Environmental Change Factor, and Material Vulnerability Factor, thereby providing a comprehensive damage evaluation (Gao & Li, 2018). Similarly, the FAHP method has been utilized in the risk assessment of bridges during

construction, demonstrating its effectiveness in identifying and ranking diverse risk factors through a fuzzy logic-based approach (Cheng, Xu & Chen, 2019). Moreover, the improved FAHP method, which introduces reliability into the judgment matrix, has been shown to enhance the precision of evaluations for large-span concrete cable-stayed bridges by addressing the fuzziness of subjective judgments (Li & Qu, 2023). The application of FAHP in the maintenance programming of masonry arch bridges further underscores its versatility, as it allows for the classification of degradation states based on a multitude of criteria and sub-criteria, ensuring a systematic and reliable assessment (Lallam, Mammeri & Djebli, 2021). Furthermore, the hierarchical nature of FAHP enables a thorough analysis of criteria, which aids in making well-informed decisions regarding damage assessment (Lallam, Djebli & Mammeri, 2023). Within the same framework, Fuzzy Analytic Hierarchy Process (FAHP) is a very effective method for determining and classifying the degree of damage in steel bridges. Research indicates that FAHP can quantitatively assess safety conditions by integrating various monitoring data, such as stress, deformation, and environmental factors, which are critical for understanding structural integrity (Yang et al., 2024; Su et al., 2024). The method's ability to handle uncertainties and subjective judgments enhances its applicability in complex evaluations, as demonstrated in studies on both steel box girder bridges and concrete cable-stayed bridges (Li & Qu, 2023; Liu et al., 2023). The study devised a Fuzzy Analytical Hierarchy Process (FAHP) to assist specialists in conducting steel bridge inspection campaigns. The approach has 35 criteria and sub-criteria, with weights derived by FAHP. The comprehensive performance indicator CPI score is categorized using IQOA notation. The methodology was utilized on the Oued Taria steel bridge, validating its efficacy in evaluating reinforced concrete bridges.

Steel girder bridges: a structural overview

Steel-girder bridges are a popular choice for transportation infrastructure, primarily relying on steel girders for support construction. These horizontal structural elements extend between two abutments or piers, supporting the load of the bridge deck. Steel girder bridges are known for their durability and longevity, making them ideal for heavily frequented highways and seismic regions. Engineers can construct steel girder bridges in straight, curved, or skewed alignments, typically for long spans with shallow depths. As shown in Figure 1, the main components of a steel girder bridge include girders, the deck, abutments, bearings,

expansion joints, a drainage system, access points, lighting, and guardrails.

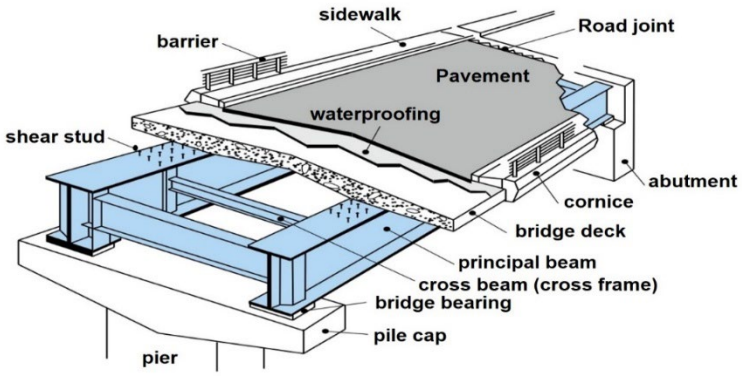

Figure 1 – Steel girder bridge

Case study: Oued Tagia steel bridge

Geographical location

The object of the study is a bridge located at kilometer point 74+900, across the Oued Tifrit on National Road NR 06. The site is situated at the entrance of the city of Taria in the wilaya of Mascara, located in the north-western part of Algeria. The GPS coordinates are as stated: they correspond to a latitude of 35.1138°N and a longitude of 0.082°E. Due to its favorable geographical location, this bridge serves as a vital thoroughfare for both local residents and tourists in the region. Figure 2 illustrates the precise geographic coordinates of this bridge, which was built using a steel framework.

GPS coordinates : Latitude : 35°06'49.7"N Longitude : 0°04'55.2"E

Figure 2 – Satellite view of the bridge as shown on Google Maps

Description of the bridge

Figure 3 depicts a comprehensive perspective of the bridge from a downstream vantage point. The assessment pertains to a structure situated in a linear configuration along National Route NR 06, crossing Oued Tifrit at KP 74+900.

Regarding the framework, the bridge superstructure consists of three main steel girders with solid webs. These girders are of the Welded Built-Up Section (WBS) type, thereby allowing them to be optimized for the 30-meter span of the bridge. Furthermore, a system of truss cross-beams reinforces the longitudinal girders, with three bracing beams placed in the middle of the span and two at each end for enhanced stability.

Moving on to the deck, it is a composite steel-concrete system with a thickness of 20 cm. Crucially, it is not merely resting on the girders; instead, it is made integral with the upper flange of each steel girder. This connection is ensured by shear connectors (studs) welded to the top flange of the girders. This design ensures composite action, where the concrete slab and steel girder work together to resist bending stresses, consequently increasing the efficiency and load-bearing capacity of the structure.

Moreover, the main structural system of the bridge is that of a simply supported beam. This design allows for a simple and direct transfer of loads to the abutments, without significant bending moments at the supports. The bridge rests on two massive reinforced concrete abutments, which are protected by gabions and reinforced with wing walls.

Figure 3 – Panoramic view downstream from the bridge

Summary of bridge damages

The bridge in question holds a crucial strategic position, serving as a vital link between the wilayas of Mascara and Saida along the national road NR06. As a result, it experiences heavy traffic and serves as an essential crossing point for both local residents and visitors to the region. Our on-site inspection, as illustrated in Figure 4, revealed a range of concerning damage types. Despite being constructed in the early 1980s according to preliminary information - a relatively recent timeframe that should suggest better condition - the bridge's health status contradicts expectations.

Figure 4 – Images depicting the extent of bridge damage: a) intrados of a cantilevered slab, b) abutment 02, c) main beams, d) cross frame, e) pavement, f) barrier

The inspection uncovered several critical issues: localized concrete spalling with exposed corroded reinforcement, water seepage marks, and efflorescence on the underside of the deck slab and abutments, as shown in Figures 4 (a-c). Furthermore, pronounced rust was clearly observed on the lower flanges of the steel girders and at the crossbeam joints; see Figures 4 (a-d). The road surface hasn't escaped damage either, with Figures 4 (e-f) showing cracking of the deteriorated pavement. The guardrails are in a particularly poor state, with detached, deformed, and generally deteriorated posts. These multiple issues, spanning various components of the bridge structure, indicate a pressing need for comprehensive maintenance and potential rehabilitation to ensure the continued safety and functionality of this important infrastructure asset.

FAHP-based procedure for evaluating the degradation of steel bridges

In order to evaluate the level of degradation of older steel bridges, this work intends to construct a numerical model using the Fuzzy Analytical Hierarchy Process (FAHP) approach. Figure 5 shows the five steps that make up the suggested flowchart. First, determine the causes of bridge deterioration and its hazards. Next, we build the hierarchical structure of the model. We use the FAHP approach to set up this structure and determine the weightings of the factors and sub-factors, as we will explain later. The next phase computes a comprehensive performance indicator (CPI) to classify the degree of degradation of the steel bridge in the final stage.

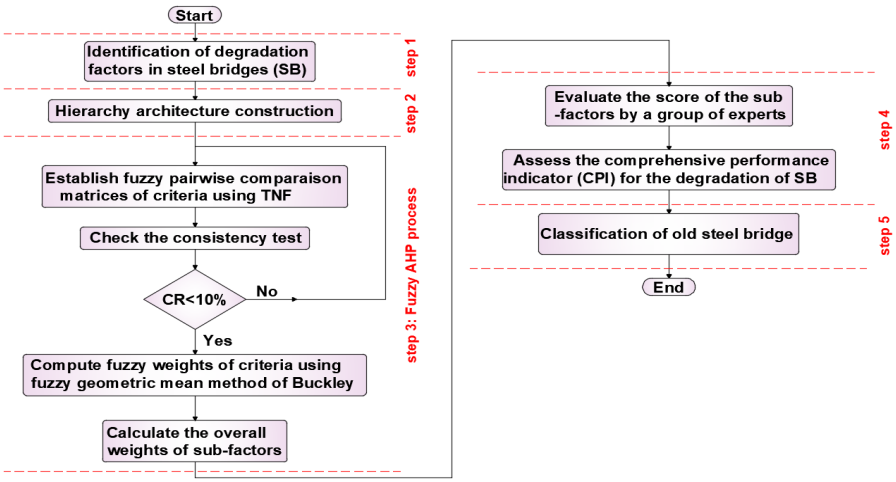

Figure 5 – Procedure flowchart for assessing the degradation of steel bridges

Identifying degradation factors and creating the hierarchical structure

The developed methodology demonstrates broad applicability to different types and structural systems of bridges, as evidenced by our practical experience on masonry road bridges (Lallam, Mammeri & Djebli, 2021) and reinforced concrete bridges (Berrekheroukh et al., 2025), as well as its potential extension to pedestrian bridges and steel or composite steel-concrete structures. The fundamental principles of our approach are sufficiently flexible to adapt to these various structural configurations, with the required adaptations primarily focusing on adjusting the criteria and sub-criteria for assessing the degree of degradation based on the specificities of each case study. The structural system, including the support configuration (simply supported beams, continuous beams, etc.), indeed constitutes a determining factor that our methodology integrates during the scoring of criteria related to the load-bearing elements of the analyzed bridge, thus enabling an assessment adapted to the specific mechanical and behavioral characteristics of each structure.

The methodology for calculating the model begins with a crucial step: identifying and selecting factors likely to influence the degradation of the structure. This initial phase is of paramount importance as it lays the foundation for all subsequent analysis. To ensure the comprehensiveness and relevance of this selection, a dual approach is adopted. On the one hand, a thorough examination of specialized literature is conducted, allowing for the identification of factors recognized by the scientific community as significant in the bridge degradation process. This literature review provides a solid base, grounded in theoretical and empirical knowledge accumulated over the years by researchers and practitioners in the field. On the other hand, this foundation is enriched and refined through valuable advice from industry experts. Their practical experience and in-depth understanding of the specific challenges related to civil engineering structures allow for the adjustment of factor selection based on real-world considerations. Once this first step is completed, the procedure continues with the development of the model's hierarchical structure, illustrated in Figure 6. This structure forms the backbone of the evaluation model and organizes in a logical and coherent manner the criteria and sub-criteria identified as having the most significant impact on the degradation of steel bridges. This hierarchization not only allows for a clear visualization of the relationships between different factors but also prepares the ground for the subsequent application of the FAHP method, which requires a well-defined structure for the attribution of weightings.

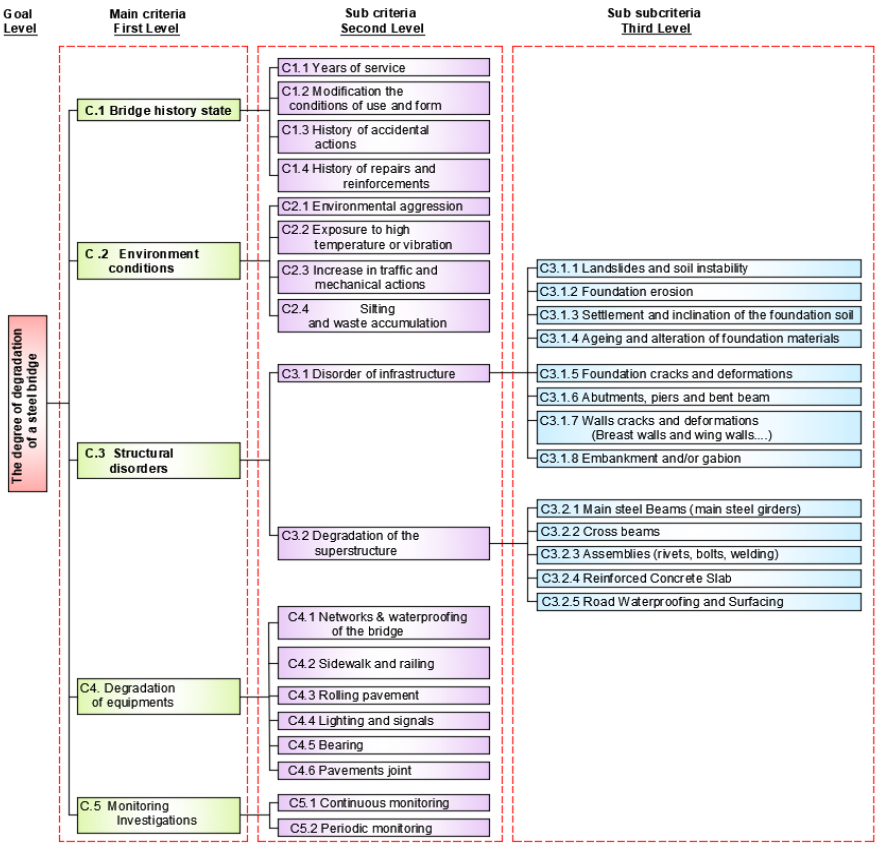

Figure 6 – The established evaluation criteria hierarchy

Calculating weighting coefficients: the FAHP method in practice

Triangular fuzzy numbers (TFN): an overview

We have decided to include triangular fuzzy numbers (TFN) within the FAHP technique framework to handle the inherently uncertain and ambiguous aspects of our study. Because it is simple to numerically implement, this method is preferred by many researchers. The three values that define a TFN are 'a' for the lower limit ,'m' for the middle point, and 'u' for the upper limit. The membership function of a TFN is illustrated graphically in Figure 7. Our study's examination of complicated parameters is greatly enhanced by this method, which enables more accurate modelling of uncertain or imprecise data. We are able to successfully

detect and quantify minute differences and nuances that may escape a classical method by incorporating TFNs into the FAHP process.

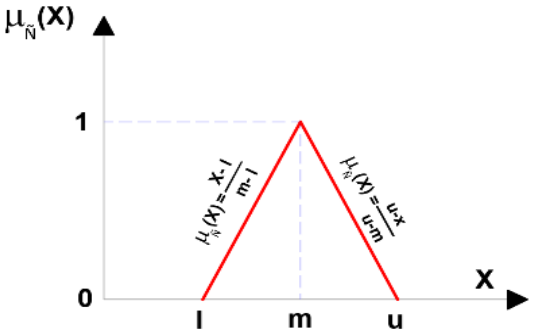

Figure 7 – Graphical illustration of TFN

The conventional comparative scale

The choice of a suitable triangular fuzzy number (TFN) is determined by a comprehensive analysis carried out by our team of experts. This approach entails the simultaneous assessment of two crucial criteria, the relative significance of which varies depending on the specific goals of the study. Figure 8 provides a comprehensive depiction of the intricate procedure involved in making this conclusion. The experts must exhibit profound discernment in order to achieve the optimal equilibrium between these two criteria, both of which exert a significant impact on the relevance of the selected TFN. This two-dimensional approach guarantees that the chosen TFN is the best fit for the unique requirements of our research project. The researchers' specialized knowledge is essential for negotiating the intricacies of this process and making a selection that accurately represents the subtleties and uncertainties inherent in our field of study.

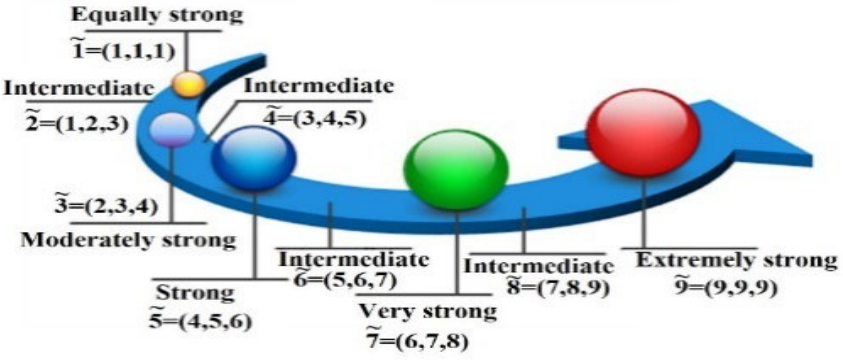

Figure 8 – Evaluation scale for criteria in terms of TFNs

Fuzzy geometric mean method (FGMM)

Figure 9 is a flowchart illustrating the steps involved in implementing a Fuzzy Analytic Hierarchy Process (FAHP). The approach commences by generating matrices for pairwise comparisons, utilizing triangular fuzzy integers to represent uncertain judgements. We subsequently convert the imprecise numbers into exact values to streamline computations. Next, we perform a consistency check to confirm the reliability of the pairwise comparisons. The procedure involves calculating the fuzzy geometric mean and weights, which are then defuzzified and normalized. The FAHP approach provides a systematic framework for effectively managing uncertain information and prioritizing options based on multiple criteria. This refers to Table 1, which is part of the flow chart.

Table 1 – Random coherence index (RI)

n	3	4	5	6	7	8	9	10
RI	0.525	0.882	1.109	1.248	1.342	1.406	1.450	1.485

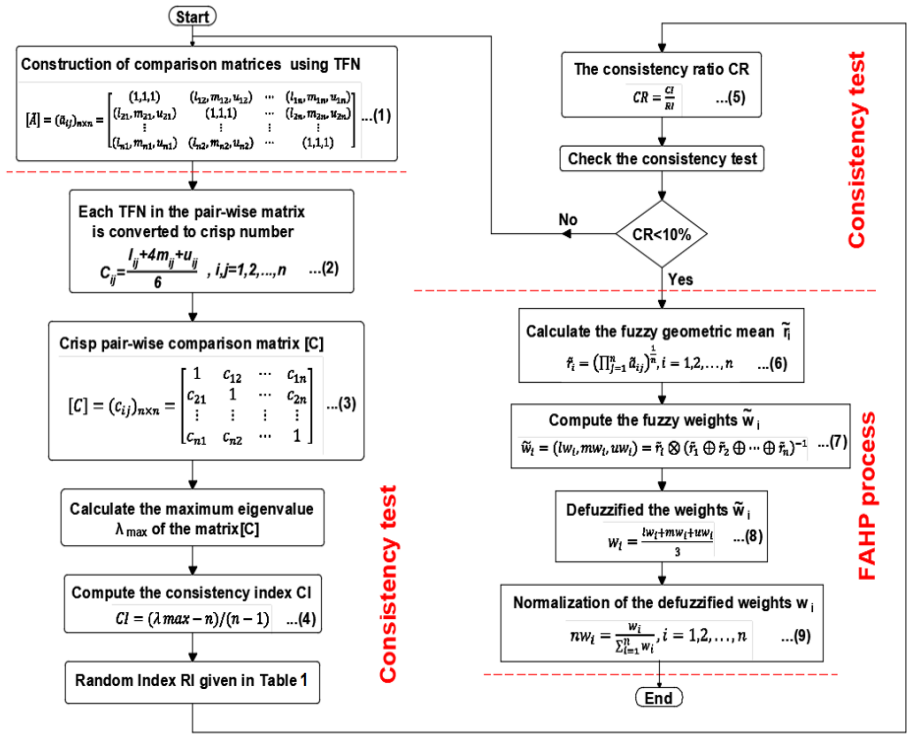

Figure 9 – A flowchart that demonstrates the process of calculating weight using the fuzzy geometric mean method

Assessment of expert rating (ER)

The FAHP approach is employed in this section of the study to ascertain the relative weights of each element. Afterwards, experts award an intersectional functioning index (ER) to each element, ranging from 0 to 10. This index represents the comparative significance of each component in assessing the efficient operation of the intersection. Table 2 displays the relationship between the 'ER' and its equivalent scale.

Table 2 – Status of risk scale

ER	State condition of scaling
[0,2]	no risk grade noticed
[2,4]	low- grade risk
[4,6]	moderate risk
[6,8]	high risk
[8,10]	super high risk

The collective expert assessment (CEA) is derived using the following equation:

$$CEA_i = \frac{\sum_{j=1}^{m} ER_j}{m}, \tag{1}$$

where *m* signifies the total number of participating specialists in the evaluation process.

To conclude, the comprehensive performance indicator (CPI), which represents the overall operational effectiveness of the intersection under scrutiny, is mathematically expressed as:

$$CPI = \sum_{i=1}^{K} w_i \times CEA_i, \tag{2}$$

In this formula, *i* ranges from 1 to *k*, where *k* denotes the number of sub-factors chosen for analysis.

Steel bridge classification and degradation as stated by IQOA

The IQOA (Lallam, Djebli & Mammeri, 2023) is a standardized assessment method in France for evaluating bridge condition. It identifies deteriorations and assigns a score, allowing for monitoring over time and anticipating maintenance. This system is crucial for infrastructure managers to make informed decisions about bridge safety and durability.

This study classifies the degree of degradation of steel bridges using the IQOA scoring system. Table 3 illustrates the concept of assessing and categorizing structures using the comprehensive performance indicator (CPI). A Class 1 design has a fair apparent condition and a CPI score between 0 and 2. Class 3U, on the other hand, denotes a very critical condition with severe structural failure (CPI score of 8–10).

Table 3 – IQOA classification to evaluate the degradation of steel bridges

Class	CPI	Apparent Condition
1	[0,2]	Good overall state
2	[2,4]	Equipment failures or minor structure damage. Non urgent maintenance needed
2E	[4,6]	Equipment failures or minor structure damage. Urgent maintenance needed
3	[6,8]	Structure deterioration. Non urgent maintenance needed
3U	[8,10]	Serious structure deterioration. Urgent maintenance needed

Results analysis

In order to optimize the procedure, the algorithm calculation process was carried out using Excel spreadsheet software, as shown in Figure 5. Based on the criteria evaluation scale in terms of TFNs (Figure 8), a detailed examination of the comparisons conducted between the various parameters is presented in Table 4. The Consistency Ratios (CR) demonstrated strong coherence, with every CR falling below the usual threshold, following a comprehensive analysis of the judgement matrices to confirm their consistency.

Table 4 – Matrices used for pairwise comparisons and the consistency tests results

C1	**C2**	**C3**	**C4**	**C5**	**Consistency test**
$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{6}^{-1}$	$\tilde{2}$	$\tilde{2}$	λmax=5.022, CI=0.005, RI=1.120, CR=0.48%< 10%
$\tilde{2}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{4}$	$\tilde{4}$	
$\tilde{6}$	$\tilde{3}$	$\tilde{1}$	$\tilde{9}$	$\tilde{9}$	
$\tilde{2}^{-1}$	$\tilde{4}^{-1}$	$\tilde{9}^{-1}$	$\tilde{1}$	$\tilde{1}$	
$\tilde{2}^{-1}$	$\tilde{4}^{-1}$	$\tilde{9}^{-1}$	$\tilde{1}$	$\tilde{1}$	
C1.1	C1.2	C1.3	C1.4		
$\tilde{1}$	$\tilde{2}$	$\tilde{1}$	$\tilde{2}$		λmax=4.001, CI=0.005, RI=0.900, CR=0.05%< 10%
$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$		
$\tilde{1}$	$\tilde{2}$	$\tilde{1}$	$\tilde{2}$		
$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$		

C1	**C2**	**C3**	**C4**	**C5**				**Consistency test**
C2.1	C2.2	C2.3	C2.4					
$\tilde{1}$	$\tilde{2}$	$\tilde{1}$	$\tilde{4}$					λmax=4.050, CI=0.017, RI=0.900, CR=1.86%< 10%
$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$					
$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$					
$\tilde{4}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$					
C3.1	C3.2							
$\tilde{1}$	$\tilde{1}$							CR not verified for comparison between two criteria
$\tilde{1}$	$\tilde{1}$							
C3.1.1	C3.1.2	C3.1.3	C3.1.4	C3.1.5	C3.1.6	C3.1.7	C3.1.8	
$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{3}^{-1}$	$\tilde{2}$	$\tilde{2}$	λmax=8.026, CI=0.004, RI=1.410, CR=0.26%< 10%
$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{3}^{-1}$	$\tilde{2}$	$\tilde{2}$	
$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{3}^{-1}$	$\tilde{2}$	$\tilde{2}$	
$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{3}^{-1}$	$\tilde{2}$	$\tilde{2}$	
$\tilde{2}$	$\tilde{2}$	$\tilde{2}$	$\tilde{2}$	$\tilde{1}$	$\tilde{1}$	$\tilde{4}$	$\tilde{4}$	
$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$	$\tilde{1}$	$\tilde{6}$	$\tilde{6}$	
$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{4}^{-1}$	$\tilde{6}^{-1}$	$\tilde{1}$	$\tilde{1}$	
$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{4}^{-1}$	$\tilde{6}^{-1}$	$\tilde{1}$	$\tilde{1}$	
C3.2.1	C3.2.2	C3.2.3	C3.2.4	C3.2.5				
$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{2}$	$\tilde{4}$				λmax=5.034, CI=0.009, RI=1.120, CR=0.76%< 10%
$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$				
$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$				
$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$				
$\tilde{4}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$				
C4.1	C4.2	C4.3	C4.4	C4.5	C4.6			
$\tilde{1}$	$\tilde{2}$	$\tilde{1}$	$\tilde{2}$	$\tilde{2}^{-1}$	$\tilde{1}$			λmax=6.098, CI=0.020, RI=1.24, CR=1.58%< 10%
$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{1}$			
$\tilde{1}$	$\tilde{2}$	$\tilde{1}$	$\tilde{2}$	$\tilde{1}$	$\tilde{1}$			
$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{1}$			
$\tilde{2}$	$\tilde{3}$	$\tilde{1}$	$\tilde{3}$	$\tilde{1}$	$\tilde{2}$			
$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$			

C1	C2	C3	C4	C5	Consistency test
C5.1	C5.2				
$\tilde{1}$	$\tilde{2}$				CR not verified for comparison between two criteria
$\tilde{2}^{-1}$	$\tilde{1}$				

Table 5 presents a concise overview of the weights allocated to the several evaluation criteria, both locally and globally, following the verification of their coherence. The results emphasize the great significance placed on situations of structural disorder, which account for 55.80% of the total weight at the first level of the hierarchy. The environmental conditions account for 21.55% of the degradation of metal bridges, highlighting the substantial impact of the environment on their deterioration. Conversely, the structure's historical condition, equipment deterioration conditions, and monitoring conditions were given lower weights of 11.09% and 5.78% respectively, indicating that these elements have a less significant influence on the overall condition of the structures. Figure 10 shows a hierarchical sunburst diagram, a useful data visualization tool for organizing information. Each circular ring represents a level in a hierarchy, with each segment representing a category. This intuitive representation helps understand interconnections and patterns. However, the diagram reveals significant discrepancies in the overall significance of sub-factors, highlighting their impact on steel bridge deterioration.

