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Original Article

New Structures in Fuzzy Binary Soft Topological Spaces

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Abstract - *Separation axioms are fundamental, widely used and highly influential concepts in classical topology. They play a crucial role in addressing problems in digital topology and establishing more restricted families of topological spaces. These concepts were extended to soft, fuzzy, and binary soft (BS) topology. Fuzzy binary soft topological spaces (FBS topological spaces) emerge as a more powerful tool than fuzzy soft topological spaces. However, the separation axioms must be explored in the FBS topological spaces. This paper introduces and investigates the separation axioms within the framework of FBS-topological spaces. Fuzzy binary soft points and their corresponding neighbourhoods were defined in this article, laying the foundation for the development of fuzzy binary soft.* T_0, T_1 *and* T_2 *spaces. Furthermore, characterizations of regularity, normality, and FBS-connectedness are provided.*

Keywords - *Fuzzy soft set, Binary soft set, Fuzzy soft set, Fuzzy binary soft topology, Fuzzy binary soft point, Separation axioms.*

AMS Subject Classifications*: 54A05, 06D72.*

1. Introduction

Molodtsov [1] introduced a novel mathematical approach known as soft set theory to address uncertainties and vagueness. Traditional methods like fuzzy sets [2] and rough sets [3] could not precisely define objects. Soft set theory differs from these conventional tools for handling uncertainty. It defines a soft set as a collection of approximate descriptions of an object based on parameters using a set-valued map. Maji et al. [4] initiated the study of hybrid structures combining fuzzy sets and soft sets, known as fuzzy soft sets, a concept that many researchers have since explored. Various extensions of classical fuzzy soft sets, such as generalized fuzzy soft sets, have been proposed. Kharal et al. [5] defined the notion of a mapping on classes of fuzzy soft sets, which is of fundamental importance in fuzzy soft set theory. Tanya et al. [6] and Gunduz [7] began studying the topological aspects of fuzzy soft sets. Further, [8] T. H. Dizman defined the fuzzy soft topology over a fuzzy soft set with a fixed parameter set and investigated the topological concepts as neighbourhood systems, fuzzy soft interior and fuzzy soft closure point, for fuzzy soft sets, etc.

Furthermore, Atmaca and Zorlutuna [9] investigated the notions of fuzzy soft closure of a soft set, fuzzy soft base and fuzzy soft continuity in the fuzzy soft topological spaces. Mahanta and Das [10] introduced and analyzed fuzzy soft T_0, T_1 and T_2 spaces, extending classical separation axioms into the fuzzy soft context. They characterized fuzzy soft T_1 and T_2 spaces using fuzzy soft points and neighbourhoods. Alaa M. Abd El-Latif [11] studied the fuzzy soft pre-open and pre-closed sets, leading to the definition of fuzzy soft pre-interior and pre-closure operators. These concepts facilitated the development of fuzzy soft pre-separation axioms, such as pre-T_0 and pre-T_1 spaces. A. Acikgoz et al. [12] defined and studied the properties of binary soft sets, which deal with two universal sets and a parameter set. Benchalli et al. [13] introduced the binary soft topological space and studied its basic properties. Further, Patil et al. [14] introduced separation axioms on binary soft topology. Also, Sabir Hussain [15] studies connectedness on binary soft topology. Matilda et al. [16], [17] defined fuzzy binary soft sets (FBSs) as involving two universal sets and a parameter set, assigning membership values to the universal sets. They also defined fuzzy binary soft topological spaces. Patil et al. [18] studied applications of fuzzy binary soft sets. Since the FBS topological spaces are emerging, there is a need to explore the separation axioms, which is essential in studying the connected properties of the topological spaces. This article gives the foundation for the separation axioms in the FBS topological spaces. This paper aims to study the fuzzy binary soft separation axioms (FBS-separation axioms). This paper begins with preliminaries and introduces the concept of a fuzzy binary soft point as a generalization of the fuzzy point to create different neighbourhood structures in fuzzy binary soft topological space. Section 3 discusses the notion of separation axioms denoted as FBS-Ti for i = 0,1,2,3,4 spaces and their basic properties. Section 4 introduced the connectedness in FBS-topological spaces.

