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A COMMON FIXED POINT RESULT IN STRICTLY CONVEX MENGER PM-SPACES

Nataša A. Ćirović *, *Siniša N. Ješić* and *Rale M. Nikolić*

In this paper, using the notions of normal structure and convex structure, we prove existence of a common fixed point for two self-mappings, where one of these mappings is also non-expansive, where one of these mappings is also non-expansive, defined on strictly convex Menger PM-spaces.

1. INTRODUCTION AND PRELIMINARIES

The notion of statistical metric spaces, as a generalization of metric spaces, with non-deterministic distance, was introduced by Menger [**8**] in 1942. Schweizer and Sklar in [**10**] and [**11**] studied in depth the properties of these spaces. The first result from the fixed point theory in probabilistic metric spaces was obtained by Sehgal and Bharucha–Reid [**12**] as a generalization of the classical Banach Contraction Principle.

The concept of normal structure was introduced in 1948 by Brodskii and Milman [**1**]. In 1970, Takahashi [**13**] has defined convex and normal structures for sets in metric spaces. General set-theoretic convexity in the study of the fixed point property of non-expansive mappings made its first explicit appearance in the work of Penot [**9**]. In 1987, Hadžić [**4**] has defined convex structure for sets in probabilistic metric spaces. Ješić [**6**] has observed a wide class of non-expansive mappings defined on intuitionistic fuzzy metric spaces with convex, strictly convex

*Corresponding author. Nataša Ćirović
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and normal structure and proved existence of a fixed point for that class of non-expansive mappings in strictly convex intuitionistic fuzzy metric spaces. Recently, Ješić et al. [**7**] introduced a notions of strictly convex and normal structure in Menger PM-space and proved the existence of a common fixed point for two self-mappings defined on strictly convex Menger PM-spaces.

We provide some fundamental concepts of probabilistic metric space theory. For a comprehensive exposition on the topic we refer the reader to [**5**] and [**11**].

We denote by D^+ the set of all distribution functions $F : \mathbb{R} \to [0,1]$, such that F is non-decreasing, left-continuous mapping, $F(0) = 0$ and $\sup_{x\in\mathbb{R}} F(x) = 1$. The space D^+ is partially ordered by the usual point-wise ordering of functions. The maximal element for D^+ in this order is the distribution function given by

$$\varepsilon_0(t) = \begin{cases} 0, & t \le 0, \\ 1, & t > 0. \end{cases}$$

Definition 1. [**11**] *A binary operation $T : [0,1] \times [0,1] \to [0,1]$ is continuous t-norm if T is associative, commutative, nondecreasing, continuous and satisfies $T(a,1) = a$ for all $a \in [0,1]$.*

Some basic examples of t-norm are $T(a,b) = \min\{a,b\}$, $T(a,b) = ab$, $T_L(a,b) = \max\{a+b-1, 0\}$.

The t-norms are defined recursively by $T^1 = T$ and

$$T^n(x_1, \ldots, x_{n+1}) = T(T^{n-1}(x_1, \ldots, x_n), x_{n+1})$$

for $n \ge 2$ and $x_i \in [0,1]$ for all $i \in \{1, \ldots, n+1\}$.

Definition 2. *A Menger probabilistic metric space (briefly, Menger PM-space) is a triple $(X, \mathcal{F}, T)$ where X is a nonempty set, T is a continuous t-norm, and $\mathcal{F}$ is a mapping from $X \times X$ into D^+ such that the following conditions hold:*

(PM1) $F_{x,y}(t) = \varepsilon_0(t)$ if and only if $x = y$,
(PM2) $F_{x,y}(t) = F_{y,x}(t)$,
(PM3) $F_{x,z}(t+s) \ge T(F_{x,y}(t), F_{y,z}(s))$ for all $x, y, z \in X$ and $s, t \ge 0$,

where $F_{x,y}$ denotes the value of $\mathcal{F}$ at the pair (x,y).

For a metric space (X,d) and a continuous t-norm $T(a,b) = \min\{a,b\}$, let us define $F_{x,y}(t) = \varepsilon_0(t - d(x,y))$ for all $x, y \in X$ and $t > 0$. Then the triple $(X, \mathcal{F}, T)$ is a PM-space induced by the metric d.