Table 5 – Weights assigned to factors and sub-factors at both local and global levels

Level 1		Level 2		Level 3		Global weights
Factors	**Local weights w_i**	**Sub-Factors**	**Local weights w_i**	**Sub-Factors**	**Local weights w_i**	**W_i**
C1	0.1109	C1.1	0.3219	-	-	0.0357
		C1.2	0.1781	-	-	0.0197
		C1.3	0.3219	-	-	0.0357
		C1.4	0.1781	-	-	0.0197
C2	0.2155	C2.1	0.3663	-	-	0.0789
		C2.2	0.2534	-	-	0.0546
		C2.3	0.2854	-	-	0.0615
		C2.4	0.0949	-	-	0.0204
C3	0.558	C3.1	0.500	C3.1.1	0.1006	0.0281
				C3.1.2	0.1006	0.0281
				C3.1.3	0.1006	0.0281
				C3.1.4	0.1006	0.0281
				C3.1.5	0.2081	0.0581
				C3.1.6	0.2793	0.0779
				C3.1.7	0.0551	0.0154
				C3.1.8	0.0551	0.0154

Level 1		Level 2		Level 3		Global weights
Factors	Local weights w_i	Sub-Factors	Local weights w_i	Sub-Factors	Local weights w_i	W_i
				C3.2.1	0.4078	0.1138
				C3.2.2	0.1584	0.0442
		C3.2	0.500	C3.2.3	0.1584	0.0442
				C3.2.4	0.1759	0.0491
				C3.2.5	0.0995	0.0278
		C4.1	0.1763	-	-	0.0102
		C4.2	0.1087	-	-	0.0063
		C4.3	0.1895	-	-	0.0110
C4	0.0578	C4.4	0.1087	-	-	0.0063
		C4.5	0.2791	-	-	0.0161
		C4.6	0.1377	-	-	0.0080
		C5.1	0.6439	-	-	0.0372
C5	0.0578	C5.2	0.3561	-	-	0.0206

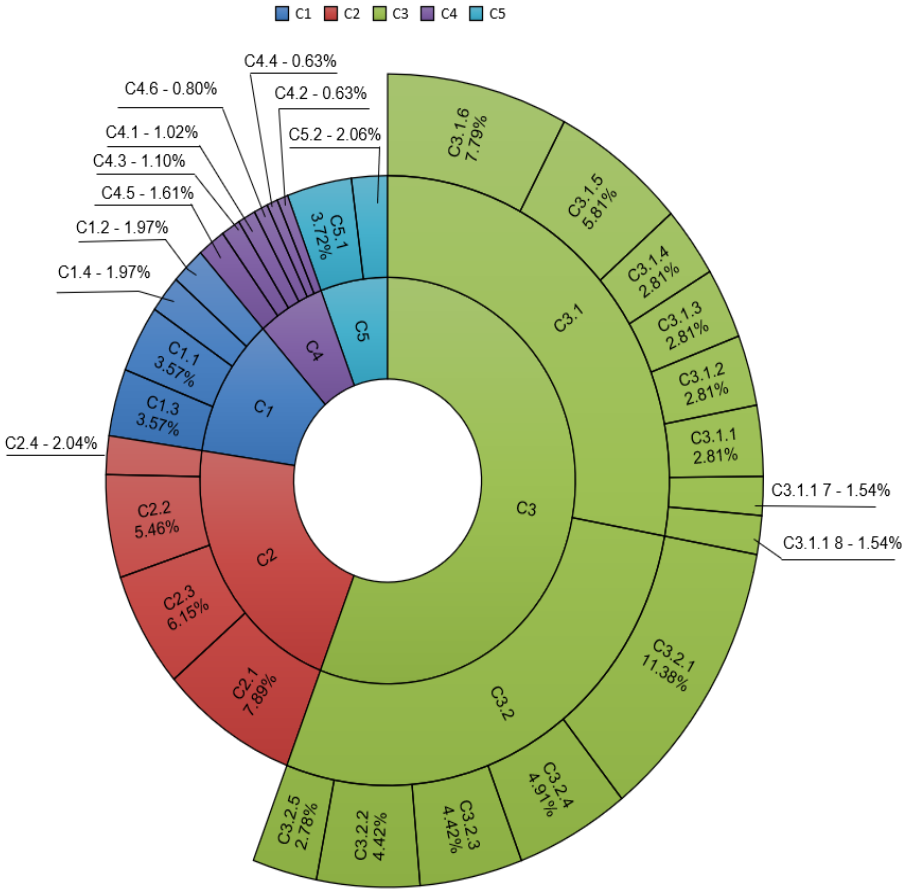

Figure 10 – Sunburst chart for global weightings

Ultimate goal: categorization of the steel bridge at Oued Taria

We invited an expert to the site to conduct a precise assessment of the Oued Taria bridge's condition. The objective was to allocate a relative condition rating (ER) to each of the previously stated criteria. The rating, which spans from 0 to 10, indicates the influence of each criterion on the overall deterioration of the metal structure of the bridge. A score of 0 signifies a minimal effect, while a score of 10 corresponds to a significant effect. Simply put, a higher score indicates that the criterion contributed more to the deterioration of the bridge. Table 6 succinctly presents the findings of this assessment, which adheres to the comprehensive methodology outlined in the preceding sections.

Table 6 – Assessment of sub-criteria and categorization of the analyzed steel bridge

N°	**Factors**	**ER**	**W_i(%)**	**ER × W_i**
1	C1.1	3.70	0.0357	0.1321
2	C1.2	3.00	0.0197	0.0592
3	C1.3	5.00	0.0357	0.1784
4	C1.4	1.00	0.0197	0.0197
5	C2.1	5.00	0.0789	0.3946
6	C2.2	5.00	0.0546	0.2731
7	C2.3	9.00	0.0615	0.5535
8	C2.4	3.00	0.0204	0.0613
9	C3.1.1	3.00	0.0281	0.0842
10	C3.1.2	1.00	0.0281	0.0281
11	C3.1.3	1.00	0.0281	0.0281
12	C3.1.4	3.00	0.0281	0.0842
13	C3.1.5	3.00	0.0581	0.1742
14	C3.1.6	1.00	0.0779	0.0779
15	C3.1.7	3.00	0.0154	0.0461
16	C3.1.8	7.00	0.0154	0.1075
17	C3.2.1	7.00	0.1138	0.7963
18	C3.2.2	7.00	0.0442	0.3094
19	C3.2.3	7.00	0.0442	0.3094
20	C3.2.4	7.00	0.0491	0.3435
21	C3.2.5	5.00	0.0278	0.1388
22	C4.1	7.00	0.0102	0.0714

N°	Factors	ER	W_i(%)	ER × W_i
23	C4.2	5.00	0.0063	0.0314
24	C4.3	7.00	0.0110	0.0767
25	C4.4	9.00	0.0063	0.0566
26	C4.5	9.00	0.0161	0.1453
27	C4.6	9.00	0.0080	0.0717
28	C5.1	9.00	0.0372	0.3352
29	C5.2	9.00	0.0206	0.1854
$CPI=\sum_{i=1}^{29} W_i \times ASC_i=5.173$, class: 2E, Degradation of equipment or minor structural damage. Urgent maintenance is required.				

On a scale from 0 to 10, the comprehensive performance indicator (CPI) yielded a score of 5.173 for the overall evaluation of the steel bridge, as shown in Table 6. The bridge is categorized as Class 2E in Table 3. Equipment deterioration or minor structural damage necessitating immediate repair is indicated by this categorization.

Conclusion

This study used a Fuzzy Analytical Hierarchy Process (FAHP) approach to thoroughly evaluate and classify the condition of steel truss bridges. The 36 carefully chosen criteria and sub-criteria that made up the hierarchical structure made it possible to find the factors that had the most significant effect on the final assessment of the bridge's condition. This hierarchical structure categorizes the different aspects, such as structural disorders, environmental conditions, the bridge's historical background, equipment degradation, and professional intervention, according to their respective levels of importance. The application of this methodology to the Oued Taria bridge revealed minor structural damage and equipment degradation, necessitating increased monitoring and preventive maintenance. Although the FAHP approach allows for uncertainty management and subjectivity reduction through fuzzy logic, the role of experts remains critical in score assignment. The proposed method aims to minimize this issue by rationalizing the process and facilitating rapid and efficient implementation. Furthermore, its user-friendly formulation and adaptability to various contexts make it a practical tool for evaluating the condition of steel bridges.

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Praćenje degradacije čeličnih mostova primenom višekriterijumskih pristupa

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OBLAST: građevinarstvo
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Cilj rada je formulacija metode zasnovane na fazi analitičkom hijerarhijskom procesu (eng. FAHP) koja može pomoći stručnjacima u ispitivanju čeličnih mostova. Pristupi zasnovani na fazi logici su poželjni zbog svoje sposobnosti da obrađuju neizvesne informacije na način koji odražava procese ljudskog rasuđivanja, što ih čini posebno pogodnim u proceni oštećenja konstrukcija.

Metode: Postupak je organizovan u hijerarhijskom okviru koji se sastoji od 35 kriterijuma i podkriterijuma. Ova struktura je osmišljena tako da

pomogne zainteresovanim stranama koje učestvuju u ispitivanju pri donošenju odluka. Težinski koeficijenti Wi ovih kriterijuma određuju se primenom metode fazi analitičkog hijerarhijskog procesa i dodatnih ekspertskih procena kako bi se izračunao sveobuhvatni pokazatelj performansi (eng. CPI) koji predstavlja stepen oštećenja ispitivanog mosta. Konstrukcija se klasifikuje na osnovu ukupne vrednosti CPI korišćenjem notacije IQOA.

Rezultati: Radi rigorozne procene praktične primenljivosti i tačnosti razvijene metodologije FAHP, ova studija slučaja je urađena na stvarnoj konstrukciji. Metodologija je primenjena za procenu stanja čeličnog mosta koji se nalazi u Ued Tariji, u regionu Maskara. Primena ovog sveobuhvatnog pristupa dala je rezultate koji su pokazali izuzetnu usklađenost i snažnu povezanost sa prethodnim nezavisno sprovedenim ekspertskim procenama iste konstrukcije.

Zaključak: Uspešna primena i potvrđeni rezultati nedvosmisleno potvrđuju naučnu efikasnost i praktičnu korisnost ovog alata zasnovanog na metodi FAHP. On predstavlja robustan i pouzdan sistem za podršku procesu odlučivanja i značajno unapređuje sposobnosti stručnjaka za preciznu procenu složenih i često subjektivnih aspekata oštećenja čeličnih mostova. Ova metodologija ne samo da pojednostavljuje proces ispitivanja, već doprinosi i objektivnijim i doslednijim procenama, što u krajnjem rezultatu dovodi do boljeg planiranja održavanja i veće bezbednosti kritične mostovske infrastrukture.

Ključne reči: čelični mostovi, fazi analitički hijerarhijski proces (FHAP), sveobuhvatni pokazatelj performansi (CPI).

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Mechanical behavior of silty sand reinforced with natural discrete elements: effect of silt content, fiber content and other parameters

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Abstract:

Introduction/purpose: Many studies have reported a notable reduction in the shear strength of sandy soils when fine fractions are present, resulting in soils with poor geotechnical properties. With the lack of suitable soils for construction, it is now imperative to alter the properties of soil to make it suitable for engineering purposes. Numerous methods and techniques exist to enhance soil stability. The inclusion of discrete elements as reinforcement is particularly effective due to its contribution to a variety of desirable results.

Methods: This paper investigates the impact of natural discrete elements on the shear strength behavior of silty sand at medium relative density prepared with different dispositional methods using different moisture contents. The study focuses on different parameters, namely, silt, fiber and water contents.

Results: The experimental results indicate a reduction of strength with an increase in silt content and water content. Furthermore, the strength, volumetric change, and mechanical properties of the mixtures greatly improved with the addition of sisal fibers at low moisture contents. However, no significant improvement was recorded at high moisture contents, indicating the negative influence of moisture content on the fiber reinforcement mechanism.

Conclusion: Following a rigorous analysis of the obtained results, it was determined that Sisal fibers can be judiciously used for improving soil characteristics.

Key words: sand, silt, natural fiber, moisture content, shear strength, mechanical characteristics.

Introduction

Post-earthquake field investigations have revealed that sand samples extracted from liquefaction-induced sand boils often contain a significant percentage of fines. In geotechnical engineering, soils are frequently encountered as mixtures of sand-clay or sand-silt, with plastic or non-plastic fines, necessitating a thorough understanding of their mechanical behavior to ensure safe infrastructure design. The role of low-plasticity fines in altering the liquefaction resistance of sand-fines mixtures has been a focal point of research over the past two decades. Despite extensive studies, the geotechnical community remains divided on how fines content (FC) influences liquefaction potential, highlighting the complexity of these soil systems. For instance, Amini and Qi (2000) argued that increasing fines content enhances liquefaction resistance, attributing this to the filling of void spaces between sand particles, which reduces pore pressure

buildup. Conversely, Lade and Yamamuro (1997), Belkhatir et al. (2010), Monkul et al. (2016), and Bouri et al. (2019) reported that higher fines content diminishes resistance by disrupting intergranular contacts, leading to weaker soil matrices. A third perspective, proposed by Xenaki and Athanasopoulos (2003), Bouferra and Shahrour (2004), and Benghalia et al. (2015), suggests a nonlinear relationship: liquefaction resistance initially decreases with fines addition until a threshold FC is reached, beyond which resistance improves. Another trend was reported by Feknous et al. (2024), who found that adding 10% silt to clean Chlef sand resulted in an increase in shear strength, whereas a further increase in silt content beyond this value led to a reduction in strength. These discrepancies underscore the influence of factors such as fines plasticity, particle gradation, and testing conditions on outcomes. The undrained shear strength, or liquefaction resistance, of sandy soils is governed by a multitude of interrelated factors. Laboratory studies have highlighted the role of fines content (FC), particle size, shape, and packing density in dictating mechanical behavior under static and cyclic loads. For instance, Georgiannou et al. (1991), Belkhatir et al. (2012, 2014), and Yazdani et al. (2022) demonstrated that increasing fines content can alter soil fabric, reducing permeability and promoting pore pressure buildup. These discrepancies suggest that fines content alone is insufficient to predict liquefaction; microstructure, particle arrangement, initial water content, and testing methods must also be considered.

Soil reinforcement has been a pivotal innovation in geotechnical engineering, offering solutions to enhance the mechanical properties of weak or unstable soils. Among the various techniques, the use of randomly distributed fibers has emerged as a superior alternative to conventional geosynthetics due to its cost-effectiveness, ease of application, and environmental benefits. The concept of fiber reinforcement draws inspiration from plant root systems, which naturally stabilize soil by creating a cohesive network that resists erosion and displacement. Similarly, flexible, discrete, and randomly distributed fibers replicate this biological mechanism, reinforcing near-surface soils where low effective stress often leads to failure (Wu et al., 1988; Greenwood et al., 2004). Soil reinforcement using synthetic materials has gained significant interest in geotechnical engineering, offering innovative solutions to enhance soil strength and stability. In addition to these materials, natural plant fibers such as coconut, jute, palm, and sisal offer a compelling alternative. These materials are cost-effective, biodegradable, and recyclable, aligning with global demands for eco-friendly engineering practices (Zakikhani et al., 2014; Bordoloi et al., 2017; Rangappa et al., 2022; Reis et al., 2023).

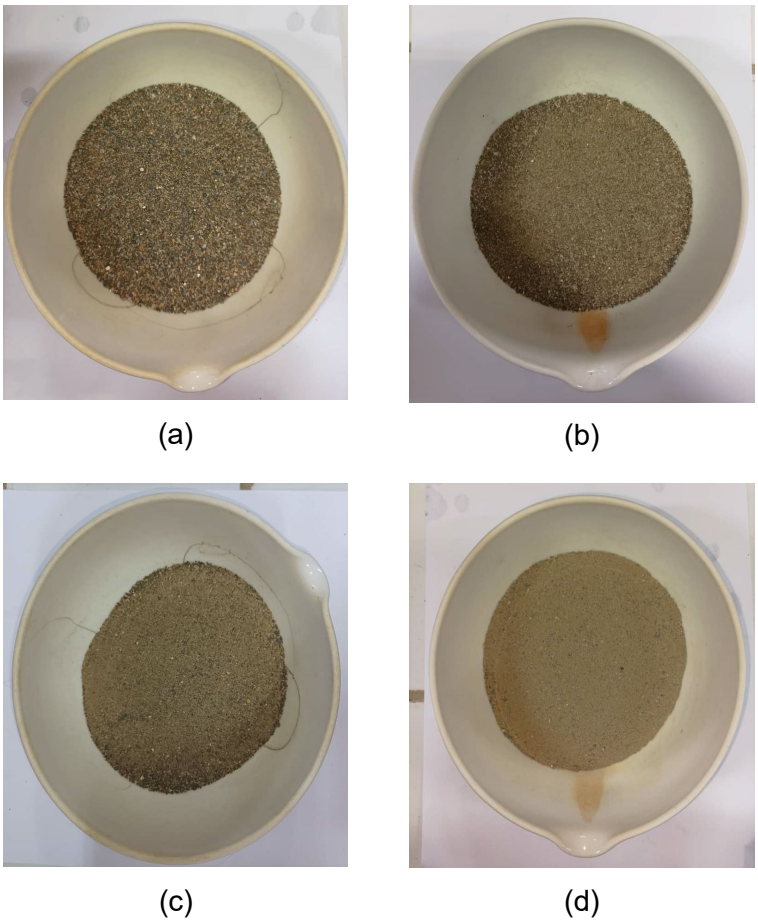
Incorporation of randomly distributed fibers stands out as a method that bolsters the stability of soil masses by increasing resistance near the surface, where low effective strength often poses challenges (Noorzad and Zarinkolaei, 2015), and reducing post-peak strength loss (Al-Refeai, 1991; Ahmad et al., 2010; Diambra et al., 2010; Anagnostopoulos et al., 2013; Zhang et al., 2022). When integrated into soil, fibers act as a composite material, where high-tensile-strength fibers interact with the soil matrix to enhance mechanical properties. During shear stress, the fibers mobilize their tensile resistance, transferring loads and limiting soil particle displacement (Ghiassian et al., 2008; Jamshidi et al., 2010). This interaction forms a three-dimensional network that interlocks soil grains, creating a unified matrix with improved cohesion and reduced deformation. Such behavior is critical in liquefaction-prone areas, as the fiber network redistributes stresses and mitigates sudden strength loss during dynamic loading. Extensive studies by researchers such as Maher and Woods (1990), Edinçliler and Ayhan (2010), and Ali et al. (2020) have demonstrated that fiber reinforcement significantly enhances key geotechnical properties, including shear strength, stiffness, compaction characteristics, and bearing capacity (Sridhar, 2017). Fiber reinforcement is dependent on different parameters related to both fibers (fiber aspect ratio, fiber length and fiber content) and soil characteristics (relative density, normal stress, particle size and gradation). Additionally, fiber-reinforcement efficiency is highly dependent on spatial configuration, including matrix packing and orientation (Abtahi et al., 2008; Ghiassian et al., 2008). The behavior of fiber-reinforced soil also varies according to the type and structure of the fibers, whether natural or synthetic. Benziane et al. (2022) investigated the shear behavior of natural Chlef sand reinforced with three types of randomly distributed fibers, namely polypropylene, glass, and sisal fibers. They found that adding sisal fibers to sand improved its strength parameters more than the incorporation of glass or polypropylene fibers did, and that the optimum sisal fiber content was 0.75%.

The behavior of sand-fines mixtures has been largely documented; however, the influence of fibers on the mechanical behavior of sand-fines mixtures remains understudied. This experimental study aims to investigate the shear behavior of silty sand reinforced with natural discrete elements, focusing on the effect of fiber content, silt content, water content and sample preparation method.

Materials and methods

Soil

The soil used in this study was sand collected from the Chlef river banks in the north of Chlef (Algeria). During the last earthquake of October 1980, this region experienced a case of soil liquefaction (Krim et al., 2024) mainly attributed to the presence of silt in the soil mass. The silty sand mixtures used in this study (Figure 1) are classified as poorly graded sand (SP). Figure 2 presents the grain size distribution curve of the mixtures and their engineering properties are given in Table 1.



(a) (b) (c) (d)

Figure 1 - Silty sand: (a) Sc=0%, (b) Sc=10%, (c) Sc=20%, (d)Sc=30%

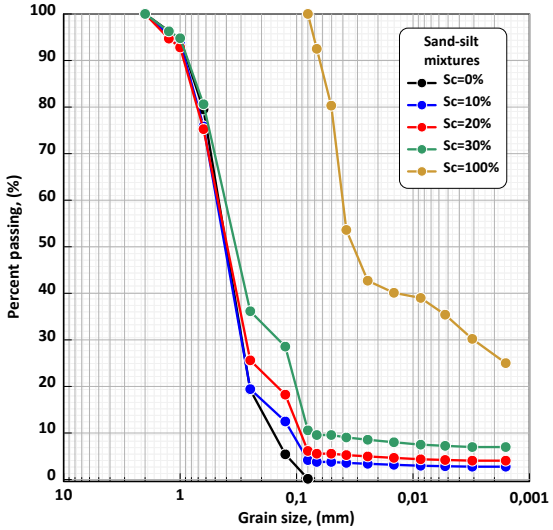


Figure 2 - Grain size distribution curve of Chlef sand-silt mixtures

Table 1 - Properties of Chlef sand-silt mixtures

Parameter	Sand-silt mixtures			
Silt content, Sc (%)	0	10	20	30
Maximum grain size, D_{max} (mm)	2.00			
Mean grain size, D_{50} (mm)	0.43	0.41	0.39	0.35
Coefficient of uniformity, Cu (.)	3.28	4.64	5.44	5.86
Coefficient of curvature, Cc (.)	0.85	1.5	1.65	0.6
Minimum void index, e_{min} (.)	0.59	0.485	0.446	0.437
Maximum void index, e_{max} (.)	0.885	0.823	0.747	0.724
Mean specific gravity, G_S (.)	2.74	2.733	2.726	2.718

Reinforcement

The fibers used in this study are sisal fibers with similar length (Fl = 12mm) and different fiber contents, Fc = 0%, 0.3%, 0.5%, and 0.8% by dry soil mass (Figure 3). Sisal is a leaf fiber with high tensile strength and is commercialized and used in different engineering applications. The physical and mechanical characteristics of fibers are presented in Table 2.

Figure 3 - Sisal fiber

Table 2 - Physical and mechanical characteristics of sisal fibers

Specific gravity	**Length (mm)**	**Diameter (μm)**	**Tensile strength (MPa)**	**Young Modulus (MPa)**
0.91	12	35	550	19

Experimental program and sample preparation method

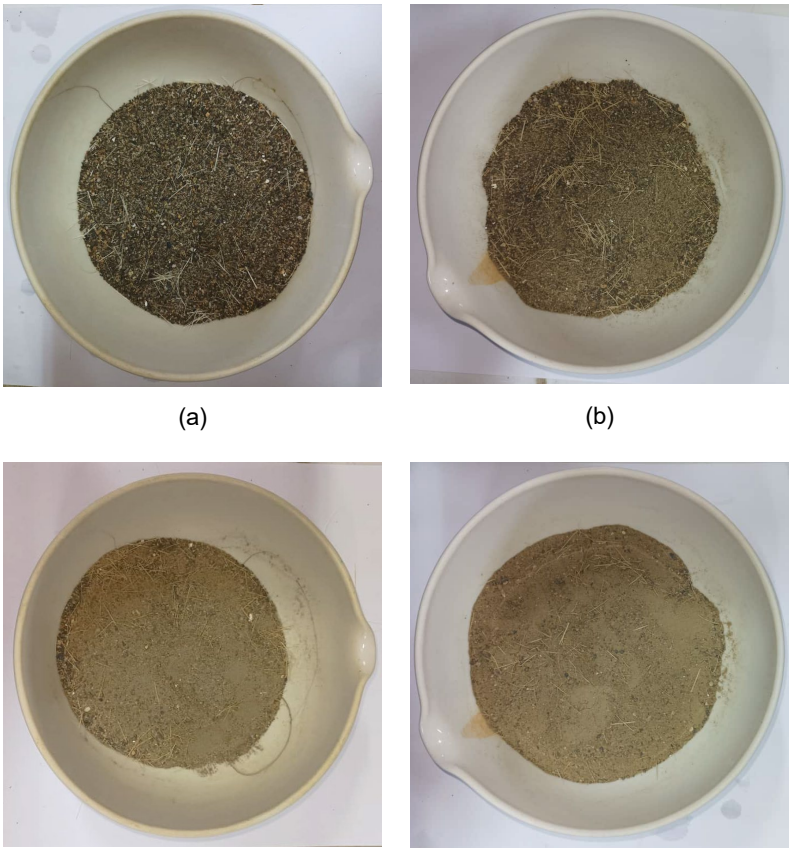
The experimental program consists of a series of direct shear tests carried out on a medium dense Chlef sand (Dr = 50%) with varying silt contents and different fiber percentages prepared with different initial water contents using two different sample preparation methods sheared under normal stresses of 50, 100 and 200 kPa. The horizontal shearing was performed at a constant displacement rate of 1.00 mm/min. Horizontal load, and horizontal and vertical displacements were acquired automatically via the apparatus load unit. All the parameters considered in the testing program are listed in Table 3.