2. Preliminaries

2.1. Definition 1 [2]

Let A be a universe. Then, fuzzy set X over A is a function defined as $X = \{(\mu_X(x)/x) : x \in A\}$, where, $\mu_X : A \to [0,1]$. Here, μ_X called membership function of X, and the value $\mu_X(x)$ is called the grade of membership $x \in A$. The value represents the degree of x belonging to the fuzzy set X.

2.2. Definition 2 [19]

Let U be a Universal set, E be a set of parameters, and $A \subset E$, F be a function defined by $F: A \to P(U)$, where $P(U)$ denotes the power set of U. Then (F, A) is called soft set over U.

2.3. Definition 3 [4]

Let X be an initial universal set, E be a set of parameters and $A \subset E$, F be a mapping, $F: A \to P(X)$, where $P(X)$ is a set of all fuzzy subset of X. Then (F, A) is called fuzzy soft set over X.

2.4. Definition 4 [9]

A fuzzy, soft point e_{x_t} Over X is a fuzzy soft set defined as follows: $e_{x_t}(k) = x_t$, if k = e and $e_{x_t}(k) = 0$, if $k \in E - e$, where x is a fuzzy point. A fuzzy, soft point e_{x_t} is said to belong to a fuzzy soft set f_A, denoted by $e_{x_t} \in f_A$. Two fuzzy soft points e_{x_t} and e_{y_t} are said to be distinct, denoted by e_{x_t}, if $x \neq y$ or $e \neq k$. The family of all fuzzy soft points in X is denoted by $P_t(X)$.

2.5. Definition 5 [12]

Let U_1 and U_2 be two universal sets. E be a set of parameters, $A \subseteq E$. Let $P(U_1), P(U_2)$ denote the power sets of U_1, U_2. A binary soft set (F, A) over U_1, U_2 is defined as a function $F: A \to P(U_1) \times P(U_2)$.

2.6. Definition 6 [16]

Let U_1 and U_2 be two universal sets. E be a set of parameters, $A \subseteq E$. Let $P(U_1), P(U_2)$ are a set of all fuzzy sets of U_1, U_2 respectively. A fuzzy binary soft set (F, A) over U_1, U_2 is defined as a function $F: A \to P(U_1) \times P(U_2)$.

2.7. Example 1 [18]

Let us consider the universal sets $U_1 = \{u_1, u_2, u_3\}$ *be the colleges,* $U_2 = \{v_1, v_2, v_3\}$ *be the courses and* $E = \{e_1, e_2, e_3, e_4, e_5\}$ *set of parameters. Let* $A = \{e_1, e_2, e_3\}$ *and* $F: A \to P(U_1) \times P(U_2)$, *defined by* $F(e_1) = \{u_1/0.5, u_2/0.4, u_3/0.7\}, \{v_1/0.2, v_2/0.6, v_3/0.9\}$

$$F(e_2) = \{u_1/0.7, u_2/0.3, u_3/0.8\}, \{v_1/0.5, v_2/0.3, v_3/0.7\}$$

$$F(e_3) = \{u_1/0.2, u_2/0.6, u_3/0.5\}, \{v_1/0.3, v_2/0.1, v_3/0.9\}$$

Where,

$(F, A) = \{(e_1, \{u_1/0.5, u_2/0.4, u_3/0.7\}, \{v_1/0.2, v_2/0.6, v_3/0.9\}),\ (e_2, \{u_1/0.7, u_2/0.3, u_3/0.8\}, \{v_1/0.5, v_2/0.3, v_3/0.7\}), e_3, \{u_1/0.2, u_2/0.6, u_3/0.5\}, \{v_1/0.3, v_2/0.1, v_3/0.9\})\}$. Then (F, A) is a fuzzy binary soft set.

2.8. Definition 7 [17]

A fuzzy binary soft set (F, A) over U_1, U_2 is said to be a fuzzy binary null soft set denoted by $\tilde{\phi}$ if for all $e \in A$, $F(e)$ is the null fuzzy set over U_1, U_2.