Schweizer and Sklar studied the properties of these spaces, including topology, convergence of sequences, continuity of mappings, defined the completeness of these spaces, see [**10**], [**11**].

Definition 3. *Let $(X, \mathcal{F}, T)$ be a Menger PM-space.*

(1) A sequence $\{x_n\}_n$ in X is said to be convergent to x in X if, for every $\varepsilon > 0$ and $\lambda > 0$ there exists positive integer N such that $F_{x_n,x}(\varepsilon) > 1 - \lambda$ whenever $n \ge N$.

(2) A sequence $\{x_n\}_n$ in X is said to be Cauchy sequence if, for every $\varepsilon > 0$ and $\lambda > 0$ there exists positive integer N such that $F_{x_n,x_m}(\varepsilon) > 1 - \lambda$ whenever $n, m \geq N$.

(3) A Menger PM-space is said to be complete if every Cauchy sequence in X is convergent to a point in X.

The (ε, λ)-topology in a Menger PM-space $(X, \mathcal{F}, T)$ is introduced by the family of neighbourhoods $\mathcal{N}_x$ of a point $x \in X$ given by

$$\mathcal{N}_x = \{N_x(\varepsilon, \lambda) : \ \varepsilon > 0, \lambda \in (0, 1)\},$$

where

$$N_x(\varepsilon, \lambda) = \{y \in X : \ F_{x,y}(\varepsilon) > 1 - \lambda\}.$$

The (ε, λ)-topology is a Hausdorff topology. In this topology the function f is continuous in $x_0 \in X$ if and only if for every sequence $x_n \to x_0$ it holds that $f(x_n) \to f(x_0)$, [**11**].

If the sequences $\{x_n\}, \{y_n\} \subset X$ converge to $x, y \in X$, respectively, then $\liminf_{n\to\infty} F_{x_n,y_n}(t) = F_{x,y}(t)$, [**11**].

Definition 4. *Let $(X, \mathcal{F}, T)$ be a Menger PM-space and $A \subseteq X$. The closure of the set A is the smallest closed set containing A, denoted by $\overline{A}$.*

Definition 5. *Let $(X, \mathcal{F}, T)$ be a Menger PM-space, $r \in (0, 1)$, $t > 0$ and $x \in X$. The set $N_x[\varepsilon, \lambda] = \{y \in X : \ F_{x,y}(\varepsilon) \geq 1 - \lambda\}$ is called closed (ε, λ)-neighbourhood of a point $x \in X$.*

Definition 6. *A subset K of a Menger PM-space is called compact if following statement holds*

$$K \subseteq \bigcup_{\alpha\in\Lambda} U_\alpha \quad \Longrightarrow \quad K \subseteq \bigcup_{i=1}^{n} U_{\alpha_i} \quad \text{for some} \quad \alpha_1, \ldots, \alpha_n \in \Lambda,$$

for every collection $\{U_\alpha : \alpha \in \Lambda\}$ of open sets $U_\alpha \subset X$.

Lemma 7. *Let $(X, \mathcal{F}, T)$ be a Menger PM-space and let $K \subseteq X$. Then, K is compact if and only if for every collection of closed sets $\{F_\alpha\}_{\alpha\in\Lambda}$ such that $F_\alpha \subseteq K$ it holds that*

$$\bigcap_{\alpha\in\Lambda} F_\alpha = \emptyset \quad \Longrightarrow \quad \bigcap_{i=1}^{n} F_{\alpha_i} = \emptyset \quad \text{for some} \quad \alpha_1, \ldots, \alpha_n \in \Lambda.$$

Proof. The proof follows from Definition 6 and De-Morgan's laws. □

Unlike in metric spaces, where a set is either bounded or unbounded, in Menger PM-space there are three distinct possibilities: boundedness, unboundedness and probabilistic boundedness. The concept of probabilistic boundedness was introduced by Egbert in [**2**]. Here we give a version of this definition.