Table 3 - Experimental program

Sample preparation method	**Normal stress σn (kPa)**	**Silt content Sc (%)**	**Fiber content Fc (%)**	**Water content w (%)**
Dry disposition	50, 100 and 200	0, 10, 20 and 30	0, 0.3, 0.5 and 0.8	0
Wet disposition		10	0, 0.3, 0.5 and 0.8	1.5, 3 and 5

The experimental program was divided into two sets. The first set of samples was prepared using the dry disposition method in order to

investigate the influence of silt and natural fibers on the behavior of Chlef sand. The test specimens were prepared by mixing clean sand with different silt fractions and fiber percentages by dry soil mass until a homogeneous mixture was obtained (Figure 4). The second set was carried out on unreinforced and reinforced silty sand at 10% silt content prepared using the wet disposition method in order to study the influence of moisture content and sample preparation methods on the behavior of unreinforced and reinforced silty sand. Test specimens were obtained by mixing sand, silt and fibers with different contents of distilled water (Figure 5). Test specimens obtained through the different preparation methods were then placed into the shear box cavity (60 × 60 × 25 mm^3) in three layers and gently leveled off to achieve a medium-dense state.



(a) (b)

(c) (d)

Figure 4 - Reinforced silty sand prepared with the dry disposition method: (a) Sc=0%, (b) Sc=10%, (c) Sc=20%, (d) Sc=30%

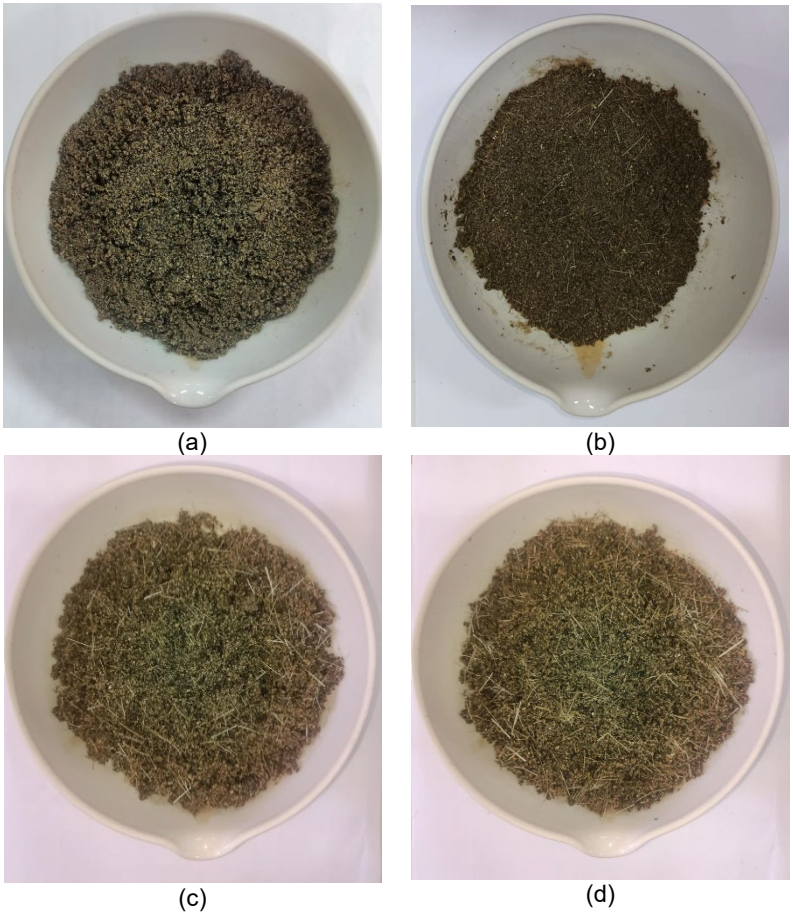


Figure 5 - Unreinforced and reinforced silty sand (Sc=10%) prepared with the wet disposition method: (a) Fc=0%, (b) Fc=0.3%, (c) Fc=0.5%, (d) Fc=0.8%

Results analysis and discussion

Influence of silt content

Figure 6 presents the results of direct shear tests conducted on untreated Chlef sand-fines mixtures prepared at a medium relative density Dr = 50% using the dry pluviation preparation method. The data show that the maximum shear stress decreases proportionally with an increase in fines content (Fig. 6a). Sand-fines mixtures can be considered as binary systems constituted of two submatrices a coarser grain matrix and a finer grain matrix. At lower fines content the fines occupy the voids between the sand grains and the overall strength of the mixture is governed by the

coarser grain matrix. With further addition of fines, the coarse grains become separated from each other and the coarse particles interaction dissipates (Yazdani et al., 2022). Beyond a specific threshold, the mechanical behavior of the mixtures is then ruled by the finer grain matrix. Similar results were observed by Georgiannou et al. (1991), Belkhatir et al. (2013), Arab and Belkhatir (2012), and Benghalia et al. (2015).

Figure 6b illustrates the evolution of vertical displacement as a function of horizontal displacement for sand-fines mixtures with varying fines contents (Fc = 0%, 10%, 20% and 30%). The results show an intensified contraction phase, with the contractive behavior becoming more pronounced as the fines content increases. Yamamuro and Lade (1997) attribute this behavior to the formation of a highly compressible structure between the smaller and larger particles in the soil. This phenomenon is explained by the tendency of fines to initially accumulate at the points of contact between larger grains. Upon shearing, these fines are displaced to fill voids within the structure, generating a contractive response. This process can lead to static liquefaction under undrained conditions.

Figure 6c indicates that the maximum shear strength of sand-silt mixtures is very dependent on the fines content and normal stress where it was found that an increase in normal stress tends to increase maximum shear strength values. However, an increase in fines content leads to a decrease in the mixtures' strength for every normal stress studied. In addition, the effect of fines on cohesion and friction angle values of Chlef sand-fines mixtures was determined through the intrinsic curves and plotted in Figure 7. From the figure, it is noted that the cohesion of sand-silt mixtures slightly increased with an increase of fines content. The obtained cohesion values were 0, 5.5, 7.5 and 11.03 for fines content of 0, 10, 20 and 30%, respectively (Figure 7a). This is due to silt particles penetrating into the voids between the larger sand particles, creating more contact points and enhancing the interaction between the particles leading to an increase in the overall cohesion of the sand-silt mixture. Regarding the internal friction angle, it was found that the inclusion of silt fines results in a decrease in the internal friction angle of sand-fine mixtures (Figure 7b). This result is attributed to the smooth surface of silt reducing the effective inter-particle friction. This reduction of friction is enhanced at higher percentages of silt.

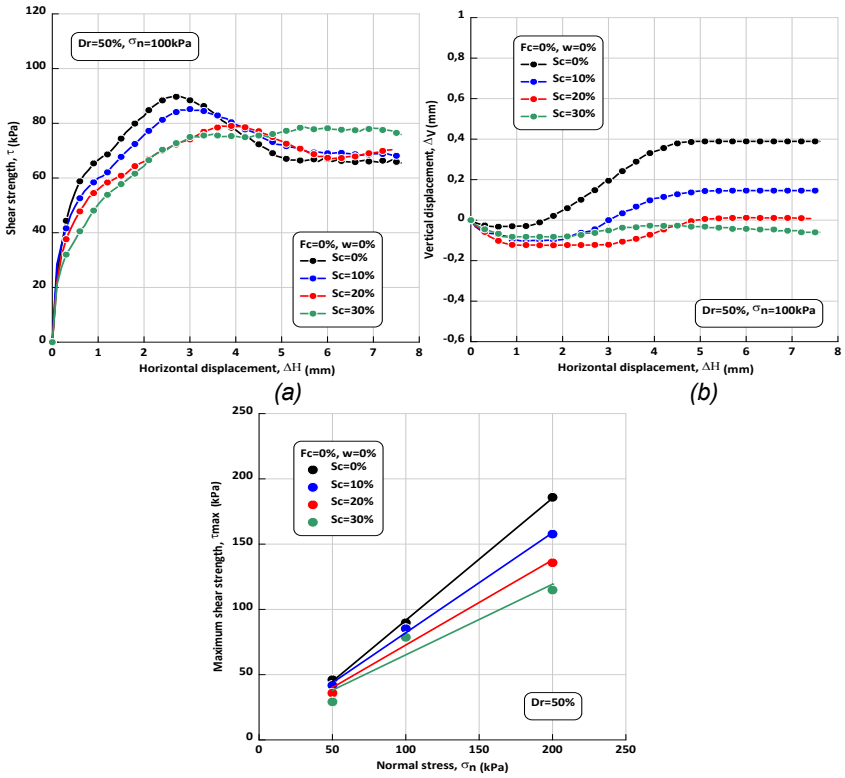


Figure 6 - Influence of silt content on the mechanical behavior of clean Chlef sand in the dry state under a normal stress of 100 kPa: (a) variation of shear strength as a function of horizontal displacement, (b) variation of vertical displacement as a function of horizontal displacement, (c) variation of maximum shear strength as a function of normal stress

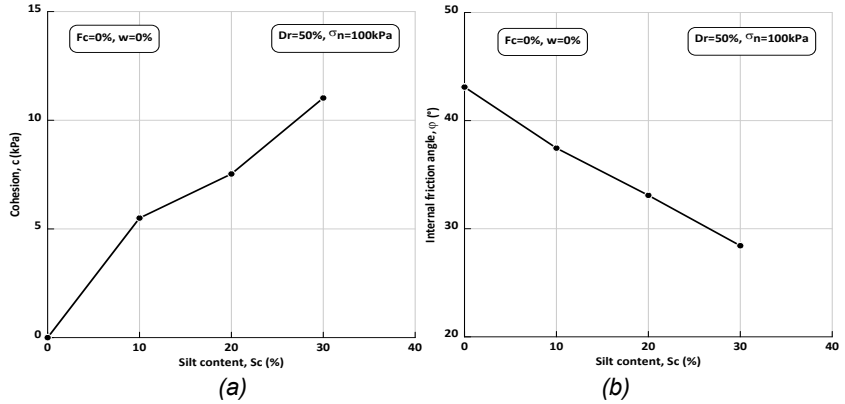
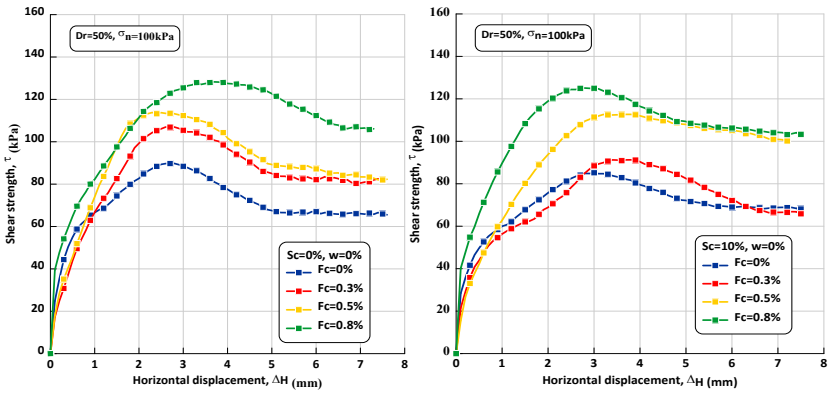


Figure 7 - Evolution of the cohesion and internal friction angle of Chlef clean sand as a function of silt content

Influence of fiber content

Figure 8 shows the influence of fiber reinforcement on the shear behavior of sand-fines mixtures prepared at a medium relative density Dr = 50% using the dry pluviation preparation method. From the figure, it is apparent that the inclusion of fibers greatly influences the stress-dilatancy behavior of the sand-silt composites, where it was found that the resistance of silty sand, characterized by the shear stress, increases significantly with an increase in fiber content for all silt contents studied (Figure 8a). Wei et al. (2018) postulated that an increase in fiber content results in a greater contact area between the fibers and soil particles, which in turn enhances the frictional resistance at the fiber-soil interface. Additionally, the presence of fibers facilitates the formation of multiple intersecting points, contributing to the development of fiber networks within the soil matrix. These networks improve the spatial confinement effect, thereby leading to an increase in the overall cohesion of the mixture. However, it is noticeable from the figures that an increase in silt content decreases the sand-silt-fiber composites' strength. These results indicate that the mechanism of fiber reinforcement operates in contrast to the influence of silt on sandy soil. Fiber reinforcement enhances the contact between sand particles, leading to an increase in the composite strength. This is due to the fibers improving particle interlocking and friction at the particle interfaces. In contrast, the addition of silt reduces the contact between sand particles, as the fine silt particles tend to occupy void spaces and reduce the inter-particle friction, resulting in a decrease in the composite strength. The values of maximum shear strength obtained for unreinforced and reinforced sand-silt mixtures are summarized in Table 4.



(a) (b)

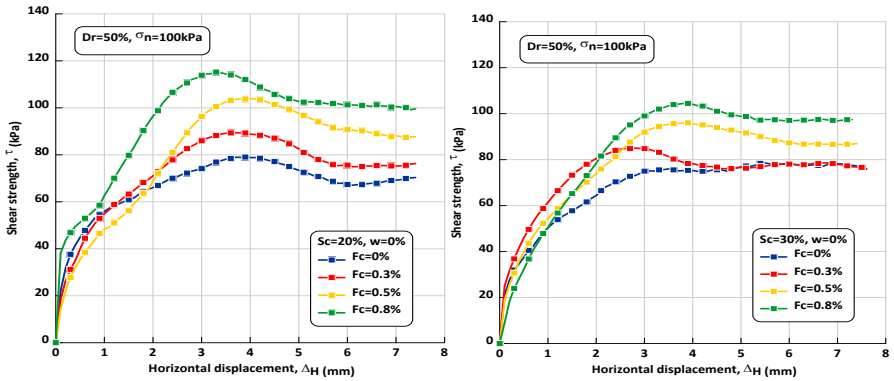


Figure 8 - Influence of fiber content on the variation of shear strength of Chlef silty sand in the dry state under a normal stress of 100 kPa: (a) Sc=0%, (b) Sc=10%, (c) Sc=20%, (d) Sc=30%

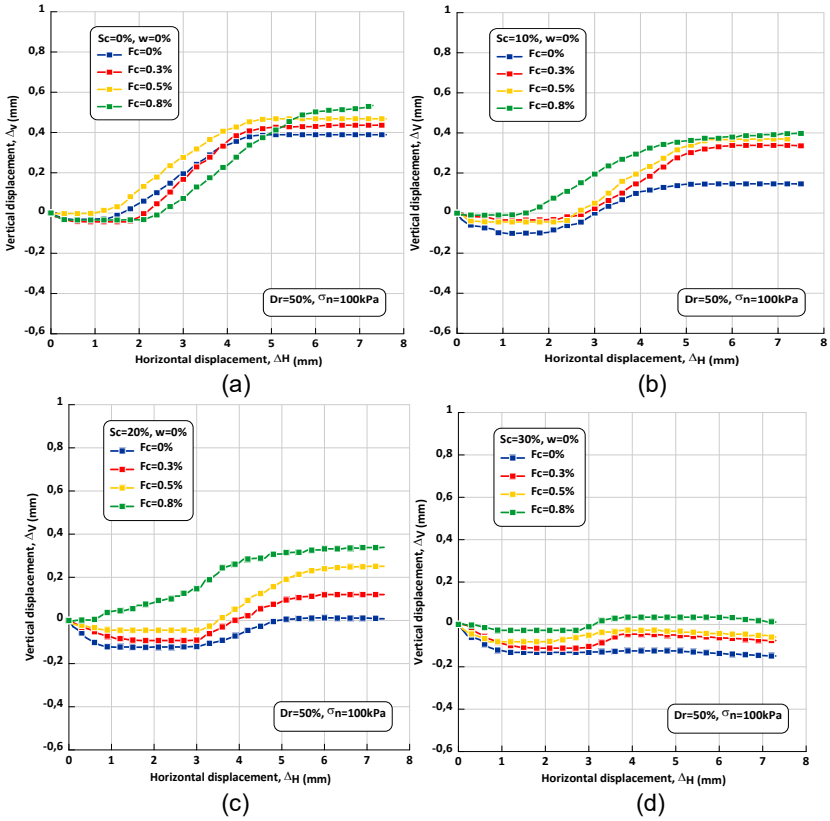
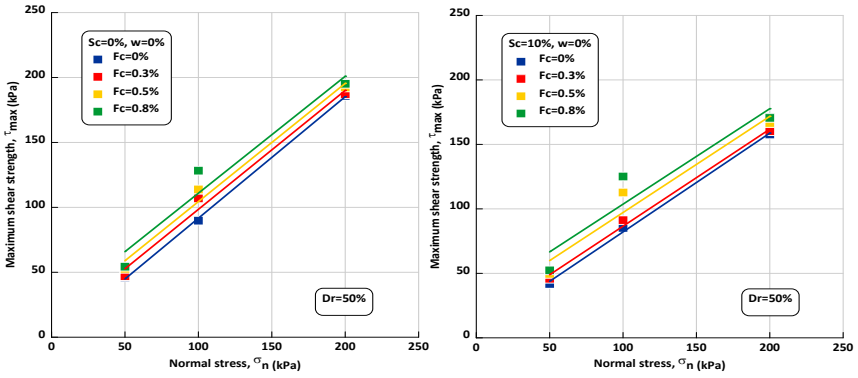


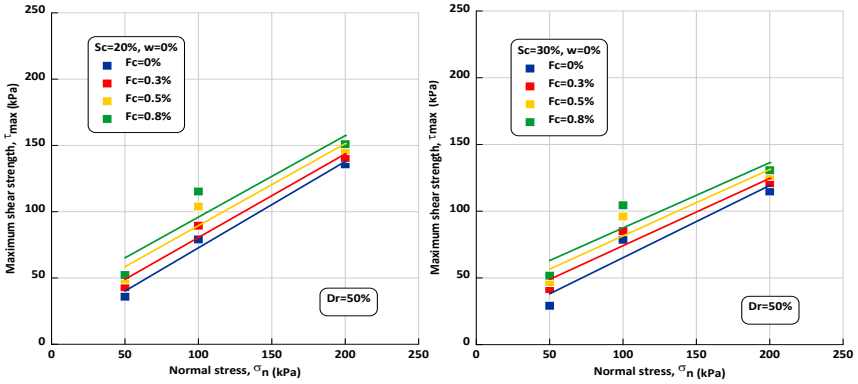
Figure 9 - Influence of fiber content on the variation of volumetric deformation of Chlef silty sand in the dry state under a normal stress of 100 kPa: (a) Sc=0%, (b) Sc=10%, (c) Sc=20%, (d) Sc=30%

Figure 9 presents the vertical displacement curves of unreinforced and reinforced sand-silt specimens. It has been noted that the introduction of fiber inclusions counteracts the detrimental effects of silt on the soil dilatancy, where it was observed that an increase in fiber content results in the accentuation of the soil dilative behavior. These results are in good agreement with those of Ibrim and Fourmont (2007), Diambra et al. (2010), and Eldesouky et al. (2016), who reported that fiber-reinforced sand exhibited a higher dilation tendency than unreinforced sand.

Figure 10 illustrates the evolution of maximum shear strength as a function of silt content (Sc), fiber content (Fc) and normal stress (Ϭn) for samples prepared at medium density in a dry state. From the figures, it can be seen that the maximum shear strength decreases with increasing silt content. Inversely, the maximum shear strength values increased proportionally with an increase in fiber content and normal stress. Furthermore, the shear strength parameters (internal friction angle and cohesion) obtained from the linear regression analysis for different contents of silt and fibers are presented in Figure 11 and summarized in Table 4. It is noted from Figure 11a that the cohesion of fiber-reinforced sand-silt specimens increased with an increase in silt content. This increase is accentuated with an increase of fiber content. However, no significant influence was observed regarding the effect of fiber reinforcement on the variation of the internal friction angle of sand-silt mixtures (Figure 11b).

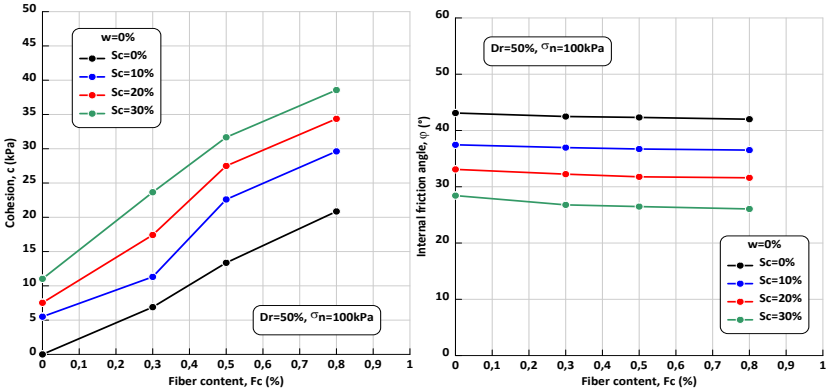


(a) (b)



(c) (d)

Figure 10 - Influence of fiber content on the variation of maximum shear strength of Chlef silty sand in the dry state under a normal stress: (a) Sc=0%, (b) Sc=10%, (c) Sc=20%, (d) Sc=30%



(a) (b)

Figure 11 - Evolution of cohesion and internal friction angle of silty sand as a function of fiber content

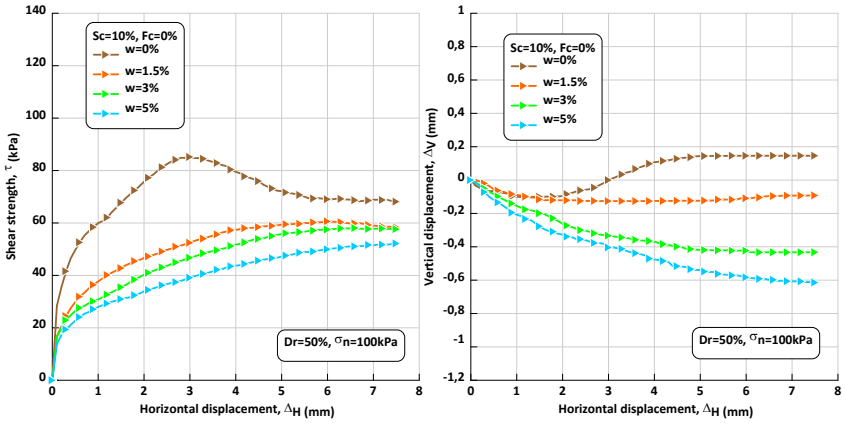
Table 4 - Mechanical characteristics of fiber-reinforced silty sand

	Sc=0%		**Sc=10%**		**Sc=20%**		**Sc=30%**	
	c (kPa)	**φ (°)**	**c (kPa)**	**φ (°)**	**c (kPa)**	**φ (°)**	**c (kPa)**	**φ (°)**
Fc=0%	0	43,10	5,50	37,46	7,53	33,09	11,03	28,43
Fc=0.3%	6,89	42,48	11,31	36,96	17,42	32,24	23,66	26,78
Fc=0.5%	13,37	42,32	22,61	36,71	27,50	31,77	31,67	26,48
Fc=0.8%	20,86	42.00	29,62	36,51	34,37	31,59	38,57	26,05

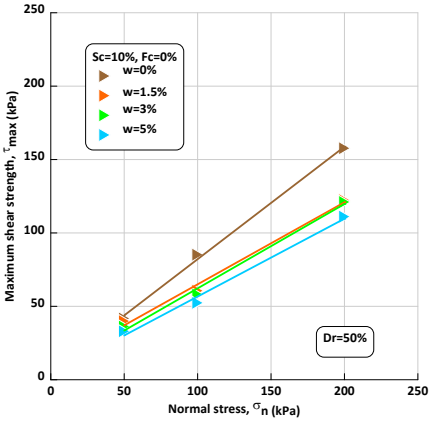
Influence of water content

Unreinforced sand

Figure 12 presents the effect of water content on the mechanical properties of silty sand for silt content Sc = 10% at a medium relative density Dr = 50%. An increase in the shear strength with horizontal displacement has been observed in Figure 12a up to its peak at around 3 mm of horizontal displacement, followed by a slight decrease, resulting in a residual strength for the dry specimens (w = 0%). However, the strength shift phase and residual shear strength were not found for the wet specimens (w = 1.5, 3 and 5%). Furthermore, it is noted that the shear strength of sand-silt mixtures decreased with increasing water contents. The maximum shear strength values recorded were: 85.19, 60.61, 58.08 and 52.36 kPa for water contents of 0, 1.5, 3 and 5%, respectively. Figure 12b represents the variation of vertical displacement versus horizontal displacement of sand-silt mixtures at different water contents. Dry specimens have shown initially a contractive phase until a horizontal displacement of around 3 mm, followed by a dilative phase until the end of the test. On the other hand, all wet specimens have shown a pure contractive behavior. This contractancy is accentuated with increasing water content. These results are in good agreement with those of Benessalah et al. (2016) and Ali et al. (2020). Figure 12c illustrates the variation of the maximum shear strength as a function of water content and normal stress for silty sand samples prepared at a medium-density state. It appears from the figure that the maximum shear strength increased with an increase in normal stress and decreased proportionally with an increase in moisture content.



(a) (b)



(c)

Figure 12 - Influence of water content on the mechanical behavior of fiber reinforced silty sand (Sc = 10%) under a normal stress of 100 kPa: (a) variation of shear strength as a function of horizontal displacement, (b) variation of vertical displacement as a function of horizontal displacement, (c) variation of maximum shear strength as a function of normal stress

Reinforced sand

Figure 13 shows the influence of moisture content and sample preparation method on the shear behavior of fiber-reinforced sand-fines mixtures prepared at a medium relative density Dr = 50% using the dry deposition preparation method (w = 0% by mass of dry sand) and the wet deposition method (w = 1.5, 3 and 5% by mass of dry sand). From the figure, it is apparent that an increase in moisture content greatly influences the stress-dilatancy behavior of reinforced sand-silt composites, where it was found that the shear strength of reinforced silty sand decreases proportionally with an increase in moisture content. In addition, it is noted that the inclusion of fiber reinforcements increased the shear strength of silty sand at low moisture contents (w = 0 and 1.5%); however, the reinforcing effect of fibers gradually diminished at higher moisture contents until no substantial amelioration was recorded (w = 5%). This result is due to the lubricating effect of water. Since the fiber reinforcement mechanism is purely frictional, the surface roughness of fibers influences their strength mobilization with the interacting soil particles (Benziane et al., 2022). However, the added water forms a thin film between sand particles and the fiber surface, reducing the matrix inter-friction during shearing, resulting in a loss of strength. This loss of strength is more pronounced at higher moisture contents.