2.9. Definition 8 [17]

A fuzzy binary soft set (F, A) over U_1, U_2 is said to be a fuzzy absolute soft set denoted by $\tilde{A}$ if for all $e \in A$, $F(e)$ is the absolute fuzzy set over U_1, U_2.

2.10. Definition 9 [17]

Let τ be the collection of fuzzy binary soft sets over. U_1, U_2, then $\tilde{\tau}$ is said to be a fuzzy binary soft topology on U_1, U_2 if

1. $\widetilde{\phi}$, $\tilde{A} \in \tau$
2. The union of any member of fuzzy binary soft sets in $\tilde{\tau}$ belongs to $\tilde{\tau}$.

3. The intersection of any two fuzzy binary soft sets in $\tilde{\tau}$ belongs to $\tilde{\tau}$. Then (U_1, U_2, τ, E) is called a fuzzy binary soft topological space over U_1, U_2.

3. Separation Axioms in Fuzzy Binary Soft Topological Spaces

3.1. Definition 10

A FBS point $e_{(x_{t_1}, y_{t_2})}$ over U_1, U_2 is an FBS set defined as $e_{(x_{t_1}, y_{t_2})}(l) = (x_{t_1}, y_{t_2})$ if l=e and $e_{(x_{t_1}, y_{t_2})}(l) = (0,0)$ if $l \in E - e$, where x_{t_1}, y_{t_2} It is fuzzy points. Two fuzzy binary soft points $e_{(x_{t_1}, y_{t_2})}, k_{(m_{\alpha_1}, n_{\alpha_2})}$ are said to be distinct, denoted by $e_{(x_{t_1}, y_{t_2})} \neq k_{(m_{\alpha_1}, n_{\alpha_2})}$ If $x \neq m, y \neq n$ or $e \neq k$.

3.2. Definition 11

A FBS set (F, B) in a FBS topological space (U_1, U_2, τ, E) is called the fuzzy binary soft neighborhood (FBS nhbd) of the FBS point $e_{(x_{t_1}, y_{t_2})}$ If there exists a fuzzy binary soft open set (H, C) such that $e_{(x_{t_1}, y_{t_2})} \in (H, C) \subseteq (F, B)$. A fuzzy binary soft set (F, B) in a FBS topological space (U_1, U_2, τ, E) is called *FBS nhbd* of the fuzzy binary soft set (G, A) if there exists a fuzzy binary soft open set (H, C) such that $(G, A) \subseteq (H, C) \subseteq (F, B)$.

The FBS nhbd system of the fuzzy binary soft point $e_{(x_{t_1}, y_{t_2})}$, denoted by $N_\tau(e_{(x_{t_1}, y_{t_2})})$ is the family of all *FBS nhbd*.

3.3. Theorem 1

Let (U_1, U_2, τ, E) be a fuzzy binary soft topological space and (F, B) a fuzzy binary soft set. Then, (F, B) is an open set if it is FBS nhbd of each of its fuzzy binary soft points.

3.4. Definition 12

Let (U_1, U_2, τ, E) be an FBS topological space and for every $e_{(x_{t_1}, y_{t_2})}, k_{(m_{t_1}, n_{t_2})}$ be FBS points over U_1, U_2 such that $e_{(x_{t_1}, y_{t_2})} \neq k_{(m_{t_1}, n_{t_2})}$, if there exists at least one FBS open set (G_1, C_1) or (G_2, C_2) such that $e_{(x_{t_1}, y_{t_2})} \in (G_1, C_1)$, $k_{(m_{t_1}, n_{t_2})} \notin (G_1, C_1)$ or $k_{(m_{t_1}, n_{t_2})} \in (G_2, C_2)$,$e_{(x_{t_1}, y_{t_2})} \notin (G_2, C_2)$. Then (U_1, U_2, τ, E) is called a FBS-T_0 space.