Definition 8. *Let $(X, \mathcal{F}, T)$ be a Menger PM-space. A subset A of X is said to probabilistic bounded if there exist $t > 0$ and $\lambda \in (0,1)$ such that $F_{x,y}(t) > 1 - \lambda$ for all $x, y \in A$.*

Definition 9 (Egbert [**2**])**.** *Let $(X, \mathcal{F}, T)$ be a Menger PM-space and $A \subseteq X$. The probabilistic diameter of set A is given by*

$$\delta_A(t) = \sup_{\varepsilon < t} \Big(\inf_{x,y \in A} F_{x,y}(\varepsilon) \Big).$$

The diameter of the set A is defined by

$$\delta_A = \sup_{t>0} \delta_A(t).$$

Theorem 10 (Egbert [**2**])**.** *Let $(X, \mathcal{F}, T)$ be a Menger PM-space. If A and B are nonempty subsets of X and $A \subseteq B$, then $\delta_A \geq \delta_B$.*

Theorem 11 (Egbert [**2**])**.** *Let $(X, \mathcal{F}, T)$ be a Menger PM-space. If A is a nonempty subset of X, then $\delta_A = \delta_{\overline{A}}$, where $\overline{A}$ denotes the closure of set A.*

Theorem 12. *Every compact subset A of a Menger PM-space $(X, \mathcal{F}, T)$ is probabilistic bounded.*

Proof. Let A be a compact subset of a Menger PM-space X. Let $\varepsilon > 0$ and $\lambda \in (0,1)$ be fixed. We consider an open cover (ε, λ)-cover $\{N_x(\varepsilon, \lambda) : x \in A\}$. Since, A is compact, there exist $x_1, x_2, \dots x_n \in A$ such that $A \subseteq \bigcup_{i=1}^{n} N_{x_i}(\varepsilon, \lambda)$. Let $x, y \in A$ be arbitrary. Then there exist $i, j \in \{1, \dots, n\}$ such that $x \in N_{x_i}(\varepsilon, \lambda)$ and $y \in N_{x_j}(\varepsilon, \lambda)$. Thus we have that $F_{x,x_i}(\varepsilon) > 1 - \lambda$ and $F_{y,x_j}(\varepsilon) > 1 - \lambda$. Additionally, let $\alpha = \min\{F_{x_i,x_j}(\varepsilon) : 1 \leq i, j \leq n\}$. It is obvious that $\alpha > 0$ and we have

$$F_{x,y}(3\varepsilon) \geq T(F_{x,x_i}(\varepsilon), F_{x_i,x_j}(\varepsilon), F_{x_j,y}(\varepsilon)) \geq T(1-\lambda, 1-\lambda, \alpha) > 1 - \beta,$$

for some $0 < \delta < 1$. Taking $\varepsilon_1 = 3\varepsilon$, we have that $F_{x,y}(\varepsilon_1) > 1 - \beta$ for all $x, y \in A$. Hence, we obtain that A is probabilistic bounded set. □

In a Menger PM-space every compact set is closed and bounded.

2. CONVEX AND STRICTLY CONVEX STRUCTURE ON MENGER PM-SPACE

Takahashi in [**13**] introduced the notion of a convex structure in metric spaces.

Definition 13 (Takahashi [**13**])**.** *Let (X, d) be a metric space. We say that a metric space possesses a Takahashi's convex structure if there exists a function $W \colon X \times X \times [0,1] \to X$ which satisfies*

$$d\big(z, W(x, y, \theta)\big) \leq \theta d(z, x) + (1 - \theta) d(z, y),$$

for all $x, y, z \in X$ and arbitrary $\theta \in [0,1]$. A metric space (X, d) with Takahashi's convex structure is called convex metric space.

Hadžić [**4**] introduced a generalization of the Takahashi's definition in Menger PM-spaces.

Definition 14 (Hadžić [**4**]). *Let $(X, \mathcal{F}, T)$ be a Menger PM-space. A mapping $S\colon X \times X \times [0,1] \to X$, is said to be a convex structure on X if for every $(x, y) \in X \times X$ holds $S(x, y, 0) = y$, $S(x, y, 1) = x$ and for all $x, y, z \in X, \theta \in (0, 1)$ and every $t > 0$*

$$F_{S(x,y,\theta),z}(2t) \geq T\left(F_{x,z}\Big(\frac{t}{\theta}\Big), F_{y,z}\Big(\frac{t}{1-\theta}\Big)\right).$$

Every metric space (X, d) with a convex structure S can be consider as a Menger PM-space $(X, \mathcal{F}, T_{min})$ (the induced PM-space) with the same function S. For nontrivial example of a Menger PM-space with a convex structure see [**4**]. A Menger PM-space $(X, \mathcal{F}, T)$ with a convex structure is called a convex Menger PM-space.