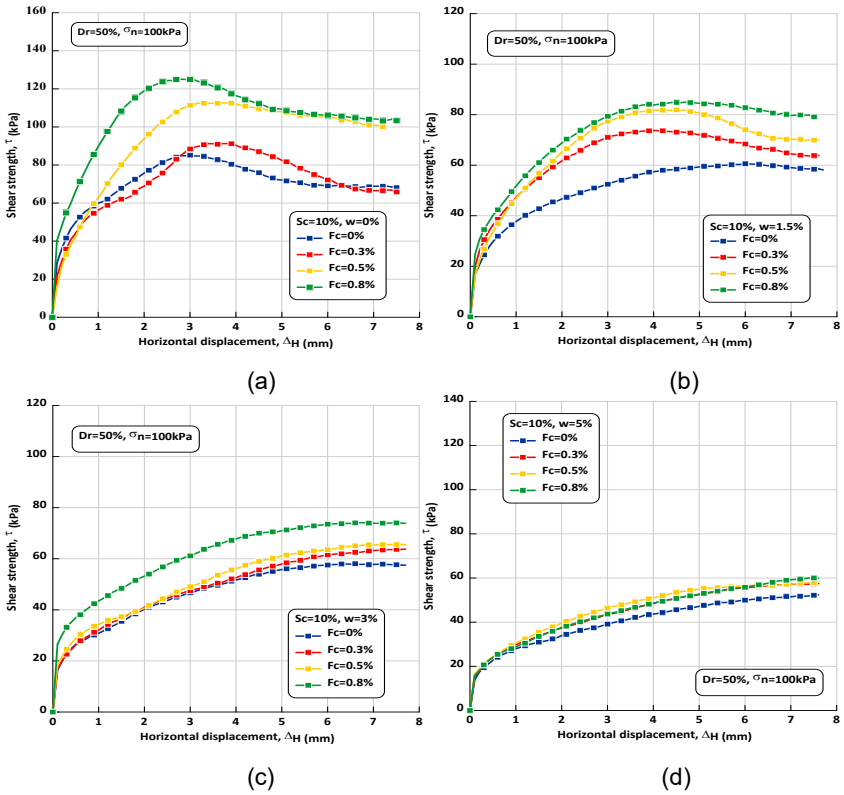


Figure 13 - Influence of water content on the variation of shear stress of fiber reinforced silty sand under a normal stress of 100 kPa: (a) w=0%, (b) w=1.5%, (c) w=3%, (d) w=5%

Figure 14 illustrates the variation of vertical displacement versus horizontal displacement of fiber-reinforced sand-silt mixtures at different water contents. From the figure, it is noted that specimens prepared at low moisture contents (w = 0 and 1.5% by dry mass of sand) have shown initially a contractive behavior until a horizontal displacement of around 3 mm for dry reinforced silty sand and around 4 mm for wet reinforced silty sand; both were followed by a dilative phase until the end of the shearing process. However, reinforced specimens prepared at higher water contents (w = 3 and 5% by dry mass of sand) have shown a purely contractive response. Nonetheless, it is noted from the figure that fiber inclusions have positively impacted the composites' deformation. It is apparent that fiber reinforcement prompted a more dilative behavior at all moisture contents studied.

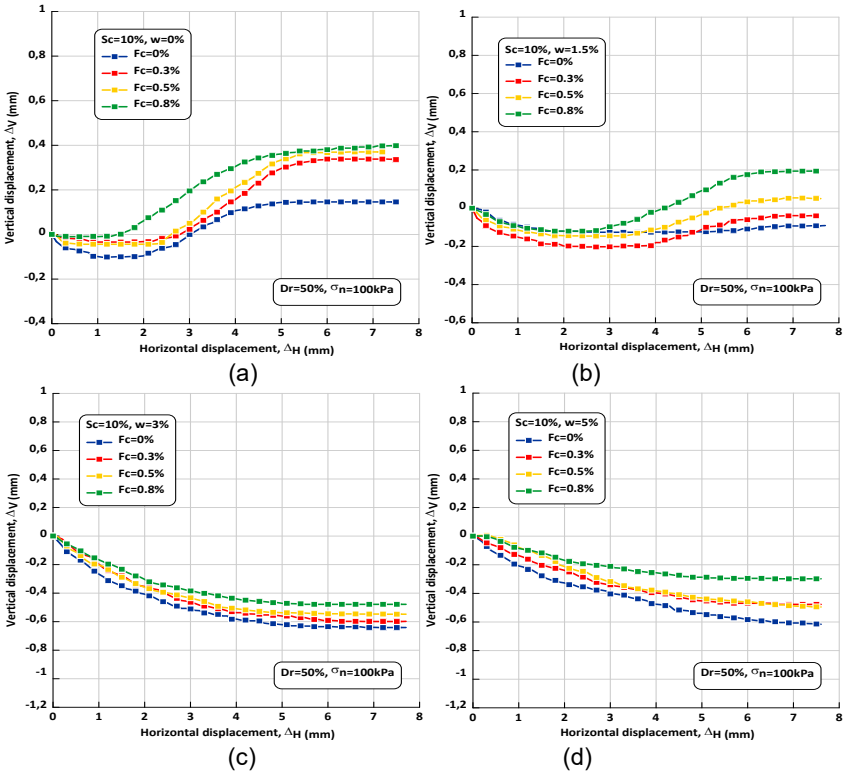


Figure 14 - Influence of water content on the variation of volumetric deformation of fiber reinforced silty sand under a normal stress of 100 kPa: (a) w=0%, (b) w=1.5%, (c) w=3%, (d) w=5%

Figure 15 presents the variation of the maximum shear strength as a function of water content and normal stress of fiber-reinforced silty sand. From the figures, it is observed that the maximum shear strength increased with an increase in fiber content and normal stress and inversely decreased with an increase in moisture content. Moreover, the mechanical characteristics (internal friction angle and cohesion) obtained from the linear regression analysis for different contents of fiber and water are presented in Figure 16 and summarized in Table 5. The results indicate that the values of the internal friction angle decreased with an increase in fiber content and moisture content (Figure 16a). With regard to the influence of moisture content on the cohesion of fiber reinforced silty sand, it was noted that there is a significant increase in cohesion with increasing fiber content and water content up to w = 1.5%, followed by an important decrease in the matrix cohesion past that moisture content. However, it is clear that the cohesion values obtained for fiber reinforced samples

prepared at low moisture contents (w = 0 and 1.5%) are much higher than those obtained for reinforced samples prepared at high moisture contents (w = 3 and 5%) (Figure 16b).

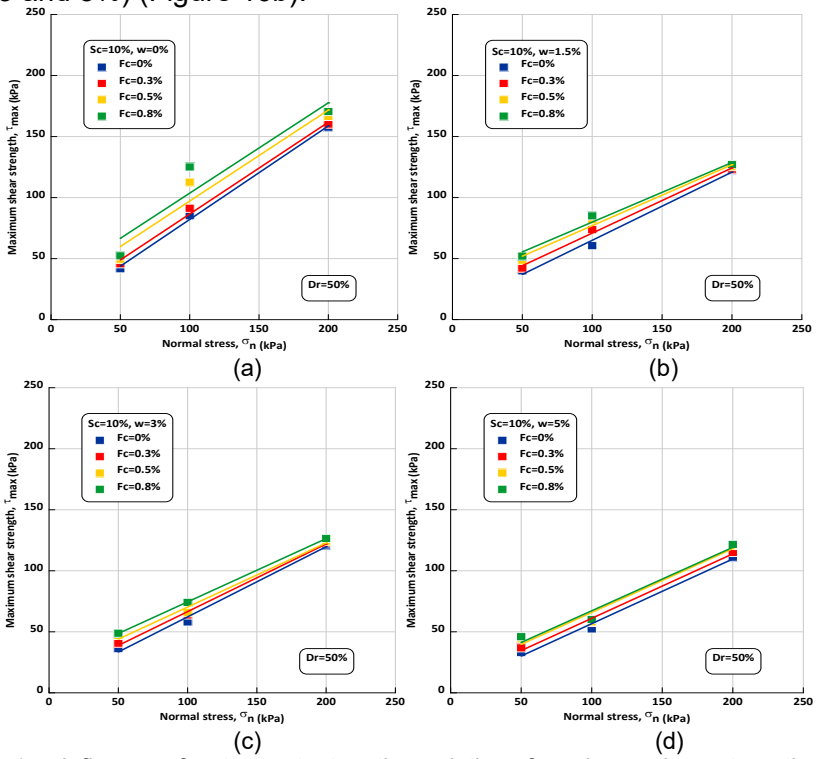


Figure 15 - Influence of water content on the variation of maximum shear strength of fiber reinforced silty sand under a normal stress of 100 kPa: (a) w=0%, (b) w=1.5%, (c) w=3%, (d) w=5%

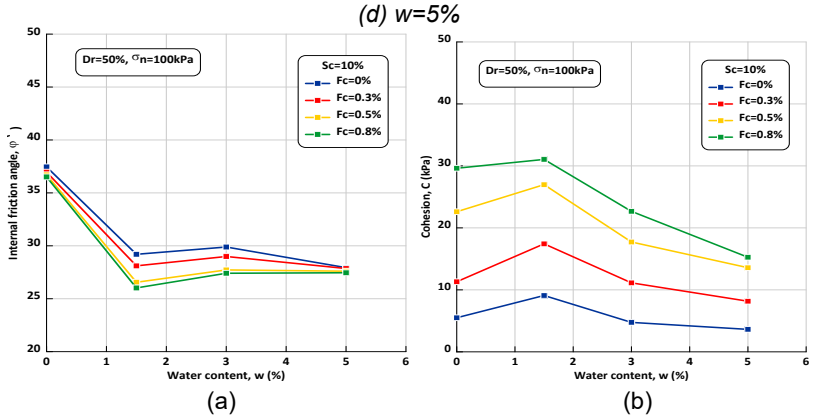


Figure 16 - Evolution of cohesion and friction angle of fiber reinfroced silty sand as function of water content

Table 5 - Influence of molding water content on the mechanical characteristics of fiber-reinforced silty sand

	Fc=0%		**Fc=0.3%**		**Fc=0.5%**		**Fc=0.8%**	
	c (kPa)	**φ (°)**	**c (kPa)**	**φ (°)**	**c (kPa)**	**φ (°)**	**c (kPa)**	**φ (°)**
w=0%	5,50	37,46	11,31	36,96	22,61	36,71	29,62	36,51
w=1.5%	9,09	29,20	17,43	28,11	26,98	26,56	31,05	26,02
w=3%	4,75	29,89	11,13	28,99	17,72	27,72	22,67	27,41
w=5%	3,63	27,94	8,17	27,86	13,58	27,60	15,26	27,46

Conclusion

A laboratory experimentation was conducted on unreinforced and fiber-reinforced sand-fines mixtures with different silt, natural fiber and moisture contents in order to study the effect of fiber reinforcement on the mechanical behavior of Chlef silty sand prepared with different dispositional methods. Taking into account the results obtained in this study, the following conclusions can be drawn:

- Silt fractions negatively affect the mechanical behavior of sand, as it was found that an increase in silt content reduced the shear strength and the dilative behavior of sand-silt mixtures. However, an increase in silt content slightly increased the cohesion of the composites.
- The efficiency of fiber inclusions is highly dependent on the fiber concentration, since the shear strength of the reinforced specimens increased relatively with the increase in fiber content.
- Test results show that the maximum values of cohesion increased with the increase of fiber content. However, no significant influence was found regarding the internal friction angle.
- The discrete element reinforcement is a promising technique to counter the influence of silt content on the mechanical behavior of sand.
- The initial moisture content has a significant impact on the shear behavior of fiber-reinforced silty sand, as an increase in water content caused less effective interfacial contact between the fiber-soil matrix, resulting in a decrease in strength. Therefore, special consideration must be given to the initial moisture content in practical applications.

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Mehaničko ponašanje muljevitog peska ojačanog prirodnim vlaknima: uticaj sadržaja mulja, vlakana i drugih parametara

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OBLAST: građevinarstvo
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Brojna istraživanja ukazuju na značajno smanjenje čvrstoće na smicanje peskovitih tla prilikom sitnih frakcija, što posledično dovodi do zemljišta sa nepovoljnim geotehničkim svojstvima. Usled nedostatka odgovarajućeg tla za građenje, danas je neophodno modifikovati svojstva zemljišta kako bi ona bila pogodna za inženjersku primenu. Postoje brojne metode i tehnike za poboljšanje stabilnosti zemljišta, a naročito efikasnu metodu predstavlja uključivanje pojedinačnih elemenata za jačanje u sastav tla, jer se na taj način doprinosi različitim povoljnim efektima.

Metode: U radu se ispituje uticaj prirodnih vlakana na ponašanje muljevitog peska pri smicanju, pri srednjoj relativnoj zbijenosti, različitim metodama pripreme uzoraka i različitim udelima vlage. Istraživanje je usmereno na različite parametre, odnosno sadržaj mulja, sadržaj vlakana i sadržaj vode.

Rezultati: Eksperimentalni rezultati ukazuju na smanjenje čvrstoće pri povećanju sadržaja mulja i sadržaja vode. Pored toga, čvrstoća mešavina, promene u pogledu zapremine i mehanička svojstva značajno se poboljšavaju dodatkom sisal vlakana pri niskim udelima vode. Međutim, pri visokim sadržajima vode nije zabeleženo značajno poboljšanje, što ukazuje na negativan uticaj vlage na mehanizam ojačanja vlaknima.

Zaključak: Nakon detaljne analize dobijenih rezultata, utvrđeno je da se sisal vlakna mogu opravdano koristiti za poboljšanje svojstava zemljišta.

Ključne reči: pesak, mulj, prirodna vlakna, sadržaj vode, čvrstoća na smicanje, mehanička svojstva.

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Holistic model for managing non-ionizing radiation in an underground mine technical room based on measurements and simulations

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FIELD: chemical technology and materials
ARTICLE TYPE: original scientific paper

Abstract:

Introduction/purpose: Underground mining environments contain numerous electromagnetic sources whose cumulative emissions may increase occupational exposure to non-ionizing radiation (NIR). The aim of this study is to assess exposure levels and propose a management model for NIR control in a mining technical room.

Methods: Field measurements of electric and magnetic fields were conducted using a Narda NBM-550 system, combined with three-dimensional electromagnetic simulations performed in CST Studio Suite. Measurements and simulations were carried out in three critical mining zones: Main Transport Tunnel, Technical Room, and Power Supply Area.

Results: The highest electric field level was recorded in the Technical Room due to simultaneous operation of multiple wireless and electrical sources.

Simulation results confirmed field superposition and reflection effects, with local peak values reaching 25.2 V/m (41% of ICNIRP reference limits).

Conclusion: The integration of measurements and simulations enables a holistic management approach for occupational NIR exposure. The proposed model supports risk assessment, preventive planning, and continuous monitoring in complex underground environments.

Key words: non-ionizing radiation, mining, electromagnetic fields, measurement, simulation, superposition, ICNIRP, occupational safety.

Introduction

Modern mining environments are increasingly equipped with numerous devices emitting electromagnetic (EM) fields, including industrial machinery, routers, repeaters, mobile devices, and external sources such as high-voltage power lines and base stations. In underground mines, confined spaces and metallic or reflective surfaces can amplify the cumulative effect of these sources, resulting in complex spatial distributions of EM energy and localized hotspots (SCHEER, 2021; ICNIRP, 2010; Dijkers et al., 2020). Such conditions are particularly critical in technical rooms and areas where workers spend extended periods.

The management of non-ionizing radiation (NIR) in occupational settings is therefore essential for worker safety and regulatory compliance. Studies have demonstrated that conventional risk assessments often underestimate exposure by neglecting interference and superposition effects from multiple simultaneous sources (Panagopoulos et al., 2015; WHO, 2007). Moreover, recent guidelines emphasize the need to consider cumulative exposure, reflections, and high-density source environments when assessing EM field levels in industrial workplaces.

This paper contributes to the field by combining direct measurements and numerical simulations to provide a comprehensive evaluation of NIR exposure in a real underground mining environment. The study focuses on three critical zones — Main Transport Tunnel (MTT), Technical Room (TR), and Power Supply Area (PSA) — to highlight the variation of exposure levels, identify areas of potential risk, and propose management measures based on both empirical and simulation-based evidence.

Methodology

The study was conducted in an underground copper mine at a depth of 120 meters, with an annual production of approximately 50,000 tons and employing around 200 workers. The mine is equipped with modern electrical systems, wireless communication networks, and heavy

machinery, providing a representative environment for assessing occupational exposure to non-ionizing radiation. Three critical zones were analyzed due to their high exposure potential:

- the Main Transport Tunnel (MTT), where workers spend extended periods near moving equipment;
- the Technical Room (TR), containing wireless communication devices;
- the Power Supply Area (PSA), with high-voltage electrical installations.

Measurements of electric and magnetic fields were conducted in each critical zone using the Narda NBM-550 device with EF 0391 and EF 5091 probes, covering frequencies from 100 kHz to 6 GHz. A grid-based measurement approach captured spatial variations, with recordings taken at different times to account for operational changes. Complementary numerical simulations were performed using CST Studio Suite software, based on detailed three-dimensional models of the mine, including material properties and source positioning. The simulated sources comprised local equipment (routers, repeaters, and industrial machinery), workers' mobile phones, as well as external sources such as a nearby base station (150 m) and a high-voltage power line (110 kV at a distance of 80 m). The simulation results were validated through comparison with measured data to ensure accuracy and reliability.

Results of measurements and simulations

The quantification of exposure in each analyzed zone is provided in Table 1, confirming the simulation model's findings regarding the variation in field intensity depending on the number and type of radiation sources.

Table 1 - Measured values of electric and magnetic fields in key mining zones

Location	Electric Field (V/m)	Magnetic Field (A/m)	Frequency
MTT	4.2	0.011	27.12 MHz
TR	13.7	0.036	2.4 / 5 GHz
PSA	9.1	0.024	50 Hz

In addition to direct measurements, simulations identified additional EM components:

- Base station - 5.1 V/m
- Mobile phones - 4.0 V/m

As observed in Table 1, the highest electric field value was recorded in the Technical Room (TR), in alignment with simulation results, which is reasonable given that this zone houses multiple simultaneously active wireless devices, servers, and networking equipment, leading to additive electromagnetic contributions and localized field enhancement. This highlights the need for special management measures in areas with multiple simultaneously active sources.

The simulation model indicated that the presence of multiple sources in the TR leads to interference and amplitude enhancement of the electric field in reflection zones. Furthermore, the impact of external sources (power lines and base stations) was low but constant. In the event of overlapping with local sources, field levels can exceed safety thresholds at specific points. The use of mobile phones and portable devices is a poorly controlled factor in total exposure (IEEE, 2019; Panagopoulos et al., 2015).

Analysis and proposed measures

In the TR, values reach 35–45% of the ICNIRP limit for frequencies of 2.4 GHz (ICNIRP, 2020). In certain scenarios, cumulative exposure exceeds 25 V/m due to source superposition, reflections from metallic surfaces, interference, and the presence of multiple portable devices.

Based on CST Studio Suite simulation, under the scenario of simultaneous sources and reflection effects in a confined metallic space, the local maximum electric field value reached 25.2 V/m, representing 41% of the ICNIRP reference limit for 2.4 GHz. This value was not obtained experimentally but derived from an interference and superposition model in a high-density source environment. The total exposure in the technical room (TR zone) results from the combined influence of multiple sources: a Wi-Fi router, workers' mobile phones, industrial cabling, and the contribution of a nearby base station. Table 1 presents the measured electric field strength of 13.7 V/m for the router, while the values of 5.1 V/m (base station) and 4.0 V/m (mobile devices) were obtained through electromagnetic simulation using CST Studio Suite software (Dassault Systèmes, 2023).

When the model includes the effects of electromagnetic wave reflection from metallic walls, as well as interference between multiple sources within a confined space, the local peak electric field value reaches 25.2 V/m. This value is not included in Table 1, as it is not derived from direct measurement but from three-dimensional simulation conducted under conditions of high source density and specific room geometry.

The simulation was based on the following input parameters:
– Room dimensions: 6 × 4 × 2.5 meters,
– Walls with metallic cladding (conductive surfaces),
– Three active sources (Wi-Fi router, mobile phones, base station),
– Presence of up to four workers carrying phones (emitting 2–3 V/m per device).

Based on these conditions, the maximum electric field strength within the interference focus area reached 25.2 V/m, representing 41% of the ICNIRP (ICNIRP, 2020) reference limit of 61 V/m for the 2.4 GHz frequency band.

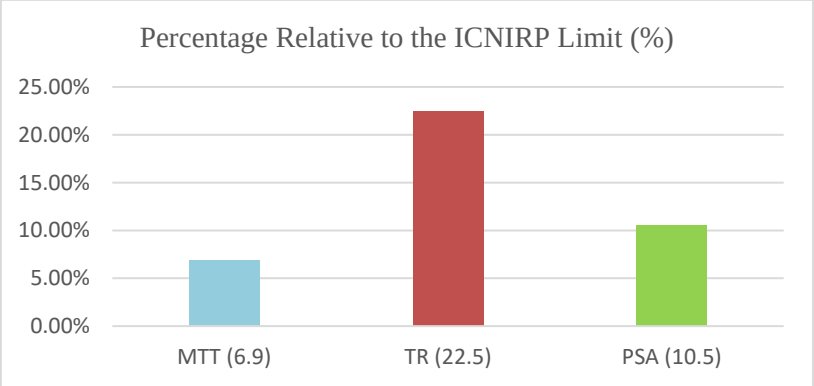

Figure 1 - Percentage of non-ionizing radiation exposure by zone

Figure 1 presents the relative electric field exposure in the three analyzed mining zones (Main Transport Tunnel – MTT, Technical Room – TR, and Power Supply Area – PSA) with respect to the ICNIRP reference limits. As shown, the highest relative exposure occurs in the TR zone, reaching 22.5% of the maximum permissible value, due to the combined effect of multiple wireless devices, industrial cabling, and reflections from metallic surfaces. The PSA and MTT zones exhibit lower relative exposure levels, 15% and 7% of the ICNIRP limit, respectively, reflecting the lower density of active EMF sources and reduced interference effects in these areas. These results highlight the importance of targeted monitoring and management measures, particularly in the TR zone, where cumulative exposure can increase under high-density source conditions.

In the TR zone, exposure reached 22.5% of the maximum permissible value, indicating the necessity for continuous monitoring to ensure safety and detect any potential increases in real time.

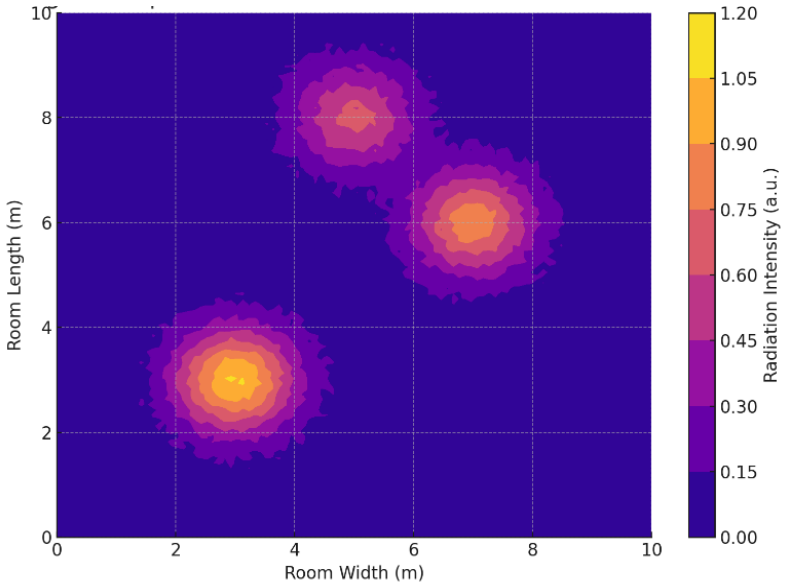

Figure 2 - Spatial distribution of radiation in the technical room (TR)

Figure 2 illustrates a simulated topographic map of electromagnetic radiation within the technical room (TR). A high concentration of radiation is observed in the vicinity of multiple sources (routers, mobile devices, metallic surfaces), confirming the risk of localized field accumulation and electromagnetic interference.

Exposure calculation

The cumulative effect of multiple simultaneous non-ionizing radiation sources is assessed using the principle of normalized superposition. According to ICNIRP (ICNIRP, 2020; IEEE, 2019; WHO, 2017), total exposure is expressed as the sum of individual contributions based on the ratio of measured values to the allowed reference limits for the given frequency:

$$\sum_{i=1}^{n}\left(\frac{Ei}{E\,ref,i}\right)^2+\sum_{j=1}^{m}\left(\frac{Hj}{H\,ref,j}\right)^2\leq 1 \qquad (1)$$

where:

Ei - Measured electric field for the i-th source (V/m)
Eref,i - Reference limit for the corresponding frequency (V/m)
Hj - Measured magnetic field value (A/m)
Href,j - Reference limit for the corresponding frequency (A/m)

This exposure summation formula is in accordance with the ICNIRP guidelines (ICNIRP, 2020; IEEE, 2019) and WHO recommendations (WHO, 2007) regarding the cumulative effect of electromagnetic fields across multiple frequencies.

Example Calculation - TR zone:

Three dominant NIR sources were identified based on field measurements and simulations:

Table 2 - Measured values of dominant non-ionizing radiation sources

Source	Frequency	Value (E)	Method	Eref (ICNIRP)
Wi-Fi Router	2.4 GHz	13.7 V/m	Measurement	61 V/m
Base Station	900 MHz	5.1 V/m	Simulation	41 V/m
Mobile Devices	2.4 GHz	4.0 V/m	Simulation	61 V/m

Measurement conditions:

- The value 13.7 V/m was measured in the presence of an active Wi-Fi router.
- The value 5.1 V/m (base station) and 4.0 V/m (mobile phones) were derived from 3D simulation using CST Studio Suite, with source positioning based on actual layout.