3.5. Definition 13

Let (U_1, U_2, τ, E) be a fuzzy binary soft topological space and for every $e_{(x_{t_1}, y_{t_2})}, k_{(m_{t_1}, n_{t_2})}$ Be fuzzy binary soft points over. U_1, U_2 such that $e_{(x_{t_1}, y_{t_2})} \neq k_{(m_{t_1}, n_{t_2})}$, if there exists at least one fuzzy binary soft open set (G_1, C_1) or (G_2, C_2) such that $e_{(x_{t_1}, y_{t_2})} \in (G_1, C_1)$, $k_{(m_{t_1}, n_{t_2})} \in (G_1, C_1)'$ or $e_{(x_{t_1}, y_{t_2})} \in (G_2, C_2)$,$k_{(m_{t_1}, n_{t_2})} \in (G_2, C_2)'$, Then (U_1, U_2, τ, E) is called an FBS-T_0^* Space.

3.6. Theorem 2

Every FBS-T_0^* Space is FBS-T_0 space.

3.6.1. Proof

Let (U_1, U_2, τ, E) be a FBS-T_0^* space and $e_{(x_{t_1}, y_{t_2})}, k_{(m_{t_1}, n_{t_2})}$ FBS points. Since (U_1, U_2, τ, E) be a FBS -T_0^*, there exists at least one fuzzy binary soft open set (G_1, C_1) or (G_2, C_2) such that $e_{(x_{t_1}, y_{t_2})} \in (G_1, C_1)$, $k_{(m_{t_1}, n_{t_2})} \in (G_1, C_1)'$ or $e_{(x_{t_1}, y_{t_2})} \in (G_2, C_2)$, $k_{(m_{t_1}, n_{t_2})} \in (G_2, C_2)'$. This implies $e_{(x_{t_1}, y_{t_2})} \in (G_1, C_1)$, $k_{(m_{t_1}, n_{t_2})} \notin (G_1, C_1)$ or $k_{(m_{t_1}, n_{t_2})} \in (G_2, C_2)$,$e_{(x_{t_1}, y_{t_2})} \notin (G_2, C_2)$.

Therefore, (U_1, U_2, τ, E) be a fuzzy binary soft T_0-space.

3.7. Theorem 3

A FBS subspace of a FBS-T_0 space is FBS-T_0.

3.8. Definition 14

A FBS-topological space (U_1, U_2, τ, E) is said to be a FBS-T_1 space for any pair of distinct points $e_{(x_{t_1}, y_{t_2})}, k_{(m_{t_1}, n_{t_2})}$, such that $e_{(x_{t_1}, y_{t_2})} \neq e_{(m_{t_1}, n_{t_2})}$, if there exist FBS-open sets (G_1, C_1) and (G_2, C_2) such that $e_{(x_{t_1}, y_{t_2})} \in (G_1, C_1)$, $k_{(m_{t_1}, n_{t_2})} \notin (G_1, C_1)$ and $k_{(m_{t_1}, n_{t_2})} \in (G_2, C_2)$,$e_{(x_{t_1}, y_{t_2})} \notin (G_2, C_2)$.

3.9. Definition 15

A FBS - topological space (U_1, U_2, τ, E) is said to be a FBS- T_1^* space for any pair of distinct points $e_{(x_{t_1}, y_{t_2})}, k_{(m_{t_1}, n_{t_2})}$, if there exist FBS-open sets (G_1, C_1) and (G_2, C_2) such that $e_{(x_{t_1}, y_{t_2})} \in (G_1, C_1)$, $e_{(m_{t_1}, n_{t_2})} \in (G_1, C_1)'$ and $k_{(m_{t_1}, n_{t_2})} \in (G_2, C_2)$, $e_{(x_{t_1}, y_{t_2})} \in (G_2, C_2)'$.

3.10. Theorem 4

Every FBS-$T_1{}^*$ Space is FBS-T_1 space.