Definition 15. *A point $x \in A$ will be called diametral if*

$$\inf_{y\in A} \sup_{\varepsilon < t} F_{x,y}(\varepsilon) = \delta_A(t)$$

holds for all $t > 0$.

Definition 16. *Let $(X, \mathcal{F}, T)$ be a Menger PM-space with a convex structure $S(x, y, \theta)$. A subset $A \subseteq X$ is said to be a convex set if for every $x, y \in A$ and $\theta \in [0, 1]$ it follows that $S(x, y, \theta) \in A$.*

Lemma 17 (Ješić et al. [**7**]). *Let $(X, \mathcal{F}, T)$ be a Menger PM-space and $\{K_\alpha\}$ for $\alpha \in \Delta$ be a family of convex subsets of X. Then the intersection $K = \cap_{\alpha\in\Delta} K_\alpha$ is a convex set.*

Ješić [**6**] defined the convex structure on intuitionistic fuzzy metric spaces and was the first to introduce the concept of strictly convex structure and normal structure in spaces with non-deterministic distances. Later Ješić et al. [**7**] introduced the notion of strictly convex and normal structure in Menger PM-spaces. These notions attracted the attention of other researchers, e.g. Gabeleh et al. use the notion of strictly convex fuzzy metric spaces in [**3**].

Definition 18 (Ješić et al. [**7**]). *A convex Menger PM-space $(X, \mathcal{F}, T)$ with a convex structure $S\colon X \times X \times [0, 1] \to X$ will be called strictly convex if, for arbitrary $x, y \in X$ and $\theta \in (0, 1)$ the element $z = S(x, y, \theta)$ is the unique element which satisfies*

$$F_{x,y}\left(\frac{t}{\theta}\right) = F_{z,y}(t), \quad F_{x,y}\Big(\frac{t}{1-\theta}\Big) = F_{z,y}(t),$$

for every $t > 0$.

Definition 19 (Ješić et al. [**7**]). *A Menger PM-space $(X, \mathcal{F}, T)$ possesses a normal structure if, for every closed, probabilistic semi-bounded and convex set $Y \subset X$,*

which consists of at least two different points, there exists a point $x \in Y$ which is non-diametral, i.e. there exists $t_0 > 0$ such that

$$\inf_{y \in Y} \sup_{\varepsilon < t_0} F_{x,y}(\varepsilon) > \delta_Y(t_0)$$

holds.

It is obvious that compact and convex sets in convex metric space possess a normal structure (see [**13**]).

Definition 20. *Let $(X, \mathcal{F}, T)$ be a convex Menger PM-space and $Y \subseteq X$. The closed convex shell of set Y, denoted by $conv(Y)$, is the intersection of all closed, convex sets that contain Y.*

Since the collection of closed, convex sets that contain Y is nonempty (X belongs to this collection), it is clear that the set $conv(Y)$ exists. From the Lemma 17 it follows that this intersection is convex set. Also, this intersection is closed as an intersection of closed sets.

Lemma 21 (Ješić et al. [**7**])**.** *Let $(X, \mathcal{F}, T)$ be a strictly convex Menger PM-space with a convex structure $S(x, y, \theta)$. Suppose that for every $\theta \in (0, 1)$, $t > 0$ and $x, y, z \in X$ holds*

$$F_{S(x,y,\theta),z}(t) > \min\left\{F_{z,x}(t), F_{z,y}(t)\right\}, \tag{1}$$

and let $K \subseteq X$ be nonempty, convex and compact subset of X. Then K possesses a normal structure.

Lemma 22 (Ješić et al. [**7**])**.** *Let $(X, \mathcal{F}, T)$ be a convex Menger PM-space with a convex structure $S(x, y, \theta)$ satisfying (1). Then closed (ε, λ)-neighbourhoods $N_x[\varepsilon, \lambda]$ are convex sets.*

Definition 23. *Let $(X, \mathcal{F}, T)$ be a Menger PM-space and let f be a self-mapping on X. We say that f is a non-expansive mapping if*

$$F_{fx,fy}(t) \geq F_{x,y}(t) \tag{2}$$

holds for all $x, y \in X$ and $t > 0$.