The total exposure is calculated per ICNIRP as follows:

- E1=13.7 V/m (router, 2.4 GHz), Eref,1=61 V/m
- E2=5.1 V/m (base station, 900 MHz), Eref,2=41V/m
- E3=4.0 V/m (mobile devices), Eref,3=61 V/m

Applying equation (1) to the measured and simulated field strengths in the Technical Room (TR) results in the following cumulative exposure index:

$$\left(\frac{13.7}{61}\right)^2 + \left(\frac{5.1}{41}\right)^2 + \left(\frac{4.0}{61}\right)^2 = 0.0504 + 0.0155 + 0.0043 = 0.0702 \quad (2)$$

This numerical example illustrates the application of the exposure summation formula defined in accordance with ICNIRP (ICNIRP, 2020; IEEE, 2019) and WHO guidelines. The result indicates a cumulative exposure index of 0.0702, which corresponds to 7.02% of the total permissible exposure limit.

This result indicates a cumulative exposure of 7.02% relative to the permissible threshold.

The measured magnetic field (H) values in this zone were:

- TR: H = 0.016 A/m
- PSA: H = 0.021 A/m

These values are significantly below ICNIRP limits (e.g., 2 A/m for 50 Hz), so electric fields dominate in exposure evaluation. These magnetic fields were excluded from this scenario's superposition calculation.

Reflection and distribution

Reflective surfaces, such as metallic panels and equipment casings, along with the specific geometric configuration of the room, significantly contribute to the creation of localized hotspots of electromagnetic energy. These effects are particularly evident in confined technical environments, where wave reflections and standing waves can lead to non-uniform field intensities. This phenomenon has been verified through simulation-based spatial mapping of the technical room (TR) zone, which revealed distinct areas of elevated electromagnetic field strength. Such patterns underscore the importance of accounting for reflection dynamics in the assessment of occupational exposure. Recent studies have emphasized the need for three-dimensional field simulations in environments with high-density EM sources to accurately predict exposure scenarios and guide mitigation strategies (Martínez-Búrdalo et al., 2023).

Management model

In occupational environments where multiple non-ionizing radiation (NIR) sources are present, such as technical rooms in underground mines, cumulative exposure may lead to elevated health and safety risks despite individual sources remaining below threshold limits. A structured and preventive approach is required to mitigate these complex interactions. The proposed model serves as a systematic framework that integrates source detection, exposure assessment, technical and organizational controls, and continuous monitoring, ensuring effective management of NIR in compliance with international safety standards.

The proposed model includes:

- Detection and quantification of sources,
- Superposition analysis of critical points,
- Technical measures (shielding, isolation, relocation),
- Organizational measures (mobile device restriction),
- Worker training and continuous monitoring.

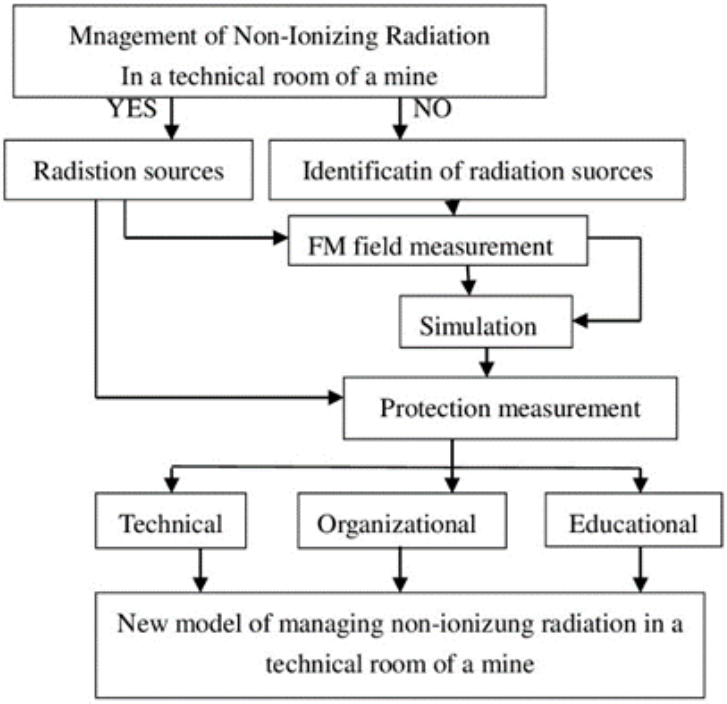

Figure 3 - Management model for NIR exposure in a mining technical room

Figure 3 graphically represents an integrated approach to the assessment and control of non-ionizing radiation exposure in a workplace with multiple sources. The model comprises six interrelated phases:

1. Source Identification (Detection) - Mapping all present sources of electromagnetic radiation within the technical room, including Wi-Fi devices, electrical cables, mobile phones, base stations, and mining equipment.
2. Measurement and Simulation (Quantification) - Instrumental measurements of electric and magnetic fields, complemented by spatial simulation using CST Studio Suite software, to obtain a comprehensive overview of the radiation distribution and intensity.
3. Superposition Analysis (Exposure Analysis) - The cumulative exposure in the technical room is assessed by applying the normalized superposition principle in accordance with ICNIRP guidelines. This approach enables the evaluation of the total

exposure index by summing the contributions of individual sources across relevant frequencies, as defined in equation (1) .

4. Technical Measures - Implementation of specific interventions such as:
    - Relocation of sources (reorganizing cables and devices),
    - Introduction of shielding and protective materials,
    - Reduction of emissions at the source (e.g. selecting devices with lower radiation power output).
5. Organizational Measures - Establishment of internal policies including:
    - Prohibition of mobile phone use within the technical room,
    - Shift planning and limitation of exposure duration,
    - Marking of critical zones and installation of warning signage.
6. Training & Monitoring - Continuous education of workers regarding radiation sources and cumulative exposure effects (SCHEER, 2021; ICNIRP, 2025; Dijkers et al., 2020), risks, training in safe behavior, and the implementation of a system for periodic monitoring and exposure review.

This model structure ensures a holistic approach to risk management, not limited solely to technical interventions, but also encompassing assessment, training, and organizational adjustments, in accordance with occupational health and safety system requirements.
This study advances the practice of non-ionizing radiation (NIR) management in occupational settings through the combined application of simultaneous measurement and simulation. In the technical room (TR), although individual sources did not exceed the threshold limits, the cumulative effect necessitated management interventions. Previous literature points to similar findings (Dijkers et al., 2020).

Conclusion

In the mining technical room, measured and simulated EM field levels reached up to 22.5% of ICNIRP 2020 limits. The proposed management model enables effective risk assessment and mitigation, grounded in objective measurement and simulation.

Exposure to non-ionizing radiation in mining environments is complex and dynamic, influenced by both fixed installations and mobile sources. Overlapping fields and reflective surfaces pose particular challenges (SCHEER, 2021; Panagopoulos et al., 2015), leading to local field amplification. Addressing these risks requires an integrated strategy

combining technical, organizational, and educational measures. The main scientific contribution of this study is the integration of measurement-based assessment and simulation-supported management modelling for occupational NIR control in confined underground environments.

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Holistički model upravljanja nejonizujućim zračenjem u tehničkoj prostoriji u podzemnom rudniku na osnovu merenja i simulacija

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OBLAST: hemijska tehnologija i materijali
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Podzemni rudarski sistemi sadrže veliki broj elektromagnetnih izvora čije kumulativno dejstvo može povećati profesionalnu izloženost nejonizujućem zračenju. Cilj rada je procena nivoa izloženosti i razvoj modela upravljanja nejonizujućim zračenjem u tehničkoj prostoriji rudnika.

Metode: Izvršena su terenska merenja električnih i magnetnih polja pomoću sistema Narda NBM-550, merenjem primenom mrežne (grid) metodologije, uz primenu trodimenzionalnih elektromagnetnih simulacija u softveru CST Studio Suite. Analiza je obuhvatila tri kritične zone: glavni transportni tunel (MTT), tehničku prostoriju (TR) i energetski blok (PSA).

Rezultati: Najveći nivo električnog polja utvrđen je u tehničkoj prostoriji usled istovremenog rada više bežičnih i elektroenergetskih izvora. Simulacije su potvrdile efekte superpozicije i refleksije, pri čemu su lokalne maksimalne vrednosti dostigle 25,2 V/m (41% referentnih ICNIRP 2020 ograničenja).

Zaključak: Kombinovanje merenja i simulacija omogućava holistički pristup upravljanju izloženošću nejonizujućem zračenju. Predloženi model podržava procenu rizika, preventivno planiranje i kontinuirani monitoring u složenim podzemnim uslovima rada.

Ključne reči: nejonizujuće zračenje, rudnik, elektromagnetna polja, merenje, simulacija, superpozicija, ICNIRP, bezbednost na radu.

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Chemical and energetic changes in thermally aged urea-stabilized double-based propellants

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FIELD: chemical technology
ARTICLE TYPE: original scientific paper

Abstract:

Introduction/purpose: Nitrocellulose-based propellants exhibit satisfactory properties for the majority of conventional munitions, although their tendency to lose effectiveness over time results in less operational efficacy and safety issues. The process of chemical aging and a decrease in certain properties occurs gradually due to the degradation of nitro esters into nitrogen oxides. A comprehensive spectrum of test processes has been established globally as a quality control system to reduce the risk of accidents in warehouses. One method that provides insight into the existing condition and estimates service life is artificial aging at specific temperatures.

Methods: The study examines the chemical stability of double-based rocket propellant after accelerated aging at 70°C for a duration of 60 days. The samples were systematically analyzed every 10 days to assess the variations in important parameters of chemical stability at the laboratory level. High-performance liquid chromatography (HPLC) was applied to determine the concentration of stabilizers, as well as other organic constituents (plasticizers and nitroglycerin), while the isoperibolic calorimeter allowed the evaluation of energetic potential.

Results: The results demonstrate that double-based propellant stabilized with urea derivatives retains significant stabilizer concentrations under artificial aging, allowing this propellant type to preserve chemical stability for extended periods. The variations in the values of nitroglycerin and plasticizer are associated with elevated temperatures and the aging of samples without an inhibitor layer.

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Conclusion: Data provided by the artificial aging of double-based gunpowder can be beneficial for assessing the chemical stability of well-preserved ammunition over time.

Key words: double-based rocket propellant, stabilizer, energetic potential, HPLC, calorimetry.

Introduction

Despite continuous developments and research, the military industry continues to primarily depend on nitrocellulose (NC) based propellants. Such energetic materials exhibit satisfactory properties for the majority of conventional munitions. The advantages of this ammunition type (cost, manufacturing methods, characteristics) are counterbalanced by its tendency to lose effectiveness over time, resulting in less operational efficacy. The nitrocellulose problem was noticed already in the final decade of the 19th century and the beginning of the 20th century, following numerous incidents in warehouses and aboard ships transporting gunpowder, leading to concerns regarding the stability of energetic materials based on nitrocellulose (Maksimović, 1985, p. 34-35). Extensive testing revealed that the chemical stability of gunpowder and rocket propellant decreases over time due to the autocatalytic decomposition of nitric acid esters, even at ambient temperatures. A number of reactions occur in nitrocellulose powders, resulting in the formation of breakdown products over time, including carbon oxides, nitric and nitrous oxides, methane, formaldehydes, water and nitrogen (Lindblom, 2004, p. 9). The main concern is nitrogen oxides, as they ultimately result in exothermic processes that establish critical conditions for self-ignition. The process, regrettably, cannot be entirely halted, but can only be mitigated by the incorporation of stabilizers - organic compounds that bind nitrogen oxides. The aging process of gunpowder is characterized by mass decrease, changes in molar masses, variations in nitrogen concentration within nitrocellulose, modifications in stabilizer composition, and heat emission (Grbović, 2025, p. 443). The manufacturer's warranty encompasses a duration of 10 years, in which the ammunition will maintain its mechanical, ballistic, and chemical properties, and after that period, according to the fact that the complete elimination of chemical aging in nitrocellulose energetic materials is unfeasible, an extensive variety of tests has been established globally to assess present chemical stability or estimate the safe shelf life. Each country in peacetime accumulates a large amount of ammunition in order to use it in wartime. To provide safety and reliability

of ammunition, it is imperative to implement protocols that reduce the risk of gunpowder self-ignition and accidents in storage facilities.

Serbia possesses its own standard, which establishes the assessment of the chemical stability of gunpowder and rocket propellants. The referenced standard is broad and highly detailed, although it applies to instruments whose performance is now considerably outdated. Nonetheless, stringent criteria and techniques facilitate the oversight of the situation and the regulation of ammunition storage, thus ensuring the secure management of ammunition resources.

The preparation, duration, and conditions of individual tests may differ considerably based on the type of gunpowder sample being evaluated. Gunpowders have advanced from single-base, mostly composed of nitrocellulose, to double-base, which includes both NC and nitroglycerin (NG), and further to triple-base, comprising NC, NG, and nitroguanidine (Jelisavac et al., 2019, p. 51). The modification of their properties, dependent upon the application and efficacy of the weapon and ammunition in which they are integrated, is accomplished by various additions of either organic or inorganic form. Some have significantly improved energetic characteristics by adding a certain amount of nitramine explosives to the composition, creating composite modified gunpowder. To enhance adequate processability, different plasticizers and chemical treatment agents are incorporated. Moreover, their configurations can vary significantly, ranging from diminutive spheres and flakes to perforated tubes or singular blocks. Certain methods include grinding the gunpowder to exact dimensions to achieve representative results, whereas others aim to replicate the conditions present in a cartridge as closely as possible. Most approaches have a commonality in elevating the temperature to expedite reactions that would otherwise occur within the gunpowder mass over an extended duration. It is essential to note that the majority of the criteria for evaluating chemical stability have been established empirically, serving as a benchmark that is consistently understood to prevent self-ignition.

The artificially aging method for gunpowder was first designed solely to assess the degradation of stabilizers over time, serving as a quantitative measure of chemical stability. The method outlined in the domestic standard (Jelisavac et al., 2018, p. 81) also facilitated the monitoring of additional parameters, including changes in the content of other organic components and the assessment of mass loss at a specified temperature, while the sample quantity was adequate to evaluate the effect on energetic potential following treatment at an elevated temperature for 60 days.

Materials and methods

This study examines four samples of double-based gunpowder (DBGP) composed of NC, NG, stabilizer (urea derivative - ethyl centralite, EC), plasticizer - dibutyl phthalate (DBP), and a certain amount of inorganic compounds. All of the samples were treated at a temperature of 70°C for 60 days. Table 1 shows data on the initial values for the tested samples before samples were artificially aged.

Table 1 – Initial values for tested materials

Sample	Organic compound (mass %)			MV, 120°C (min)	energetic potential (cal/g)
	EC	DBP	NG		
DBGP 446	2.79	2.02	32.55	46	913.8
DBGP 229	2.78	2.30	32.04	46	909.9
DBGP 515	2.78	2.25	32.74	45	909.6
DBGP 157	2.72	2.26	32.07	45	905.9

All samples are five years old; the inhibitor has been eliminated during the delaboration process, and the samples were exposed outside the rocket engine for a few weeks before analysis.

Sample preparation for artificial aging

Gunpowder samples were inserted into suitable glass test tubes with ground stoppers. If the gunpowder was of substantial size, it was shaped into sticks (Figure 1), with a length corresponding to the mass specified by the standard.

Figure 1 – Left: sample prepared for artificial aging; right: sample prepared for acclimatization in a climate chamber

A sufficient number of pieces are cut for the test, enough pieces for every 10 days and to maintain a reference piece, which will remain at ambient temperature for the whole length of the experiment. Testing is permitted only on materials that have undergone the Methyl Violet

technique for over 45 minutes prior to the test paper's complete transition from purple to salmon color.

Before the beginning of the accelerated aging process, the prepared samples and test tubes must be acclimatized in a climate chamber for 48 hours at a temperature of 20 ± 5°C and a relative humidity of 65 ± 2 % (Figure 2, left). This step is crucial, as conventional thermoblock tubes exceed the dimensions of the sample, resulting in significant free volume and air that may interact with the gases within the tube throughout the aging process.

Figure 2 – Left: samples in a climate chamber; right: samples placed in thermoblock

Elevated humidity facilitates the evaporation of gases alongside water at increased temperatures, hence enhancing safety for the operators. Upon thorough preparation, the test tubes are sealed with stoppers and sealant to inhibit gas exchange with the external environment. Fully prepared samples are placed in a thermoblock (Figure 2, right), which must maintain a consistent temperature throughout the experiment, allowing for fluctuations of ±1 °C.

The samples remain sealed inside the thermoblock for the entire experimental period at a constant temperature and are collected and examined at a specified period. At the established temperature of 70 °C, it is presumed that one test tube is extracted from the block every 10 days. Considering that the samples are at a temperature much higher than ambient temperature, they are allowed to equilibrate at room temperature for 2-3 hours following their removal from the thermoblock, which is shown in Figure 3, the first figure from the left. Subsequently, they are taken out of the test tube (Figure 3 in the middle), crushed to the requisite dimensions (Figure 3 at the right side), and prepared for analysis by the high-performance liquid chromatography (HPLC) technique. Sample preparation requires cutting the samples into dimensions of 2x2 mm, necessitating the use of a non-sparking tool.

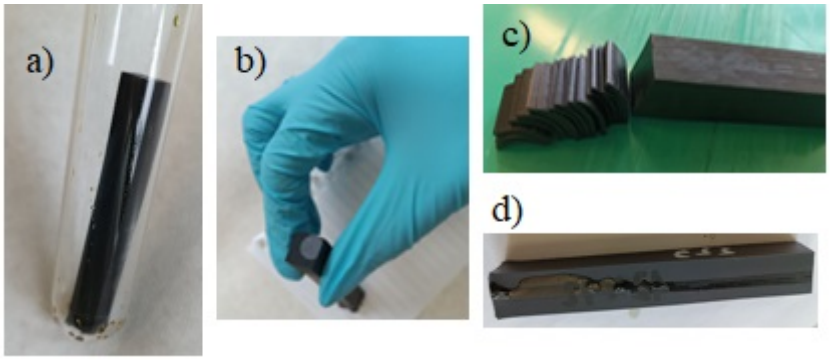

Figure 3 – a) sample in the test tube after removal from the thermoblock; b) sample after removal from the test tube; c) sample in the grinding process; d) a sample on which the consequences of the condensed phase are visible

Given that the mass of the aged samples significantly exceeds the requirements for HPLC analysis, the remaining samples were utilized for isoperibolic calorimetry testing to determine any fluctuations in energetic potential resulting from sample aging and to acquire a more precise understanding of the changes occurring in double-based propellants over time. However, considering the observable evidence of droplets on the samples (Fig. 3d), indicative of wetting and the migration of specific components, these regions were eliminated to ensure the most precise data, and only the areas devoid of visible "wet" signs were analyzed.

HPLC method and sample preparation

High-performance liquid chromatography is a crucial technique for quantifying organic constituents in gunpowder and double-based rocket propellants. The primary advantage over gas chromatography is the significantly lower operating temperatures that facilitate the detection of thermolabile substances. This is a very precise analytical technique that provides the exact identification and quantification of desired components. Each organic component possesses a distinct time frame at which it manifests on the chromatogram, dependent upon the established parameters of the procedure, and exhibits a clearly defined spectrum and wavelength distinctive of the specific chemical. This technique involves the injection of a high-pressure liquid solvent into a column filled with a solid adsorbent material, referred to as the stationary phase. Each component in the examined sample exhibits a distinct retention time owing to its specific interaction with the stationary phase, leading to the separation of components (Author et al., 2025, p. 4).

The "Waters 1525 Binary HPLC Pump," equipped with a column heating thermostat, the manual injector "Rheodine Model 7125," and the photodiode array detector "Waters 2998 PDA" were employed for the quantitative analysis of organic compound concentrations in prepared samples, with the following method characteristics: detector PDA (220 nm), column C18 (length 150 mm, ID 4.6 mm and particle size 3 μm), column temperature (not above 35ºC ± 0.5ºC) the mobile phase, acetonitrile: water (67:33 v/v), and the flow rate of 1.2 $mLmin^{-1}$.

HPLC operates by introducing known volumes of each component within the suitable range, enabling the software to generate a calibration curve for the identification and quantification of that particular component. Three calibration curves were established for the specified samples: the EC stabilizer ranged from 1% to 3.5%, the plasticizer from 1% to 3%, and NG from 25% to 35%. The processing of data and operational manipulation were carried out with the Breeze HPLC program. The outcomes were presented as mass percentages, with a precision of two decimal places.

Sample preparation for HPLC, which is shown in Figure 4, involves several steps: grinding the propellants into small fragments, passing them through sieves with a 2 mm opening, measuring exactly 1.000 g of the sample, and placing it into a flask. Next, 50 cm^3 of dichloromethane is added, and the flask containing the sample is stored in a dark place at ambient temperature for 48 hours.

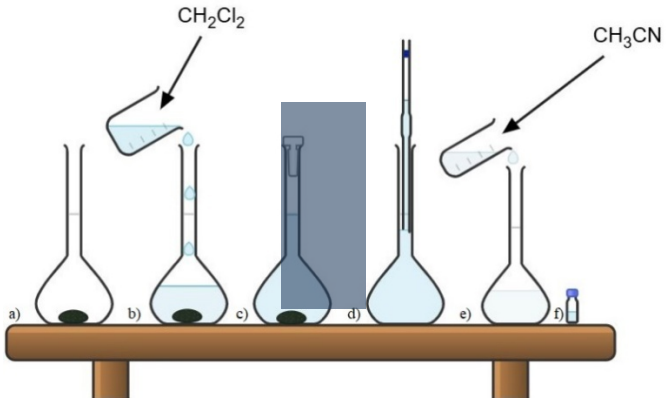

Figure 4 - Sample preparation in dichloromethane: a) 50 cm^3 flask with sample, b) adding dichloromethane to the flask, c) 48 h of extraction in the dark, d) taking 1 cm^3 of the solution for transferring to a 10 cm^3 flask, e) introducing acetonitrile into the flask after evaporation of dichloromethane, f) prepared sample for injecting into the HPLC vial

Subsequently, 1 cm³ of the solution was transferred to a 10 cm³ flask, where dichloromethane was extracted at low-temperature conditions (about 40 ºC), followed by the addition of 10 cm³ of acetonitrile. To obtain satisfactory results, it was imperative to filter the sample using a 0.5 µm PTFE filter prior to utilization (Author et al., 2022, p. 140).

To provide the repeatability and reliability of the data, each sample was prepared in duplicate, and each vial's sample was injected twice. The result shown in this study represent mean value of four measurements.

Isoperibolic calorimetry method

Combustion calorimetry is a technique that quantifies the heat released during a deflagration/combustion process. Given that powders and rocket propellants are classified as propellants, the energy released during the deflagration process is a crucial measure for assessing their efficacy. Considering that the combustion of energetic materials occurs in cartridge cases, it is essential to assess the concentration of external oxygen, specifically in an inert gas atmosphere, to accurately evaluate the energetic potential of the material under examination.

The IKA C2000 and the calorimetric bomb C5010 were employed for the experimental evaluation of the energetic potential. This technique comprises a sealed steel chamber containing the sample, immersed in water at a preset temperature. The test sample, possessing a known mass, is burned in a bomb under argon at a pressure of 20 bar. The generated heat is subsequently conveyed to a water jacket, where the temperature fluctuations are monitored (Author et al., 2024, p. 38).

Heat capacity quantifies the quantity of heat necessary to increase or decrease the temperature of a material by 1 K (Halliday et al., 2013, p. 524). The concept pertains to the ratio of heat (Q) exchanged between the material and the surroundings, along with the alteration in body temperature (ΔT). The energetic potential or heat value of combustion per gram of sample mass (m) is then:

$$\frac{\Delta T C_v}{m} = Q, \qquad (1)$$

where:
Q – energetic potential, J/g (or Q/4.1868 to express the value in cal/g);
ΔT – temperature change, K;
Cv – calorimeter heat capacity (water equivalent), $J \cdot K^{-1}$;
m – sample mass.

Figure 5 shows the sample preparation for calorimetry measurement, which involves cutting the sample to an appropriate size of 2x2 mm cubes, weighing between 2.0-2.4 g, inserting the sample into a quartz container, attaching the chrome-nickel wire for electrical connections, and sealing the bomb.

Figure 5 - Left: positioning the sample within the quartz container of the bomb; right: bomb prepared for the experiment

Given that the test is performed in an inert atmosphere, it is essential to initially evacuate the residual air from the bomb using a vacuum pump before subsequently introducing argon. Subsequently, the bomb is positioned in the calorimeter, and the remainder of the experiment proceeds autonomously.

Monitoring mass reduction

Mass loss is a significant parameter that indicates aging processes and alterations to energetic materials. While thermogravimetric analysis is predominantly employed as an instrumental technique that efficiently replicates specific processes in energetic materials, this research tracked the mass change in the tested samples using a standard gravimetric method during the entire experiment. The weight of every sample was initially measured before placement in the test tubes and exposure to the conditions within the climate chamber. Subsequently, the mass was remeasured after the samples were extracted from the test tubes, before the crushing process for further analysis started. The measurement of the mass reduction was determined as follows:

$$\frac{m_b - m_a}{m_b} x100 = m_l, \tag{2}$$

where:
m_b – mass before artifficial aging, g;
m_a – mass after artifficial aging, g;
m_l – mass reduction, %.

Results and discussion

All samples were tested consecutively; they were prepared and analyzed dynamically as they were taken from the thermoblocks every 10 days. The values obtained by the HPLC method are presented in Table 2. The accelerated aging method is solely designed for assessing the stabilizer concentration in gunpowder and rocket propellants, as this component decreases with time due to interactions with nitrocellulose degradation products.