3.10.1. Proof

Let (U_1, U_2, τ, E) be a FBS-T_1^* space, and $e_{(x_{t_1}, y_{t_2})}, k_{(m_{t_1}, n_{t_2})}$ FBS points. Since (U_1, U_2, τ, E) be a fuzzy binary soft T_1^*, there exists FBS-open sets (G_1, C_1) and (G_2, C_2) such that $e_{(x_{t_1}, y_{t_2})} \in (G_1, C_1)$, $k_{(m_{t_1}, n_{t_2})} \in (G_1, C_1)'$ and $e_{(x_{t_1}, y_{t_2})} \in (G_2, C_2)$, $k_{(m_{t_1}, n_{t_2})} \in (G_2, C_2)'$. This implies $e_{(x_{t_1}, y_{t_2})} \in (G_1, C_1)$, $k_{(m_{t_1}, n_{t_2})} \notin (G_1, C_1)$ and $k_{(m_{t_1}, n_{t_2})} \in (G_2, C_2)$,$e_{(x_{t_1}, y_{t_2})} \notin (G_2, C_2)$. Therefore, (U_1, U_2, τ, E) be a FBS-T_1-space.

3.11. Theorem 5

If every FBS point $e_{(x_{t_1}, y_{t_2})}$ of a FBS topological space (U_1, U_2, τ, E) is an FBS-closed, then (U_1, U_2, τ, E) is a FBS-T_1 space.

3.12. Theorem 6

A FBS- subspace of a FBS-T_1 space is FBS-T_1.

3.13. Definition 16

A FBS topological space (U_1, U_2, τ, E) is said to be FBS-T_2 space if for any pair of distinct points $e_{(x_{t_1}, y_{t_2})}, k_{(m_{t_1}, n_{t_2})}$, there exist disjoint FBS-open sets (F_1, E_1) and (F_2, E_2) such that $e_{(x_{t_1}, y_{t_2})} \in (F_1, E_1)$ and $k_{(m_{t_1}, n_{t_2})} \in (F_2, E_2)$.

3.14. Theorem 7

Let FBS topological space (U_1, U_2, τ, E) is FBS-T_2 if and only if for distinct FBS points $e_{(x_{t_1}, y_{t_2})}$ and $k_{(m_{t_1}, n_{t_2})}$, there exists an FBS-open set (G, A) containing $e_{(x_{t_1}, y_{t_2})}$ but not $k_{(m_{t_1}, n_{t_2})}$ such that $e_{(x_{t_1}, y_{t_2})} \notin \overline{(G, A)}$.

3.15. Definition 17

A FBS topological space (U_1, U_2, τ, E) is said to be FBS-regular space if for every FBS- point $e_{(x_{t_1}, y_{t_2})}$ and for every FBS-closed set (F, E) with $e_{(x_{t_1}, y_{t_2})} \notin (F, E)$, there exist open sets (A_1, E_1) and (A_2, E_2) such that $e_{(x_{t_1}, y_{t_2})} \in (A_1, E_1)$ and $(F, E) \subseteq (A_2, E_2)$.

A FBS topological space (U_1, U_2, τ, E) is said to be T_3 space if it is an FBS-regular and FBS-T_1 space.

3.16. Theorem 8

FBS-regularity is a hereditary property.

3.17. Theorem 9

Let FBS topological space (U_1, U_2, τ, E). (U_1, U_2, τ, E) is a FBS-T_3 space if and only if for every FBS point $e_{(x_{t_1}, y_{t_2})} \in (A_1, E_1)$, there exists (A_2, E_2) such that $e_{(x_{t_1}, y_{t_2})} \in (A_2, E_2) \subseteq \overline{(A_2, E_2)} \subseteq (A_1, E_1)$.

3.17.1. Proof

Let (U_1, U_2, τ, E) be an FBS-T_3 space and $e_{(x_{t_1}, y_{t_2})} \in (A_1, E_1)$. Since$(U_1, U_2, \tau, E)$ is an FBS-T_3 space for the FBS- point $e_{(x_{t_1}, y_{t_2})}$ And FBS closed set $(A_1, E_1)^c$, there exist distinct FBS-open sets (A_2, E_2), (A_3, A_3) such that $e_{(x_{t_1}, y_{t_2})} \in (A_2, E_2)$, $(A_1, E_1)^c \subseteq (A_3, E_3)$, Thus, $e_{(x_{t_1}, y_{t_2})} \in (A_2, E_2) \subseteq (A_3, E_3)^c \subseteq (A_1, E_1)$. Since $(A_3, E_3)^c$ is an FBS-closed set, so $\overline{(A_2, E_2)} \subseteq (A_1, E_1)^c$.