Lemma 24. [Zorn's lemma] *Let X be a nonempty partially ordered set in which every chain has a lower (upper) bound. Then X has a minimal (maximal) element.*

3. MAIN RESULTS

We will prove our main result, a common fixed point result for two self-mappings.

Theorem 25. *Let $(X, \mathcal{F}, T)$ be a strictly convex Menger PM-space with a convex structure $S(x, y, \theta)$ satisfying (1) and let $K \subseteq X$ be a nonempty, convex and compact subset of X. Let f and g be self-mappings on K, $g(K) \subseteq f(K)$, f is non-expansive mapping, such that*

$$F_{g(x),g(y)}(\varphi(t)) \geq F_{f(x),f(y)}(t), \tag{3}$$

for all $x, y \in K$, $x \neq y$, for every $t > 0$ and for some continuous function $\varphi : (0, +\infty) \to (0, +\infty)$ satisfying $\varphi(t) \leq t$, for all $t > 0$. Then f and g have at least one common fixed point on K.

Proof. Let Γ be a collection of all nonempty, closed, convex sets $K_\alpha \subseteq K$ such that $g(K_\alpha) \cap f(K_\alpha) \subseteq K_\alpha$. This collection is nonempty, because $K \in \Gamma$. Indeed, set K is closed set because it is compact set in Hausdorff's space and it holds that $g(K) \cap f(K) \subseteq K$.

If we order this collection with inclusion, then $(\Gamma, \subseteq)$ is a partially ordered set. Let $\{K_\alpha : \alpha \in \Lambda\}$ be an arbitrary chain of this collection. Then the set $\cap_{\alpha\in\Lambda} K_\alpha$ is nonempty, closed, convex subset of K, which is a lower bound of this chain. Indeed, let us assume that $\cap_{\alpha\in\Lambda} K_\alpha = \emptyset$. Then, from Lemma 7 it follows that there exists a finite sub-collection $K_{\alpha_1} \supseteq \ldots \supseteq K_{\alpha_n}$ of the chain $\{K_\alpha : \alpha \in \Lambda\}$ which has an empty intersection, which is impossible, since this intersection is $K_{\alpha_n} \neq \emptyset$. From Zorn's Lemma it follows that there exists a minimal element K_0 of the collection Γ such that $g(K_0) \cap f(K_0) \subseteq K_0$, not necessarily unique. We will prove that K_0 consists of only one point and since $g \cap f : K_0 \to K_0$, this will mean that mappings g and f have a common fixed point.

Let us assume that K_0 contains at least two different points. From Lemma 21 it follows that K possesses a normal structure. From Theorem 12 it follows that K_0 is probabilistic semi-bounded set. Since K_0 is closed and convex set, it follows that there exists some nondiametral point $x_0 \in K_0$, i.e. there exists $t_0 > 0$ such that the following inequality holds:

$$\inf_{y\in K_0} \sup_{\varepsilon < t_0} F_{x_0,y}(\varepsilon) \quad > \quad \delta_{K_0}(t_0). \tag{4}$$

Denote $1 - \xi := \inf\limits_{y\in K_0} \sup\limits_{\varepsilon < t_0} F_{x_0,y}(\varepsilon)$.

Let us denote with K_1 the closed convex shell of the set $g(K_0) \cap f(K_0)$. Since $g(K_0) \cap f(K_0) \subseteq K_0$, it follows that

$$K_1 = \overline{conv(g(K_0) \cap f(K_0))} \subseteq \overline{conv(K_0)} = \overline{K_0} = K_0.$$

Therefore, $K_1 \subseteq K_0$. Additionally, we have that

$$g(K_1) \cap f(K_1) \subseteq g(K_0) \cap f(K_0) \subseteq \overline{(conv(g(K_0) \cap f(K_0))} = K_1,$$

i.e. $g(K_1) \cap f(K_1) \subseteq K_1$. This concludes that $K_1 \in \Gamma$, and since K_0 is the minimal element, we have that $K_1 = K_0$.