Table 2 – Organic compounds content in DBGPs

DBRP 446							
day	10.	20.	30.	40.	50.	60.	ref.samp.
NG	31.49	31.46	30.64	30.46	30.20	29.0	32.18
EC	2.66	2.62	2.5	2.45	2.37	2.26	2.88
DBP	2.23	2.23	2.22	2.26	2.28	2.26	2.30
DBRP 229							
day	10.	20.	30.	40.	50.	60.	ref.samp.[1]
NG	32.27	32	31.76	31.52	31.38	28.86	/
EC	2.64	2.59	2.51	2.40	2.35	2.20	/
DBP	2.34	2.36	2.33	2.30	2.40	2.35	/
DBRP 515							
day	10.	20.	30.	40.	50.	60.	ref.samp.
NG	32.27	32.10	31.80	30.9	30.74	29.0	32.10
EC	2.80	2.62	2.54	2.41	2.30	2.24	2.83
DBP	2.24	2.23	2.20	2.19	2.18	2.22	2.21
DBRP 157							
day	10.	20.	30.	40.	50.	60.	ref.samp.
NG	33.1	31.28	31.22	31.09	30.74	30.37	31.78
EC	2.79	2.71	2.54	2.47	2.33	2.26	2.80
DBP	2.31	2.31	2.26	2.21	2.32	2.28	2.27

The results indicate that the temperature and duration of the experiment initiated rapid aging processes, as seen by the significant reduction in the starting stabilizer value. Despite the apparent degradation of the stabilizer, it did not result in a decline considered critical by the

[1]Due to an insufficient quantity of propellant, there was not enough substance for a reference sample for DBRP 229.

domestic standard. The observation that the stabilizer content decreased by no more than 20% over a 60-day period signifies that it is a fuel exhibiting considerable chemical stability.

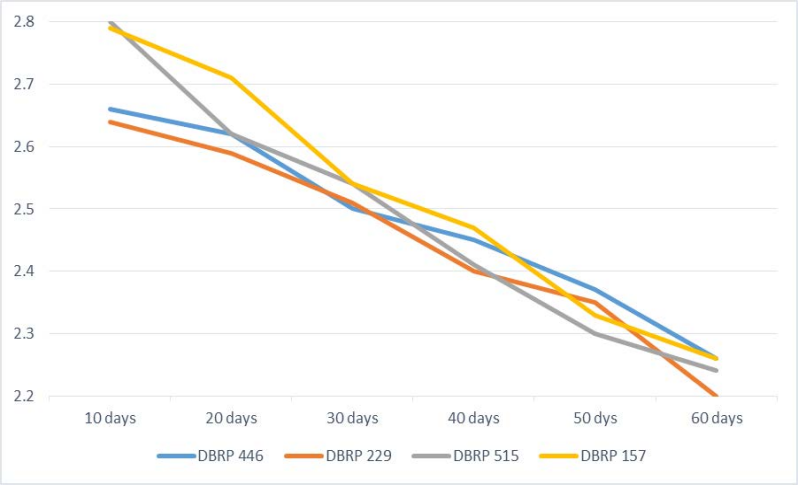

Figure 6 – Correlation between stabilizer consumption and time for DBRP 446, DBRP 229, DBRP 515 and DBRP 157

Figure 6 illustrates the correlation between stabilizer consumption and time, demonstrating a consistent decline in stabilizer value across all four samples, indicative of their identical compositions. The consumption of EC over time is minimal, a characteristic of the urea derivatives, which serve as the predominant stabilizers of double-based compositions, thus ensuring prolonged chemical stability of this category of energetic materials.

Since the HPLC method supports simultaneous analysis of all organic components in the sample, it was used in this investigation to also observe the behavior of NG and plasticizers during the accelerated aging process. However, this method is not primarily designed for such purposes. The explanation for the phenomenon is that, while the stabilizer decreases over time, the NG and plasticizer do not degrade but rather tend to migrate. This movement was notably demonstrated under artificially induced conditions, such as accelerated aging in the laboratory. The temperature of 70 °C is sufficiently elevated, and the absence of the inhibitor, which was eliminated from the fuel for this test, further expedited those processes. It became evident after the first 20 days that migration and reaction were occurring, as the elevated temperatures in the thermoblock caused a condensed phase to form on the surface of the test tube, which

then descended to the bottom during the cooling process (Figure 3). Furthermore, the samples progressively lost their original shape due to thermal exposure, as shown in Figure 7.

Figure 7 – Left: condensed phase on the surface of the test tube; right: change in shape due to heat

Table 2 shows a specific regularity in the value of NG, which progressively fluctuates over time. However, it is imperative to emphasize that this change should not be interpreted as a universal regularity applicable to all energetic materials, nor does it suggest that migration will occur in an actual inhibited rocket propellant chamber. Nitroglycerin is known to migrate into compatible materials with which it comes into contact, but it rapidly attains equilibrium.

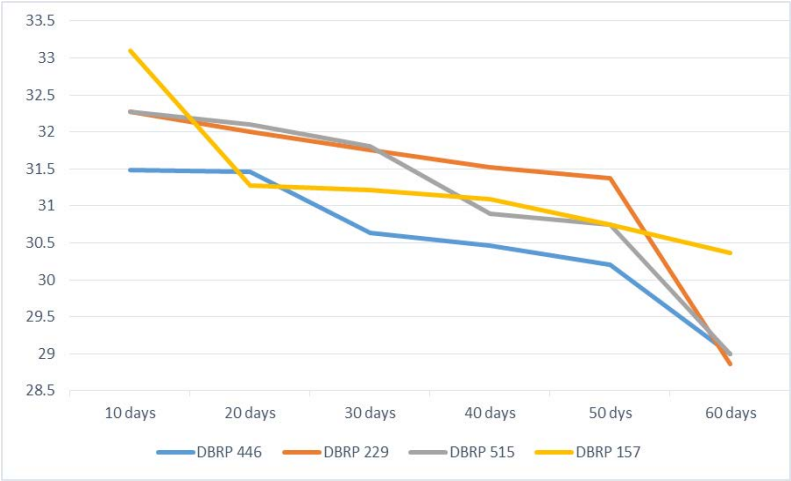

Figure 8 – Correlation of NG consumption and time for DBRP 446, DBRP 229, DBRP 515 and DBRP 157

The elevated temperature maintained during the experiment for 60 days, along with the lack of any barrier to inhibit migration, resulted in specific alterations. Although a reduction in NG content was observed throughout the experiment, it is important to highlight that on the 10th day, samples 515 and 157 exhibited values surpassing those of the reference sample. It was observed throughout all four samples that by the end of the experiment (the 60th day), a decrease of around 3% in NG was recorded relative to the original value, indicating that this quantity had migrated from the fuel.

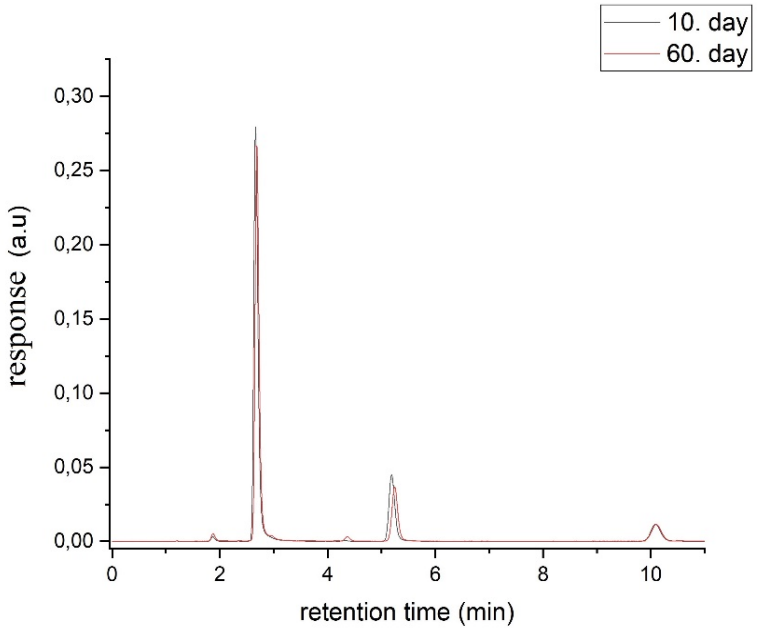

Figure 9 – Chromatogram of sample DBRP 157, 10th and 60th days

The results mentioned above should be evaluated based on the presence of the condensed phase in the test tube and the absence of the inhibitor. An optimal setting that would provide a definitive answer about the behavior of NG in double-based propellant would involve aging samples in their real dimensions and in the original cartridge. This will ascertain the direction of NG migration, whether from the center to the periphery of the grain, from top to bottom, or the opposite, and to what degree these activities are slowed down by inhibitor presence.

The values obtained by monitoring the DBP content demonstrate that the specified plasticizer exhibits considerable thermal resistance,

revealing not a decline but rather fluctuations within the samples, ranging from 0.06% to 0.1%, thereby maintaining relatively stable values, as shown in Figure 10.

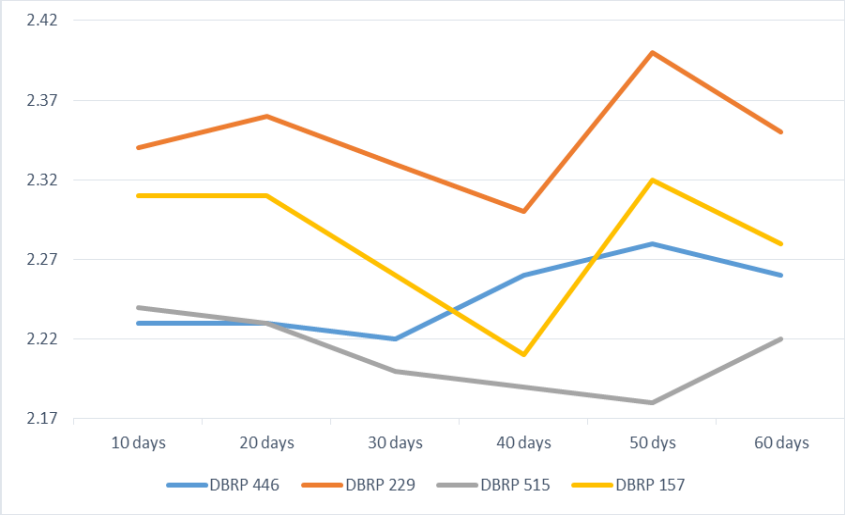

Figure 10 – Correlation of DBP consumption and time for DBRP 446, DBRP 229, DBRP 515 and DBRP 157

The energetic potential is an indicator that provides insight into the operational capacity of the composition of energetic materials such as propellants. Given that the heat of combustion (energetic potential) is a thermodynamic characteristic that directly correlates with the components of gunpowder and rocket propellants, the energetic potential was measured post-aging of the samples to assess the effect of the reduction in specific organic constituents. The variation in the energy released during combustion is directly attributable to the decrease in the concentration of the most energetic substance (NG), along with alterations in the stabilizer content. The first sample (DBRP 446) was analyzed post-removal of each test tube, revealing that changes in energetic potential values occur at a slow rate. Consequently, the remaining samples were assessed in a bomb calorimeter at intervals of 10, 30, and 60 days. The data obtained, representing the average of two measurements, with an allowable inaccuracy of 1 cal/g, are presented in Table 3.

Table 3 – Energetic potential values for samples DBRP 446,DBRP 229, DBRP 515 and DBRP 157

Day	Energetic potential (cal/g)			
	DBRP 446	**DBRP 229**	**DBRP 515**	**DBRP 157**
Ref. sample	913.6	/	909.1	908.5
10.	905.3	906.0	905.8	908.2
20.	908.2	/	/	/
30.	905.1	900.1	900.6	903.1
40.	901.7	/	/	/
50.	898.5	/	/	/
60.	887.4	880.1	885.2	900.7
Decrease in energetic potential from ref. to 60. day	26.2	25.9	23.9	7.8

The results in Table 3 correspond with the data from Table 2 about the NG content. Specifically, it is evident that the values measured on the 10th day align with the trend of energetic potential values for the samples; higher measured NG content correlates with elevated energetic potential values. On the 10th day, DBRP 157 had the largest energetic potential, although the values of samples DBRP 229 and DBRP 515 were very consistent, as were their NG contents. The minimum energetic potential was recorded for sample DBRP 446, which concurrently exhibited the lowest measured NG concentration. A similar trend is noted in the findings from the 60th day, with DBRP 157 exhibiting the highest values and DBRP 446 the lowest, while the other two samples display relative uniformity. Nonetheless, despite the apparent trend, it must be approached with caution, as there were clear indications that excess moisture, along with various components, migrated from the sample, and since it was unable to leave the test tube after cooling to room temperature, it accumulated on both the test tube and the sample. The removal and selection of samples devoid of wet traces may have affected the accuracy of the assessment of the condition of double-based propellants following accelerated aging.

Knowing that mass loss can serve as an indicator of the aging of gunpowder and double-based propellants, a gravimetric approach was employed to monitor the temporal variations in mass. The samples were weighed prior to their placement in the climate chamber and subsequent to removal from the thermoblock, with the mass differential computed in accordance with Equation 2. Tables 4-7 shows data on monitoring mass reduction for the tested samples.

Table 4 – Mass reduction over time for sample DBRP 446

Day	m_b (g)	m_a (g)	loss (%)
10.	21.1456	20.9012	1.16
20.	21.7886	21.4273	1.66
30.	19.6592	19.2923	1.87
40.	23.3835	23.0188	1.56
50.	20.7589	20.3282	2.07
60.	21.1776	20.8126	1.72
Ref.	22.1516	22.1650	+0.06

Table 5 – Mass reduction over time for sample DBRP 229

Day	m_b (g)	m_a (g)	loss (%)
10.	22.3855	22.1288	1.15
20.	22.2850	21.9908	1.32
30.	22.3698	22.0296	1.52
40.	22.1296	21.7641	1.65
50.	22.2389	21.9797	1.17
60.	22.3457	21.8692	2.13
Ref.	/	/	/

Table 6 – Mass reduction over time for sample DBRP 515

Day	m_b (g)	m_a (g)	loss (%)
10.	22.4548	22.2456	0.93
20.	22.0278	21.7731	1.16
30.	22.1609	21.8881	1.23
40.	22.0922	21.7269	1.65
50.	22.8253	22.5884	1.04
60.	22.2459	21.9909	1.15
Ref.	22.2837	22.2955	+0.05

Table 7 – Mass reduction over time for sample DBRP 157

Day	m_b (g)	m_a (g)	loss (%)
10.	22.4483	22.2092	1.07
20.	22.4625	22.1945	1.19
30.	21.8810	21.6189	1.20
40.	22.2996	22.0091	1.30
50.	22.6924	22.4584	1.03
60.	22.4100	22.1293	1.25
Ref.	21.7591	21.7700	+0.05

Tables 4-7 clearly demonstrate the tendency for mass loss to increase with the duration of exposure of the samples to elevated temperatures in the thermoblock. Despite a decline of approximately one percent within the initial 10 days, and up to 2% by the 60th day, individual variances may manifest as early as the 40th or 50th day. These discrepancies are directly correlated with the quantity of condensate retained on the samples during the cooling process, ultimately influencing the mass measured when the test tubes are opened. The most notable instance of this is sample DBRP 229 on the 50th day (Figure 3d), which exhibits a mass loss of about 1.17%, although ten days prior, the loss was 1.65%, and ten days subsequently, it increased to 2.13%. Additionally, it is notable that the samples DBRP 515 and DBRP 157, which exhibited mild deformation owing to heat, as illustrated in Figure 7, demonstrate behavior similar to that observed on day 50, when a divergence from the decreasing mass loss values occurs. For instance, a significant alteration was observed at the lower section of the sample, particularly in the area that contacted the test tube, where the highest concentration of condensate accumulated post-cooling. The results indicate that mass loss over time is apparent during the aging process and can be monitored using the gravimetric method, acknowledging that certain deviations may arise due to the

presence of moisture and the initiation of specific reactions at elevated temperatures.

Conclusion

This study focused on dual-based propellants and their aging in accordance with the domestic standard requirements. In addition to the fundamental approach of monitoring the stabilizer over time, the samples were analyzed for the presence of other organic constituents (NG and DBP) and submitted to further assessments, including the evaluation of energetic potential and the measurement of mass loss.

Based on the findings, the following conclusions were reached:

- The implementation of the domestic standard facilitates the monitoring of stabilizer consumption over time and allows for the evaluation of chemical stability based on the data received from the stabilizer,
- EC exhibits relatively low consumption over time, maintaining chemical stability and preventing self-ignition in warehouses for extended durations, which is essential for rocket propellants kept for several decades,
- A gradual decrease in the NG content of the samples was noted over time, exhibiting an obvious trend. Nonetheless, observing the migration of NG is unfeasible within such a limited sample; it is only able to document its occurrence, but not the direction it would assume under real propellant dimensions or the influence of inhibitors on this process,
- The measurement of the change in plasticizer content revealed a minor deviation in the mass distribution of the double-based propellant during the aging process. This phenomenon is related to the fact that plasticizer does not form hydrogen bonds with the polymer. By penetrating the macromolecule, it separates them and forms the plastic mass. This characteristic is identifiable by variations in the plasticizer content rather than its reduction,
- A substantial quantity of samples aged according to the national standard criteria facilitates adequate samples for additional analyses,
- The evaluation of energetic potential using calorimetry revealed a significant correlation between the reduction of the "most energetic" component (NG) and a reduction in energetic potential, which characterizes functionality rather than the chemical stability of double-based propellants,

- The gravimetric method for mass reduction measurement reveals that mass loss occurs over time due to nitrocellulose degradation processes, the consumption of stabilizers, and the migration of nitroglycerin and the sample itself. Nevertheless, the presence of moisture, increased temperatures, and degradation processes, which are partially stored in the sample post-cooling, induce distinct deviations.

The outcomes of the current study indicate that the national standard possesses several significant deficiencies: large free volume in the test tube, the introduction of moisture at the experiment's outset, and a sample of considerable mass that cannot be entirely employed for subsequent research. Minimizing the free volume and eliminating the climatic chamber phase would provide a more precise understanding of the mechanisms occurring during aging. The efficacy of monitoring NG migration and its impact on various parameters, including energetic potential, can be assessed by contrasting the results of this study with those derived from the aging of identical double-based propellants under actual conditions, encompassing total mass and dimensions, alongside the inclusion of inhibitors.

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Praćenje hemijske stabilnosti baruta i raketnih goriva. 1991. Beograd. SORS 8069/91 (In Serbian).

Hemijske i energetske promene u termalno starenim uzorcima dvobaznih raketnih goriva stabilsanih urea derivatom

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OBLAST: hemijske tehnologije
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Pogonska goriva na bazi nitroceluloze pokazuju zadovoljavajuća svojstva za većinu konvencionalne municije, iako imaju tendenciju da vremenom gube efikasnost, što rezultira manjom operativnom efikasnošću. Proces hemijskog starenja i smanjenja određenih svojstava odvija se postepeno zbog razgradnje nitroestara u azotne okside. Sveobuhvatan spektar analiza razvijen je širom sveta kao sistem kontrole kvaliteta za smanjenje rizika od nesreća u skladištima. Jedna od metoda koja pruža uvid u postojeće stanje i procenjuje vek trajanja je veštačko starenje na određenim temperaturama.

Metode: Studija ispituje hemijsku stabilnost dvobaznog raketnog goriva nakon ubrzanog starenja na 70°C tokom 60 dana. Uzorci su sistematski analizirani svakih 10 dana kako bi se procenile varijacije važnih parametara hemijske stabilnosti na laboratorijskom nivou. Tečna hromatografija visokog pritiska primenjena je za određivanje koncentracije stabilizatora, kao i drugih organskih komponenti (plastifikatora i nitroglicerina), dok je izoperibolički kalorimetar u inertnoj atmosferi omogućio merenje energetskog potencijala.

Rezultati: Dobijeni ezultati pokazuju da dvobazna raketna goriva stabilizovana derivatima uree zadržavaju značajne koncentracije stabilizatora tokom perioda ubrzanog starenja, što omogućava ovoj vrsti pogonskog goriva da očuva hemijsku stabilnost tokom dužeg perioda. Varijacije u vrednosti nitroglicerina i plastifikatora povezane su sa povišenim temperaturama i starenjem uzoraka bez sloja inhibitora.

Zaključak: Podaci dobijeni analiziranjem uzoraka ubrzano starenih dvobaznih raketnih goriva mogu biti korisni za procenu hemijske stabilnosti pravino skladistene municije.

Ključne reči: dvobazno raketno gorivo, stabiliztor, energetski potencijal, HPLC, kalorimetrija.

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Improving technical system maintenance by a computerized maintenance management support system

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FIELD: mathematics, decision sciences, industrial engineering
ARTICLE TYPE: original scientific paper

Abstract:

Introduction/purpose: The subject of this research is the work organization and execution methodology of an organization or individual responsible for the maintenance of a technical system (TS), respectively, workshop activities related to technical system technical maintenance (TMTS). In that segment of the maintenance organization's work, the possibility and need to improve the situation through the application of a computerized maintenance management system (CMMS) are observed. The assumption is that the introduction of a CMMS, along with the simultaneous application of other modern management tools, can significantly shorten the time that the technical system stays in the maintenance system and increase its availability.

Methods: The methods used in the research are: content analysis (analysis of workshop documentation and different literature sources), multi-factor and regression analysis by using the statistical software application MINITAB (experimental testing), software prototype development and che-

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cking the improvement in the real TS maintenance organization (empirical testing).

Results: It is expected to save time in the maintenance cycle in the administrative part of TS maintenance by introducing the TS maintenance management software application in maintenance organizations, because a number of activities are automated. The objectives of the software are the following: the program automates the filling out of the Workshop Sheet and Work Order, where common fields, such as the Workshop Sheet number and date, are linked and filled in automatically. Also, when filling out the Workshop Sheet, by simply clicking on the required registration (factory) number, other data in the "TS DATA" section are automatically filled in. Filling in data about the mechanic's NB is also automated by simply clicking to select the required work from the database. Finally, the program also offers printing of the Workshop Sheet and Work Order, as well as the List of Issuance and Receipt of Spare Parts.

Conclusion: Automation of individual processes in the organization and implementation of the work of TS maintenance organizations, using computers, i.e. software information systems, is an important step towards the modernization and improvement of the maintenance process of TS. By introducing the application program "PS Maintenance", it is possible to significantly facilitate individual activities and reduce the time required for the entire process of implementing the TS.

Key words: technical system, technical systems for special purpose, weapon systems, technical maintenance, overhaul, computer maintenance management system, maintenance level, maintenance system, lean maintenance.

Introduction

The system for maintenance of technical systems (TS) represents a complex organizational - technological system. Its size and complexity depend on the size and complexity of the organizational system whose TS is the subject of maintenance. How much time the TS will spend in the maintenance system (MS), due to failure or the undertaking of preventive activities, depends on numerous factors that are defined in the design and development phases of the TS, during its production, as well as on the activities in the MS which are undertaken during the exploitation of the TS. It is possible to ensure a high degree of availability or readiness of TS, in order to increase the effectiveness of its use, only by good organization and implementation of maintenance technology at all levels of maintenance, from basic maintenance, through technical maintenance ™, to general overhaul.

Analyzing the available normative documentation that determines the organization of TS maintenance and other literary sources developed by bodies responsible for the organization and implementation of TS maintenance (mostly logistics bodies in large organizational systems), individuals and software companies decades ago with the aim of improving the planning and organization of TS maintenance (Veselinović et al., 2012; https://www.sertica.com/maintenance/, 2025), it can be seen that there is a constant need to improve the situation in the field of the organization and implementation of the work of the performers of TS maintenance activities.

The improvement of the organization and implementation of the work of organizational systems for the maintenance of TS, or the improvement of workshop business using computers, represents a certain problem, because experience in the organization and implementation of the maintenance of various TS in a classical, paper-based, way is needed to identify areas for improvement, as well as the commitment of the management to improve work in this way. Furthermore, the problem is often the availability of data on the organization of maintenance systems. No sense to initiate the improvement of the current state without the analysis of that data.

In this paper, the subject of research is the methodology of the organization and implementation of the work of the organization or individual responsible for maintenance of the TS, or, more specifically, workshop activities related to TM of TS. In that segment of the maintenance organization's work, the possibility and need to improve the situation through the application of a computer maintenance management system (CMMS, Computer Maintenance Management System) are observed (Epler, 2016; Epler et al., 2017; Božanić et al., 2024).

Technical system maintenance organizations can perform their tasks in the field or in stationary, workshop conditions. Regardless of the place of execution of maintenance tasks, it is necessary to plan and organize all activities that are prescribed and standardized by technical instructions and unique time norms for each TS.

The practical realization of TS maintenance in organizations responsible for TM, from documentation management to the execution of activities, operations, movements and micro-movements of specific TS maintenance, differs from one maintenance organization to another, due to differences in the training of the workforce, its age structure, workload and infrastructure conditions. It is necessary to partially automate the maintenance of workshop documentation, maintenance procedures and spare parts (s/p) stock management. In this way, the work of similar organizations or TS maintenance services in the field of workshop

maintenance documentation would be standardized. This creates prerequisites for greater operational readiness of TS.

The main and basic goal of this paper is to describe the basic technological process of TM of most relatively simple TS (e.g. motor vehicles, weapon systems, other machines, aggregates, etc.), analyze and evaluate the existing organization and implementation of the work of most organizations for TM TS, whose data are publicly available, with a focus on workshop operations, which form the base of their work, and then to propose improvments to the current situation.

Existing technical system maintenance model

Maintenance of TS, as a field of technical and technological sciences, includes a set of measures and procedures that postpone or eliminate TS failure over a certain period of time and under given environmental conditions (Kobbacy - Murthy, 2008.). The definition of TS maintenance differs only in terms of the means to which it applies. The set of measures that should be implemented within the TS maintenance program is generally not implemented at a single workplace, i.e. level.

Maintenance levels

According to Andrejić & Sokolović (2014), TS maintenance can be organized and implemented at three levels:

- User level – I level;
- Technical maintenance workshop level – II level;
- Overhaul organization level – III level.

Figure 1 provides a display model of how is TS maintenance regulated in the Serbian Armed Forces (SAF), which has a large number of TS, and whose data on the organization and implementation of TS TM are publicly available through military literature, textbooks and manuals, without delving into the specific tactical and technical characteristics of TS, which in SAF's military literature are called technical mobile assets.

At each level of maintenance, tasks, administrative and executive bodies for maintenance are defined. An example of the organization and realization of TS maintenance in the Armed Forces can be a good basis for explaining the causes and consequences of improving TS maintenance with the support of a computer-based maintenance management system.

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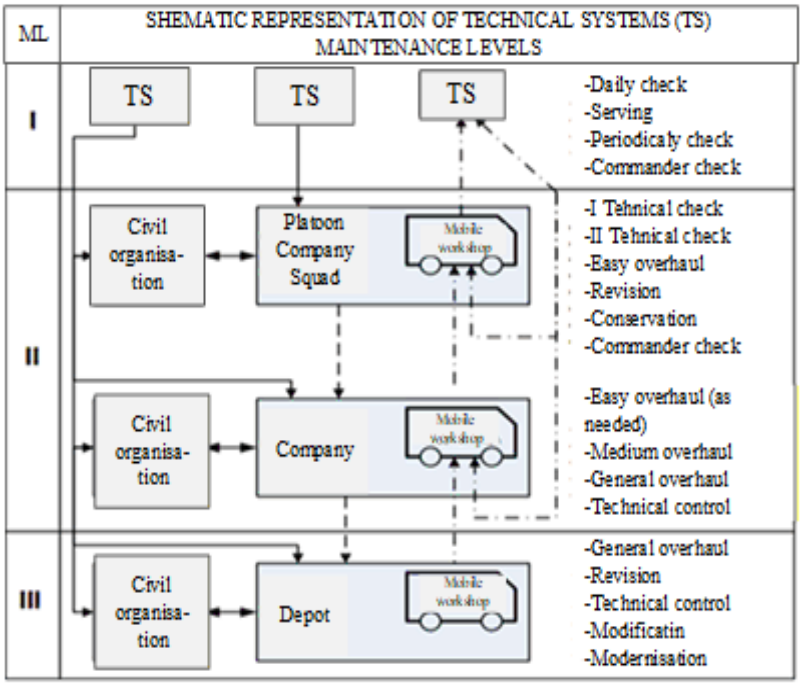

Figure 1 – Technical system maintenance levels (Andrejić & Sokolović, 2014)

Technical systems maintenance processes and problems analysis

Naumović analyzes the processes and problems in a real TS maintenance system and emphasizes that "the management of the TS maintenance process in MS, in today's conditions, is significantly more complex than before, since the requirements have increased in terms of the quality of the maintained TS, shortening maintenance deadlines, as well as in terms of maintaining increasingly complex TS. The constant complication of tasks, with the simultaneous shortening of maintenance deadlines, has created new problems and difficulties in planning and performing maintenance tasks. In addition to the price and quality of the maintained TS, the maintenance completion deadline also appears as an important factor in the maintenance market. The time reserve between the planned (standardized) cycle times for maintenance of TS (Tcmp) and the realized cycle times of technical maintenance of TS (Tcmr) was observed by analyzing the basic technological process of TS maintenance in real maintenance organizations (workshops) and the workshop documentation kept in them, which often lacks data related to the organization of the

process itself. The times due to TS waiting for work (administrative and logistical) are generally not recorded in the workshop documentation, which makes it difficult to argue for their reduction or complete elimination" (Naumović, 2025).

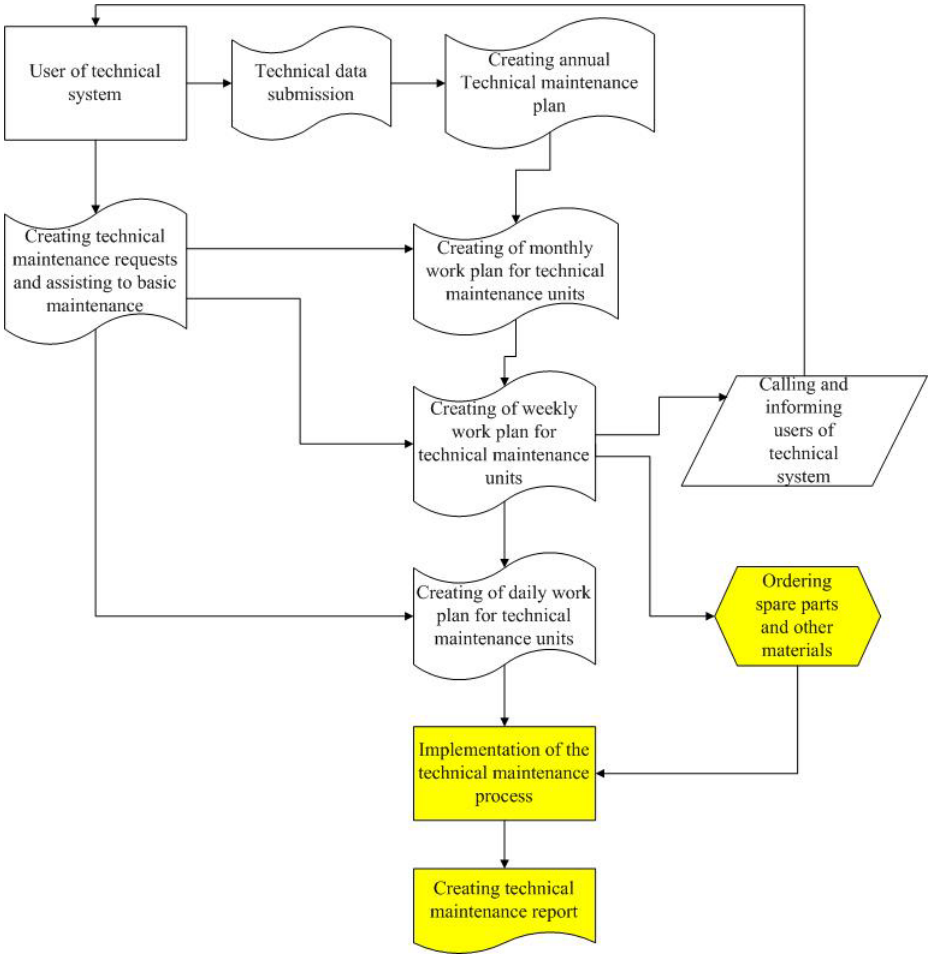

Figure 2 – Planning and organization of technical systems technical maintenance

From the above, it can be seen that today there is a lot of uncertainty and indeterminacy in most domestic MS, where maintenance management is carried out on the principles of traditional maintenance concepts (preventive and corrective). Many TS maintenance processes are not managed, under the constant excuse that this is how it should be, and this causes constant losses (material and time) in the performance of

TS maintenance. The existing technological documentation for the maintenance of most TS is “poor” from the point of view of managing the maintenance process. For this reason, the preparation of data for the use of computers, i.e. for a software information system for managing the maintenance process, is very difficult, because it relies only on currently available information from the technological maintenance process.

Algorithm of the basic technological process was created by analyzing workshop documentation and work in a real TS maintenance system, which takes place in most TS maintenance organizations, from planning to implementation (Figure 2) (Naumović, 2025).

Yellow colour on Figure 2 indicates processes that can be improved by implementing modern concepts of technical systems maintenance management that have been successfully applied around the world because the previous multi-decade efforts to organize and improve the area of TSSN maintenance management, using classic maintenance concepts, do not give satisfactory results, bearing in mind the increasing demands of the market, users and competition.

It is obvious that in such a situation, the attitude towards the management of TS maintenance processes must fundamentally change, primarily in terms of intensifying research and development of practical methods and techniques based on modern maintenance concepts, such as, for example, Lean maintenance, TPM (Total Productive Maintenance), RCM (Reliability Centered Maintenance), CMMS (Computer Maintenance Management System), etc. (Epler, 2013; Epler et al., 2017; Božanić et al., 2024.). However, this statement is easier said than done. There are many difficulties in TS maintenance management, and the most pronounced and influential are (Epler, 2016): low quality and reliability of input data contained, primarily in technological documentation; complexity of MS; long-term lack of investment in maintenance management due to the economic crisis and closure to the market where work technologies, knowledge and innovations are exchanged, and insufficient training of top management in TS maintenance to recognize and decide what is necessary and important to change in TS maintenance management to minimize maintenance process losses.

Current state of the work process and organization of TS maintenance would likely be changed qualitatively by eliminating the negative impacts of the above-mentioned factors through the application of modern concepts presented in the remainder of the paper. Qualitative changes would be reflected in (Epler, 2016; Božanić et al., 2024):

- shortening the TS maintenance cycle time (Tcmr),
- optimal use of available capacities,

– reducing costs per TS which being maintained.

Some modern concepts of technical systems maintenance management

Today, technical systems maintenance isn't just about fixing TS when they break; it's about preventing downtime before it happens.The Internet of Things (IoT) is transforming TS maintenance by integrating smart sensors, connectivity, and data analytics to optimize asset management. Through IoT-driven maintenance, companies can move from reactive and preventive strategies to a truly proactive approach-anticipating failures, optimizing resources and maximizing uptime (https://tractian.com/en/blog/iot-system-maintenance-management, 2026).

Internet of Things is a technology that connects devices to the internet, allowing them to collect, analyze, and share real-time data. This turns everyday equipment into active intelligent assets capable of monitoring operations and capturing operational insights. IoT enables TS to communicate with each other, reducing the need for manual intervention. It plays a key role in Industry 4.0, integrating multiple different tools to create connected, data-rich environments. In manufacturing, IoT is redefining how we manage and optimize operations, making systems more responsive, efficient, and intelligent. One of the greatest advantages IoT brings to maintenance management is its ability to provide continuous asset monitoring. Smart sensors collect and analyze operational data, enabling early failure detection and eliminating the need for frequent manual inspections (https://tractian.com/en/blog/iot-system-maintenance-management, 2026). We should consider incorporating such equipment into Technical systems for special - purpose (TSSP) in the military.

Historically, industries and TS maintenance relied on corrective maintenance, or fixing equipment only after it failed. This creates high costs and production downtime and TS operational readiness. Preventive maintenance improved reliability by scheduling inspections and spare parts replacements at fixed intervals. While it reduced unexpected failures, it also led to unnecessary maintenance actions. Next came condition-based maintenance (CBM), which introduced periodic measurements to assess TS conditions. Although more efficient, CBM still required manual inspections and did not eliminate unplanned failures. Now, IoT-driven predictive maintenance takes this approach to the next level, offering continuous monitoring to reduce unexpected failures and optimizing resources needed for TS maintenance.

Next picture clearly shows how IoT is enhancing reliability and efficiency across today's TS maintenance workflows.

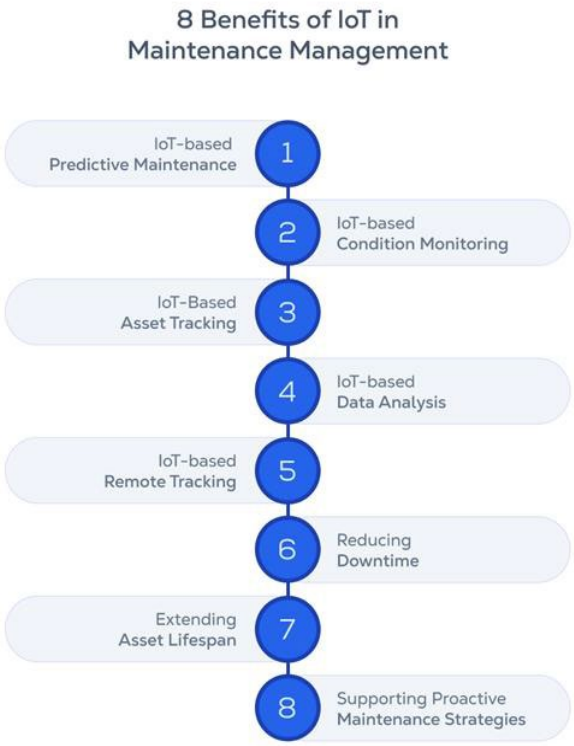

Figure 3 – Benefits of implementaing IoT in maintenance management (https://tractian.com/en/blog/iot-system-maintenance-management, 2026)

Integrating IoT with CMMS is revolutionizing how industrial and TSSP maintenance is planned and executed. As IoT collects data in real time, CMMS organizes that information, automating workflows and enabling smarter, data-driven decision-making. The CMMS reads IoT-generated insights and automatically creates work orders, notifying maintenance teams about potential failures so they can take action, ultimately reducing downtime and extending asset lifespan. Beyond automation, IoT/CMMS integration builds a comprehensive asset history, helping maintenance managers identify failure patterns, optimize scheduling, and minimize resource waste.

With advancements in Artificial Intelligence, Machine Learning, and 5G, IoT is becoming more precise, accessible, and interoperable than ever before. However, achieving this level of efficiency requires a complete solution that integrates hardware and software intelligently.

Tractian is the only end-to-end platform to prevent machine failures, protect production, and boost uptime. Tractian's industrial IoT solution combines high-precision sensors with advanced AI, delivering continuous monitoring that detects issues before they escalate. With an intuitive platform and actionable insights, your maintenance team gains an Industrial Copilot-a system designed to make predictive maintenance effortless. If your plant implemented IoT-driven predictive maintenance, now is the time (https://tractian.com/en/blog/iot-system-maintenance-management, 2026).

The manufacturing sector is evolving with the adoption of digital technologies, and one of the most impactful developments is the integration of the Internet of Things (IoT) with Computerized Maintenance Management Systems (CMMS). IoT involves connecting devices and equipment to collect real-time data, while CMMS manages maintenance activities and records. When combined, these technologies provide valuable insights, enabling manufacturers to monitor equipment health and streamline maintenance processes (https://terotam.com/blog/iot-cmms-integration-the-future-of-manufacturing, 2026).

This integration is transforming how factories operate. With real-time data from IoT sensors, CMMS can predict equipment failures before they happen, reducing unexpected downtime and improving overall efficiency. This shift towards predictive maintenance saves time and costs and also optimizes the use of resources, making manufacturing operations smarter and more effective. The Internet of Things (IoT) is transforming manufacturing by connecting machines and equipment through sensors and communication systems. These IoT devices collect real-time data on various factors like temperature, vibration, and energy use. This information helps manufacturers monitor their operations more accurately, detect issues early, and make informed decisions to improve productivity. Linking this data with other systems, like Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP), allows manufacturers to streamline operations and ensure better coordination across different processes. Beyond basic monitoring, IoT enables advanced manufacturing techniques like predictive maintenance and digital twins. Predictive maintenance uses data from IoT sensors to forecast when equipment might fail, allowing repairs to be made before problems disrupt production. Digital twins create virtual models of physical

machines, using real-time data to simulate and optimize performance. Integrating IoT with AI and machine learning can automate complex tasks, making factories more efficient and adaptable. This use of IoT is a key part of the Industry 4.0 movement, which aims to create smarter, more interconnected manufacturing systems (https://terotam.com/blog/iot-cmms-integration-the-future-of-manufacturing, 2026).

In addition to the above, and based on the study of the available literature and examples from the practice of other organizational systems, it can be said that the "lean" concept of maintenance management of TSSN (LM, Lean Maintenance) cannot represent an explicit concept of maintenance management, but rather a combination of developed and widely applied concepts of maintenance management in organizational systems (TPM, RCM, PdM, TQM, etc.), standard LM methods ("5S", "JIT", "Kaizen", "Kanban", Visual systems, "Layout"), software and other tools, such as tools for planning and managing projects, work orders and decision support (CMMS), whose joint action is channeled by unique principles, all with the aim of bringing order and reducing costs in TSSN maintenance, by detecting and eliminating all unnecessary activities in the TSSN maintenance process and striving to be better, more qualitative and more advanced than the competition every day. In order for the LM concept of TSSN maintenance management to have its full effect in MS, it is necessary to adapt the entire system to the philosophy of continuous process improvement and elimination of unnecessary costs or losses. The management of TSSP MS, based on the LM concept, is carried out by a small number of managers, controllers and maintenance technologists at the middle level, because most of the management comes from within, from authorized action teams, which consist of all employees trained for management tasks at a certain level. In this way, managers, controllers and technologists can spend more time in the maintenance plant, providing technical advice and guidance and recognizing, first-hand, the problems and needs of action teams (Epler, 2016).

Analyzing various repair and production processes, the author observed the characteristics of most domestic repair and production systems. He concluded that the current state of the work process and organization of repair and production systems would be qualitatively changed through shortening the repair cycle, optimizing the use of repair capacities and lowering costs per repair unit by removing the influence of negative factors. Applying the developed procedures in the design of the turbojet overhaul management model, with the support of Microsoft Project software tools, he performed an experimental verification of the model in terms of the application and impact of the three tools of the LM concept.

The results of the research gave the regularities of the overhaul cycle and the distribution of work as a function of the number of workers, priorities and spatial structure in the observed overhaul-production system, which can reliably assess the impact of the analyzed LM tools on the effectiveness and efficiency of the production process of each overhaul - production system (Marić, 2010).

The Boeing team was able to accelerate the return of the K-135 (Boeing Stratotanker is the primary aerial refueling aircraft for the United States Air Force (USAF)) from overhaul and thereby improve capability and customer readiness by implementing a series of LM initiatives at the Boeing Support Systems facility in San Antonio earlier in the year and planning their full implementation at the Pemco facility in Birmingham. At the beginning of 2005, it took an average of 214 days for Boeing and its partner to overhaul a KC-135. At the beginning of 2007, that time averaged 175 days, with a tendency to be shorter (https://boeing.mediaroom.com/2012-03-28-Boeing-Completes-Programmed-Depot-Maintenance-on-3rd-KC-135E-for-Chile, 2026).

In his work, Prekajski includes and explains the principles, basic methods and techniques of the LM concept. After that, he states that today the vast majority of car manufacturers, with the exception of Ferrari and a few luxury car manufacturers, apply LM methods and techniques and therefore achieve outstanding results in shortening the production cycle and saving costs in almost all company processes. The good results in the auto industry have caused interest in other types of industrial production with assembly processes, such as, for example, ship production. Shipyards that have implemented LM methods and techniques have accelerated the production process, reduced errors in welding and assembly activities, and reduced the number of spare parts necessary to produce expensive ocean freighters and for the maintenance of production machines (Prekajski, 2007).

From what has been stated so far about the modern concepts of technical systems for special purpose maintenance management, it can be concluded that the proactivity of all participants, prediction of future technical systems for special purpose unwanted states, automation of as many activities as possible, process optimization are common to all. In the practice of most production and overhaul systems in the world, the approach or management concept called Lean has proven itself well, and its CMMS tool has proven itself well and has become crucial for monitoring and optimizing the technical systems for special purpose maintenance process.

Table 1 – Results obtained by application LM tools "5S", "VS-Visual Systems", CMMS, "LO-Layout", "KAN-Kanban" (Epler et al., 2017)

Function of maintenance system	Applied LM tool	Tc (h) before application LM tool	Tc (h) after application LM tool	IMPROVEMENT
Preparation of repair	5S, "VS", CMMS	2,83	0,7	2,13 (75%)
Realization of repair	5S, "VS", "LO"	11,1	10,2	0,9 (8%)
Spares supply	CMMS, KANBAN	1,17	0,2	0,97 (8%)
Finalization and report	CMMS	0,5	0,02	0,48 (96%)

Epler et al. (2017) proposed a maintenance management model in which, firstly, the analysis of the impact of CMMS and other lean tools is conducted, which in a relatively short period of time, could lead to reducing the repair time, improving the effectiveness and efficiency of the TSSP maintenance system. The proposed model can be considered modern, because, compared to the conventional method applied in maintenance management, it does not consider the maintenance system as a priori disordered and a large part of activities as impossible to manage. The greatest achievement of the proposed model is its holistic approach to the maintenance management, which is reflected in the consistent application of selected CMMS and other lean tools and principles in all functions and activities within the maintenance cycle, in order to achieve a greater improvement compared to the previous state. For the verification of the proposed model, the empirical and experimental testing with results analysis was performed. Empirical verification of the TSSP maintenance model was made in the workshop for technical (tactical level) maintenance. The empirically obtained results are shown in Table 1. Table 1 also shows the trend of decreasing the duration of maintenance cycle for TSSP after CMMS and other lean tools (5S, CMMS, LO, VS and KANBAN). The maximum effect is obtained when all five lean tools are applied at the same time. The data shows that the greatest improvement was achieved after the implementation of a group of tools with CMMS.

After empirical tests of the proposed model for TSSP maintenance, the 22 multi-factor analysis of the impact of the described CMMS and other lean tools is performed. The analysis of influence factors is considered in relation to the duration of the maintenance cycle time T_c, using statistical software MINITAB. For this experiment, lean tools are grouped as follows:

Factor 1: LAYOUT with two levels: 1.0 – current state and 2.0 – future state, Factor 2: group of LEAN TOOLS with the following levels: 1.0 – 5S, 2.5 – 5S+VS, 4.0 – 5S+VS+CMMS, and 5.5 – 5S+VS+CMMS+KANBAN. At the beginning of the experimental verification, a starting matrix for regression analysis and analysis of variance of the influence of factors on T_c was formed. From statistically obtained results, it could be seen that factors (LAYOUT and CMMS and other LEAN TOOLS) have an impact on cycle time (T_c). The interaction of those factors does not have an impact on maintenance cycle – time. Statistical impact evaluation test shows that factors LAYOUT and CMMS and other LEAN TOOLS affect the change of T_c, that this influence is statistically significant, and their interaction does not change T_c. In addition to this, the data show that the mathematical model for TSSP has a high level of adequacy. The special significance of the developed model is the regression analysis, the outputs of which are equations that mathematically describe the changes in T_c depending on the applied lean tools (especially CMMS) and the possibility of their spatial graphics representation. The regression equations enable one to see the magnitude of the impact of specific factors on maintenance cycle time T_c, and show that it is possible to influence them.

In Božanić et al. (2024), the authors present a multi-criteria decision-making model based on the application of two methods, DIBIR II and MABAC. The DIBIR II method was used to define weight coefficients. The MABAC method was used to rank alternatives (six tools of the Lean management concept, “VS”, 5S, CMMS, KANBAN, KAIZEN and NAGARA SYSTEM) and it was applied in a rough environment. Four experts were engaged in defining the criteria (five criteria, C1-Reduction maintenance cycle time, C2-Optimisation level of equipment and working positions, C3-effectiveness TSSP increase percentage, C4-Maintenance system efficiency increase level, C5-Reduction in the number of executors of maintenance operations) and alternatives, as well as in the relation between criteria. The model was applied for ranking the methods and techniques of the Lean organisation systems management in the maintenance of TSSP. At the end of the application, a sensitivity analysis was conducted, which proved the stability of the obtained results. The final ranking alternatives shows that alternative CMMS takes the high second place among six alternatives in the improvement of the work process and organization management of TSSP technical maintenance.

Based on the results obtained in the research described in Epler et al. (2017) and the dissertation by Epler (2016), this paper continues with a proposal for improving the mentioned TSSP maintenance management processes by implementing a simple CMMS software solution designed

for technical maintenance management (Naumović, 2025), which does not require much investment to demonstrate the possibility of significant improvements in TSSP maintenance management.

Proposal for improving the technical systems maintenance using computers

"CMMS is a computer-based maintenance management system, or software solution used to plan, track, report and optimize maintenance processes in companies. Such a software solution helps in the efficient management of TS, spare parts required for maintenance, reducing downtime and extending the lifespan of TS" (https://www.worktrek.com/glossary/what-is-cmms, 2025).

The following paper describes part of the research in the diploma thesis (Naumović, 2025) as part of which the testing and filling of the database of the software solution for managing the maintenance of special purpose technical systems was carried out earlier (Epler, 2016; Epler et al., 2017), with the basic goal of contributing to improving TS maintenance on the basis of the Lean concept of managing organizational systems, i.e. improving the current state in most real systems for technical maintenance (STM), also taking into account international standards for the effective management of technical systems throughout their life cycle, such as: ISO 55000, ISO 14224, and EN 17007. One of the goals of the thesis (Naumović, 2025) is the creation of a prototype, an internal tool for academic application with a smaller number of users, with the possibility of improvement for application in a larger real system for the technical maintenance of technical systems of special purpose, such as, for example, weapons systems. The computer tool called "Održavanje PS" ("Technical system maintenance"), was created in the Microsoft Access 2010 program package.

Microsoft Access is a simple software tool for working with databases that is part of the widely distributed Microsoft Office suite. It is intended for smaller applications and individual users or smaller teams. It allows the quick creation of tables, forms, queries and reports without much programming. The main limitations of Access are lower performance with large databases, a limited number of concurrent users, and lower reliability in demanding production environments. There are also shortcomings in areas that are important for software used for military purposes and relate to the area of cyber-security, backup/redundancy mechanisms, integration with ERP/MES systems, work in a distributed environment, data transfer problems. That is why it is often used for smaller projects, prototypes or internal tools, while for large business systems more robust database

server systems are used. In contrast, the more complex maintenance management systems described in the previous chapter work with the help of MySQL, PostgreSQL or Microsoft SQL software systems, which are intended for working with large amounts of data and a large number of users at the same time. They offer better compatibility, security, performance and advanced functionalities (transactions, query optimization, working in distributed systems).