Let us define the sets

$$C := \Big(\bigcap_{y \in K_0} N_y[\xi, t_0] \Big) \bigcap K_0,$$

and

$$C_1 := \Big(\bigcap_{y \in g(K_0) \cap f(K_0)} N_y[\xi, t_0] \Big) \bigcap K_0.$$

The set C is nonempty, since $x_0 \in C$. Indeed, from inequality (4) it follows that $F_{x_0,y}(t_0) \geq 1 - \xi$, i.e. $x_0 \in N_y[\xi, t_0]$ for all $y \in K_0$. Consequently, $x_0 \in C$. We will show that $C = C_1$. Since $g(K_0) \cap f(K_0) \subseteq K_0$ we have that $C_1 \supseteq C$.

Now, let $z \in C_1$. We will prove that $z \in C$. Since $z \in C_1$, for arbitrary $y \in g(K_0) \cap f(K_0)$ it holds that $F_{y,z}(t_0) \geq 1 - \xi$ i.e. $y \in N_z[\xi, t_0]$. Since y is arbitrary point from $g(K_0) \cap f(K_0)$, it follows that $g(K_0) \cap f(K_0) \subseteq N_z[\xi, t_0]$. Since $N_z[\xi, t_0]$ is closed convex set which contains $g(K_0) \cap f(K_0)$, we conclude that

$$K_1 = \overline{conv(g(K_0) \cap f(K_0))} \subseteq N_z[\xi, t_0].$$

Since $K_0 = K_1$, it follows that $K_0 \subseteq N_z[\xi, t_0]$. From the last we have that for every $y \in K_0$ it holds that $z \in N_y[\xi, t_0]$, concluding that $C_1 \subseteq C$, i.e. $C = C_1$.

We will show that $C \in \Gamma$. Set C is closed and convex set as an intersection of closed and convex sets. Also, the set C is nonempty, since $x_0 \in C$. Indeed, from (4) it follows that $F_{x_0,y}(t_0) \geq 1 - \xi$, i.e. $x_0 \in N_y[\xi, t_0]$, for all $y \in K_0$. Consequently, $x_0 \in C$.

Let us prove that $g(C) \cap f(C) \subseteq C$.

Let $z \in C$ and $y \in g(K_0) \cap f(K_0)$. Then there exists $x \in K_0$ such that $y = f(x)$ and $y = g(x)$. Since $F_{x,y}(\cdot)$ is nondecreasing, $\varphi(t) \leq t$ for all $t > 0$ holds, and applying the inequality (3) for $t = t_0$, we have

$$F_{g(z),y}(t_0) = F_{g(z),g(x)}(t_0) \geq F_{g(z),g(x)}(\varphi(t_0)) \geq F_{f(z),f(x)}(t_0) = F_{f(z),y}(t_0).$$

Since $z \in C$, it follows that $z \in N_y[\xi, t_0]$, i.e. $F_{z,x}(t_0) \geq 1 - \xi$. From this and the fact that f is non-expansive, it follow that

$$F_{f(z),y}(t_0) = F_{f(z),f(x)}(t_0) \geq F_{z,x}(t_0) \geq 1 - \xi.$$

This means that $g(z), f(z) \in C_1$. Since z is arbitrary point from $z \in C$ we obtain $g(C) \cap f(C) \subseteq C_1$ and because $C_1 = C$, we have that $g(C) \cap f(C) \subseteq C$.

Since $C \subseteq K_0$ and K_0 is the minimal element of collection Γ it follows that $C = K_0$. Now we have that $\delta_C(t_0) \geq 1 - \xi > \delta_{K_0}(t_0)$. This is a contradiction with $C = K_0$, i.e. the assumption that K_0 contains at least two different points is wrong. Consequently, it follows that K_0 contains only one point, which is a common fixed point of the mappings g and f. □

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Nataša A. Ćirović
Department of Applied Mathematics,
University of Belgrade - School of Electrical Engineering,
Belgrade, Serbia
E-mail: *natasa@etf.bg.ac.rs*
https://orcid.org/0000-0002-0202-807X

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Siniša Ješić
Department of Applied Mathematics,
University of Belgrade - School of Electrical Engineering,
Belgrade, Serbia
E-mail: *jesic@etf.bg.ac.rs*
https://orcid.org/0000-0002-2827-0657

Rale M. Nikolić
Department of Natural Sciences and Mathematics,
Military Academy, University of Defence,
Veljka Lukića Kurjaka 33, 11042 Belgrade, Serbia
E-mail: *rale.nikolic@va.mod.gov.rs*
https://orcid.org/0000-0002-8703-3029