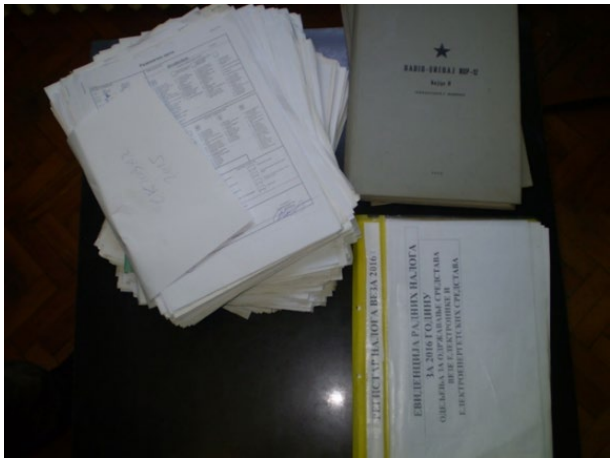

Figure 4 – Maintaining workshop documentation before implementing the "PS maintenance" software application (Naumović, 2025)

The developed software application represents a unique tool, which can be a significant segment of the TS maintenance management information system in which, for a start, activities can be automated from the acceptance of the TS into STM to the completion of maintenance and the preparation of the TM report, because after many years of observation and work in the STM (Epler, 2016) and the analysis of the workshop documentation presented by Naumović (2025), it was observed that, in the current state of the TS maintenance system, there are many activities that are unnecessarily repeated every time when the TS comes to STM, such as re-entering data about the same type of TS, activities that need to be done again, etc., and that they can be removed by automating the processes, which are partially illustrated in Figure 4.

This unique software tool also enables management of the supply of spare parts (sp) and consumables, with certain limitations, which significantly shortens the duration of the TS maintenance cycle time and introduces a certain order into the maintenance process, reducing the "paperwork" and the amount of manual work of the TM workshop manager

and work record keeper, i.e. increasing their efficiency and accuracy, as illustrated in Figure 5.

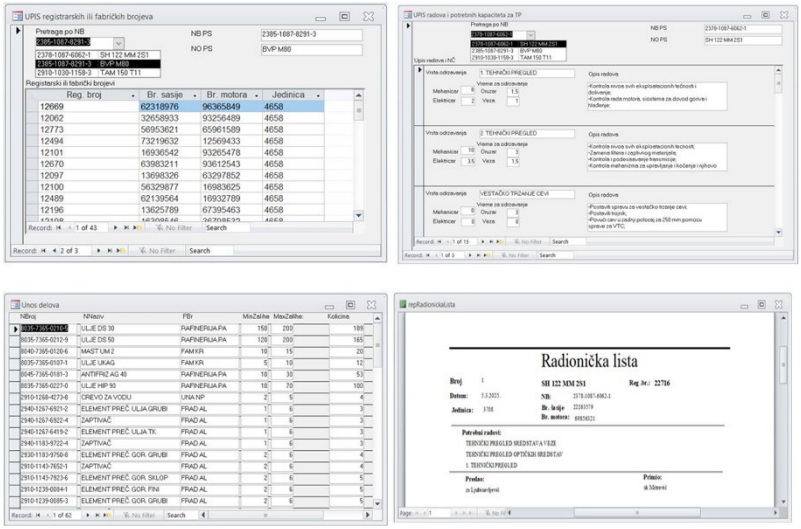

Figure 5 – Maintaining workshop documentation after implementing the "PS maintenance" software application (Naumović, 2025)

A description of the structure and operation of the software application is shown below.

Description of the structure of the "TS maintenanance" application

The "TS maintenance" application was created in the Microsoft Access 2010 software package, which is intended for managing relational databases. It consists of a database that stores all entered data necessary for the functioning of the program and a graphical environment, which forms the connection between the user and the database.

The database consists of the following interconnected tables (Figure 6):

1) tblTMS (tblTS) – contains data on the nomenclature number necessary for TS designation;
2) tblSredstvo (tblSpecificTS) – contains data about the specific vehicle (registration number, chassis number, engine number and identification number of the organization to which the vehicle belongs);
3) tblTP (tblTechnicalInspection) – contains data about the type of corrective and preventive maintenance operations with a

description of the work and the required times (RT) for maintenance by specialty;

4) tblDelovi (tblSpareParts) – contains data about sp and consumables stocks in the warehouse and minimum andmaximum quantities (necessary for creating requirements);
5) tblRadionickaLista (tblWorkshopList) – contains data about the Workshop sheet (serial number, opening date, finish date, achieved capacities by specialty and the name and surname of the person who received and handed over the TS);
6) tblPotrebniDelovi (tblRequiredSpareParts) – contains information about the sp required for the maintenance of a specific TS;
7) tblOdrzavanje (tblMaintenance) – contains information on the required type of maintenance for a specific TS.

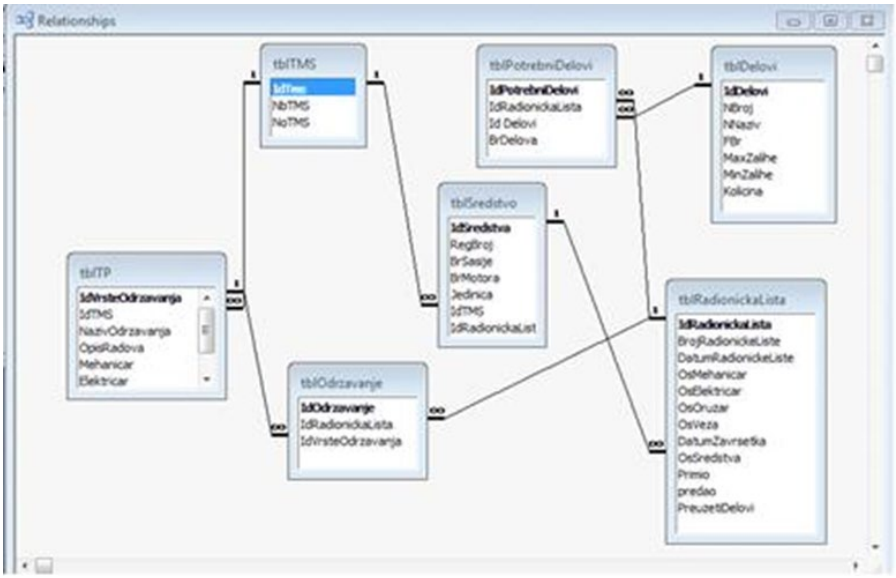

Figure 6 - Scheme of logical connections between tables within the database of the "TS Maintenance" program (Naumović, 2025)

Description of the operation of the "PS maintenance" application

When the software application is started, the initial window appears as shown in Figure 7.

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Figure 7 – Initial window of the program "TS maintenance" (Naumović, 2025)

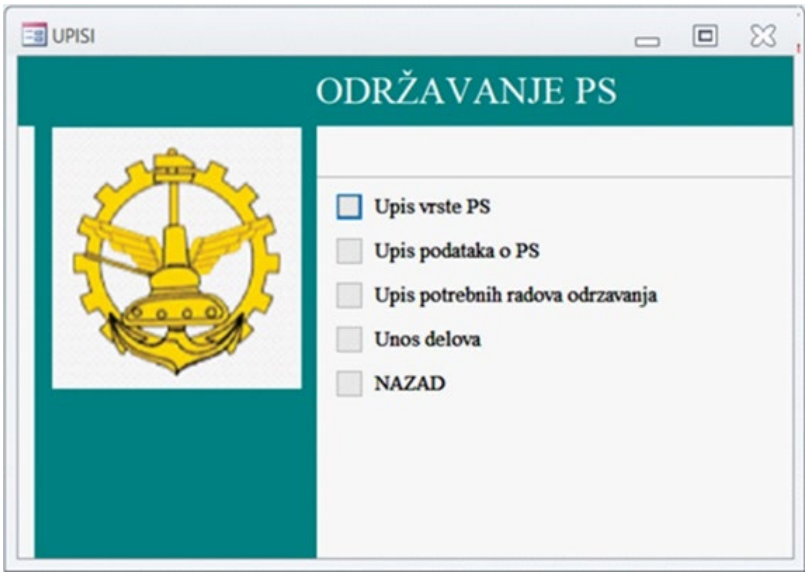

Figure 8 – Window "Entries" – for TS data entries (Naumović, 2025)

During the first access to the software application, it is necessary to fill the database with the necessary data in order to start the "RADIONIČKO POSLOVANJE" ("Workshop Business"), in order to automate it and make it more efficient. This is achieved by clicking on the "UPISI" ("Entries") button (Figure 8).

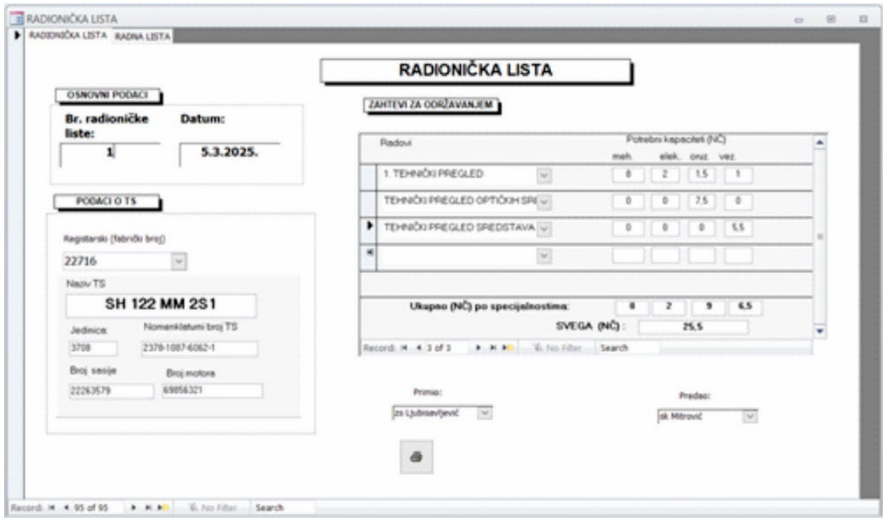

Figure 9 – An example of a filled Workshop sheet in the "TS maintenance" application

Figure 10 –An example of a filled Worksheet in the "PS maintenance" application

When all necessary entries for TS have been made, click on the "NAZAD" ("Back") button to access workshop operations, when clicking on the button "RADIONIČKO POSLOVANJE" ("Workshop operations"), the screen as shown in Figures 9 and 10 appears.

From the above displays, it is obvious that the "PS Maintenance" application enables automated management of spare parts inventory, but

also obtaining all necessary reports on TS maintenance activities, which makes the TS maintenance system manageable and flexible, i.e. efficient in resource management, which is very important for achieving good business results. Reports are accessed at the touch of the button "IZVEŠTAJI" ("Reports") (Figure 11).

Figure 11 – Window "ANALIZA RADIONIČKOG POSLOVANJA" ("Workshop business analysis") (Naumović, 2025)

Press the "Close Print Preview" button after each requested report and then the "Back" button.

Conclusion

Automation of individual processes in the organization and implementation of the work of TS maintenance organizations, using computers, i.e. software information systems, is an important step towards the modernization and improvement of TS. By introducing the software application "PS Maintenance", it is possible to significantly facilitate individual processes and reduce the time of the entire process of implementing the TS.

It is expected to save time in the maintenance cycle in the administrative part of TS maintenance by introducing the TS maintenance management software application in maintenance organizations, because

a number of activities are automated. First, the program automates the filling in of the Workshop and Work order, where common fields, such as the Workshop sheet number and date, are linked and filled in automatically. Also, when filling out the Workshop sheet, by simply clicking on the required registration (factory) number, other data in the “TS DATA” section are automatically filled in. Filling in data about the mechanic's NB is also automated by simply clicking to select the required work from the database. Finally, the program also offers printing of the Workshop and Work order, as well as the List of Issuance and Receipt of Spare Parts.

Since the program stores each completed Workshop and Work order in the database, it is potentially possible to replace extensive Workshop registers written by hand with the database of this program.

The program also automates the monitoring of the state of spare parts and other materials for maintenance stocks in warehouses, which would reduce the likelihood of errors and omissions by the operator when monitoring and updating their levels. The program also enables the management of spare parts and other materials supply, with certain restrictions, which also contributes to saving the TS maintenance cycle time that should be minimized.

The possibility of creating a Workshop Report in the program also contributes to the improvement of the Maintenance system. By simply selecting the TS name and its registration number, the program retrieves data on the achieved capacities and parameters in a certain period that can also be selected.

The obtained results show that it is possible to develop and implement the Lean concept and tools in each function of maintenance cycle, among which CMMS has a special place and importance due to influence of which is reflected in the reduction of the maintenance cycle time, which is around 23 %, depending on the applied function.

In order for the described software solution to be applied with the greatest possible effect in a real military system or some other system for technical maintenance, the determination of the management to start improving the management of the maintenance of technical systems for special purposes, a detailed description of as many maintenance procedures as possible, the adoption of a unique nomenclature of spare parts, the procurement of hardware and software of a compatible generation and the training of as many users as possible, familiarizing users with the advantages of the upgrade, entering all the necessary data before using the application and continuously updating the changes of the entered data are necessary. The implementation results of this paper, in real terms, contributed to changing the mindset of management and

employees in a real workshop for technical maintenance, in the direction of accepting the change in a positive way.

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Unapređenje održavanja tehničkih sistema primenom računarskog sistema za upravljanje održavanjem

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OBLAST: matematika, operaciona istraživanja, industrijsko inženjerstvo
KATEGORIJA (TIP) ČLANKA: pregledni rad

Sažetak:

Uvod/cilj: Predmet istraživanja je metodologija organizacije ili pojedinca odgovornog za održavanje tehničkog sistema (TS), odnosno radioničkih aktivnosti vezanih za tehničko održavanje tehničkog sistema (TOTS). U tom segmentu rada organizacije održavanja uočavaju se mogućnost i potreba za poboljšanjem stanja primenom računarskog sistema za upravljanje održavanjem (CMMS). Pretpostavka je da uvođenje CMMS-a, uz istovremenu primenu drugih savremenih alata upravljanja, može značajno skratiti vreme boravka tehničkog sistema u sistemu održavanja i povećati njegovu dostupnost.

Metode: Metode korišćene u istraživanju su: analiza sadržaja (analiza dokumentacije radionice i različitih literaturnih izvora), višefaktorska i regresiona analiza korišćenjem statističke softverske aplikacije MINITAB (eksperimentalno testiranje), razvoj prototipa softvera i provera poboljšanja u stvarnoj organizaciji održavanja TS (empirijsko testiranje).

Rezultati: Očekuje se ušteda vremena u ciklusu održavanja u administrativnom delu održavanja TS uvođenjem softverske aplikacije za upravljanje održavanjem TS u organizacijama za održavanje, jer je niz aktivnosti automatizovan. Ciljevi softvera su sledeći: program automatizuje popunjavanje Radioničkog lista i Radnog naloga, gde su uobičajena polja, kao što su Broj i datum radioničkog lista, povezana i automatski se popunjavaju. Takođe, prilikom popunjavanja Radioničkog lista, jednostavnim klikom na potreban registarski (fabrički) broj, automatski se popunjavaju i ostali podaci u odeljku "PODACI TS". Popunjavanje podataka o NB mehaničara je takođe automatizovano jednostavnim klikom kako biste izabrali potreban rad iz baze podataka. Konačno, program nudi i štampanje Radioničkog lista i Radnog naloga, kao i Listu izdavanja i prijema rezervnih delova.

Zaključak: Automatizacija pojedinačnih procesa u organizaciji i realizaciji rada organizacija za održavanje TS, korišćenjem računara, odnosno softverskih informacionih sistema, predstavlja važan korak ka modernizaciji

i unapređenju procesa održavanja TS. Uvođenjem aplikativnog programa "Održavanje TS", moguće je značajno olakšati pojedinačne aktivnosti i skratiti vreme celog procesa implementacije TS.

Ključne reči: tehnički sistem, tehnički sistemi za posebne namene, sistemi naoružanja, tehničko održavanje, remont, sistem upravljanja održavanjem računara, nivo održavanja, sistem održavanja, lean održavanje.

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Military Technical Courier / Vojnotehnički glasnik (www.vtg.mod.gov.rs/index-e.html, ISSN 0042-8469 – print issue, e-ISSN 2217-4753 – online, UDC 623+355/359, DOI: 10.5937/VojnotehnickiGlasnik; https://doi.org/10.5937/VojnotehnickiGlasnik), is a peer-reviewed scientific journal.

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Tekući naslov se ispisuje sa strane svake stranice članka radi lakše identifikacije, posebno kopija članaka u elektronskom obliku. Sadrži prezime i inicijal imena autora (ako autora ima više, preostali se označavaju sa „et al." ili „i dr."), naslove rada i časopisa i

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Navodi se pun (zvanični) naziv i sedište ustanove u kojoj je autor zaposlen, a eventualno i naziv ustanove u kojoj je autor obavio istraživanje. U složenim organizacijama navodi se ukupna hijerarhija (npr. Univerzitet odbrane u Beogradu, Vojna akademija, Katedra prirodno-matematičkih nauka). Bar jedna organizacija u hijerarhiji mora biti pravno lice. Ako autora ima više, a neki potiču iz iste ustanove, mora se, posebnim oznakama ili na drugi način, naznačiti iz koje od navedenih ustanova potiče svaki od navedenih autora. Afilijacija se ispisuje neposredno nakon imena autora. Funkcija i zvanje autora se ne navode.

Kontakt podaci

Adresa ili e-adresa svih autora daje se pored imena i prezimena autora.

Kategorija (tip) članka

Kategorizacija članaka obaveza je uredništva i od posebne je važnosti. Kategoriju članka mogu predlagati recenzenti i članovi uredništva, odnosno urednici rubrika, ali odgovornost za kategorizaciju snosi isključivo glavni urednik.

Vojnotehnički glasnik objavljuje naučne članke.

Naučni članak je:

– originalan naučni rad (rad u kojem se iznose prethodno neobjavljeni rezultati sopstvenih istraživanja naučnim metodom);

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– naučna kritika, odnosno polemika (rasprava na određenu naučnu temu, zasnovana isključivo na naučnoj argumentaciji) i osvrti.

Izuzetno, u nekim oblastima, naučni rad u časopisu može imati oblik monografske studije, kao i kritičkog izdanja naučne građe (istorijsko-arhivske, leksikografske, bibliografske, pregleda podataka i sl.), dotad nepoznate ili nedovoljno pristupačne za naučna istraživanja.

Radovi klasifikovani kao naučni moraju imati bar dve pozitivne recenzije.

Ako se u časopisu objavljuju i prilozi vannaučnog karaktera, naučni članci treba da budu grupisani i jasno izdvojeni u prvom delu sveske.

Poželjno je da obim kratkih saopštenja bude 4 do 7 stranica, naučnih članaka i studija slučaja 10 do 14 stranica, dok pregledni radovi mogu biti i duži. Broj stranica nije strogo ograničen i, uz odgovarajuće obrazloženje, prijavljeni članci takođe mogu biti duži ili kraći.

Ako su radovi koji su prethodno objavljeni na konferenciji prošireni, urednici će proveriti da li je dodato dovoljno novog materijala koji ispunjava standarde časopisa i kvalifikuje podnesak za postupak recenzije. Dodati materijal ne sme biti prethodno objavljen. Novi rezultati nisu nužno potrebni, ali su poželjni. Međutim, podnesak treba da sadrži proširene

ključne ideje, primere, razrade, itd., koji su prethodno bili sadržani u podnesku sa konferencije.

Jezik rada

Jezik rada treba da bude engleski.

Tekst mora biti jezički i stilski doteran, sistematizovan, bez skraćenica (osim standardnih). Sve fizičke veličine moraju biti izražene u Međunarodnom sistemu mernih jedinica – SI. Redosled obrazaca (formula) označava se rednim brojevima, sa desne strane u okruglim zagradama.

Sažetak

Sažetak jeste kratak informativan prikaz sadržaja članka koji čitaocu omogućava da brzo i tačno oceni njegovu relevantnost. U interesu je uredništava i autora da sažetak sadrži termine koji se često koriste za indeksiranje i pretragu članaka. Sastavni delovi sažetka su uvod/cilj istraživanja, metodi, rezultati i zaključak. Sažetak treba da ima od 100 do 250 reči i treba da se nalazi između zaglavlja (naslov, imena autora i dr.) i ključnih reči, nakon kojih sledi tekst članka.

Ključne reči

Ključne reči su termini ili fraze koje adekvatno predstavljaju sadržaj članka za potrebe indeksiranja i pretraživanja. Treba ih dodeljivati oslanjajući se na neki međunarodni izvor (popis, rečnik ili tezaurus) koji je najšire prihvaćen ili unutar date naučne oblasti. Za npr. nauku uopšte, to je lista ključnih reči Web of Science. Broj ključnih reči ne može biti veći od 10, a u interesu je uredništva i autora da učestalost njihove upotrebe bude što veća. U članku se pišu neposredno nakon sažetka.

Sistem ASISTENT u tu svrhu koristi specijalnu alatku KWASS: automatsko ekstrahovanje ključnih reči iz disciplinarnih tezaurusa/rečnika po izboru i rutine za njihov odabir, tj. prihvatanje odnosno odbacivanje od strane autora i/ili urednika.

Datum prihvatanja članka

Datum kada je uredništvo primilo članak, datum kada je uredništvo konačno prihvatilo članak za objavljivanje, kao i datumi kada su u međuvremenu dostavljene eventualne ispravke rukopisa navode se hronološkim redosledom, na stalnom mestu, po pravilu na kraju članka.

Zahvalnica

Naziv i broj projekta, odnosno naziv programa u okviru kojeg je članak nastao, kao i naziv institucije koja je finansirala projekat ili program, navodi se u posebnoj napomeni na stalnom mestu, po pravilu pri dnu prve strane članka.

Prethodne verzije rada

Ako je članak u prethodnoj verziji bio izložen na skupu u vidu usmenog saopštenja (pod istim ili sličnim naslovom), podatak o tome treba da bude naveden u posebnoj napomeni, po pravilu pri dnu prve strane članka. Rad koji je već objavljen u nekom časopisu ne može se objaviti u *Vojnotehničkom glasniku* (preštampati), ni pod sličnim naslovom i izmenjenom obliku.

Tabelarni i grafički prikazi

Poželjno je da naslovi svih prikaza, a po mogućstvu i tekstualni sadržaj, budu dati dvojezično, na jeziku rada i na engleskom jeziku.

Tabele se pišu na isti način kao i tekst, a označavaju se rednim brojevima sa gornje strane. Fotografije i crteži treba da budu jasni, pregledni i pogodni za reprodukciju. Crteže treba raditi u programu word ili corel. Fotografije i crteže treba postaviti na željeno mesto u tekstu.

Za slike i grafikone ne sme se koristiti snimak sa ekrana računara programa za prikupljanje podataka. U samom tekstu članka preporučuje se upotreba slika i grafikona neposredno iz programa za analizu podataka (kao što su Excel, Matlab, Origin, SigmaPlot i drugi).

Navođenje (citiranje) u tekstu

Način pozivanja na izvore u okviru članka mora biti jednoobrazan.

Vojnotehnički glasnik za referenciranje (citiranje i navođenje literature) primenjuje Harvardski sistem referenci, odnosno Harvardski priručnik za stil (Harvard Referencing System, Harvard Style Manual). U samom tekstu, u običnim zagradama, na mestu na kojem se vrši pozivanje, odnosno citiranje literature nabrojane na kraju članka, obavezno u običnoj zagradi napisati prezime citiranog autora, godinu izdanja publikacije iz koje citirate i, eventualno, broj stranica. Npr. (Petrović, 2012, pp.10–12).

Detaljno uputstvo o načinu citiranja, sa primerima, dato je na stranici sajta *Uputstvo za Harvardski priručnik za stil*. Potrebno je da se pozivanje na literaturu u tekstu uradi u skladu sa pomenutim uputstvom.

Sistem ASISTENT u svrhu kontrole navođenja (citiranja) u tekstu koristi specijalnu alatku CiteMatcher: otkrivanje izostavljenih citata u tekstu rada i u popisu referenci.

Napomene (fusnote)

Napomene se daju pri dnu strane na kojoj se nalazi tekst na koji se odnose. Mogu sadržati manje važne detalje, dopunska objašnjenja, naznake o korišćenim izvorima (na primer, naučnoj građi, priručnicima), ali ne mogu biti zamena za citiranu literaturu.

Lista referenci (literatura)

Citirana literatura obuhvata, po pravilu, bibliografske izvore (članke, monografije i sl.) i daje se isključivo u zasebnom odeljku članka, u vidu liste referenci. Reference se ne prevode na jezik rada i nabrajaju se u posebnom odeljku na kraju članka.

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Literatura se obavezno piše na latiničnom pismu i nabraja po abecednom redosledu, navodeći najpre prezimena autora, bez numeracije.

Detaljno uputstvo o načinu popisa referenci, sa primerima, dato je na stranici sajta *Uputstvo za Harvardski priručnik za stil.* Potrebno je da se popis literature na kraju članka uradi u skladu sa pomenutim uputstvom..

Nestandardno, nepotpuno ili nedosledno navođenje literature u sistemima vrednovanja časopisa smatra se dovoljnim razlogom za osporavanje naučnog statusa časopisa.

Sistem ASISTENT u svrhu kontrole pravilnog ispisa liste referenci koristi specijalnu alatku RefFormatter: kontrola oblikovanja referenci u skladu sa Harvardskim priručnikom za stil.

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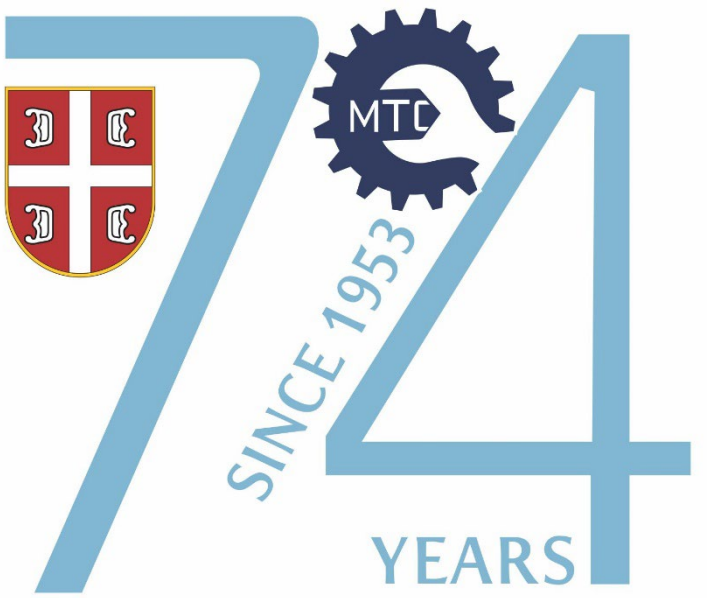
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