3.18. Definition 18

A FBS topological space (U_1, U_2, τ, E) is said to be FBS-normal space if for every pair of distinct FBS closed sets (F_1, E_1)

and (F_2, E_2), there exist open sets (A_1, B_1) and (A_2, B_2) such that $(A_1, B_1) \subseteq (F_1, E_1)$ and $(A_2, B_2) \subseteq (F_2, E_2)$. A FBS topological space (U_1, U_2, τ, E) is said to be T_4 space if it is an FBS-normal and FBS-T_1-space.

3.19. Theorem 10

Let FBS topological space (U_1, U_2, τ, E), (U_1, U_2, τ, E) is a FBS-T_4 space if and only if for each FBS-closed set (F, E) and FBS-open set (A_1, E_1) with $(F, E) \subseteq (A_1, E_1)$, there exists an FBS-open set (A_2, E_2) such that $(F, A) \subseteq (A_2, E_2) \subseteq \overline{(A_2, E_2)} \subseteq (A_1, E_1)$.

4. Fuzzy Binary Soft Connectedness

4.1. Definition 19

Let (U_1, U_2, τ, E) FBS topological space over U_1, U_2. Then (U_1, U_2, τ, E) is said to be FBS-connected if there does not exist a pair (F, E) and (G, E) of nonempty disjoint FBS-open subsets of (U_1, U_2, τ, E) such that $(F, E) \cup (G, E) = \widetilde{E}$. Otherwise (U_1, U_2, τ, E) is said to be FBS- disconnected.

4.2. Theorem 11

Let (U_1, U_2, τ, E) FBS topological space is fuzzy binary soft connected if and only if there exists a nonempty fuzzy binary soft subset (F, E) of (U_1, U_2, τ, E), which is both FBS-open and FBS-closed in (U_1, U_2, τ, E).

4.3. Theorem 12

If (M, E) and (N, E) from a FBS-disconnected in FBS-topological space (U_1, U_2, τ, E) and (K, E) be an FBS-connected subspace of (U_1, U_2, τ, E). Then (K, E) is contained in (M, E) or (N, E).

4.3.1. Proof

Suppose that (K, E) is neither contained in (M, E) nor in (N, E). Then $(K, E) \cap (M, E)$, $(K, E) \cap (N, E)$ and their union gives (K, E),. This gives that pair of disconnection of (K, E) this is a contradiction. Hence (K, E) is contained in (M, E) or (N, E).

4.4. Theorem 13

Let (F, E) be an FBS-connected subset of a FBS-topological space (U_1, U_2, τ, E) and (G, E) are fuzzy binary soft subsets such that $(F, E) \subseteq (G, E) \subseteq \overline{(F, E)}$. Then (G, E) is FBS-connected.

4.4.1. Proof

It is sufficient to show that. $\overline{(F, E)}$ Is FBS-connected. Suppose that $\overline{(F, E)}$ Is FBS- disconnected? Then there exists a (H, E) and (K, E) of $\overline{(F, E)}$ That is $(H, E) \cap (F, E)$,$(K, E) \cap (F, E)$ FBS-open sets in (F, E) such that $(H, E) \cap (F, E) \cap (K, E) \cap (F, E) = \tilde{\phi}$ And $(H, E) \cap (F, E) \cup (K, E) \cap (F, E) = (F, E)$. This gives an FBS-disconnection of (F, E), a contradiction. This proves that $\overline{(F, E)}$ Is FBS-connected. Hence, the proof.

4.5. Corollary

If (F, E) be an FBS-connected subspace of (U_1, U_2, τ, E), then $\overline{(F, E)}$ Is FBS- connected?

5. Conclusion

Separation axioms provide a structured way to classify topological spaces based on their ability to separate points or sets using open neighbourhoods. Studying separation axioms not only aids in classifying and comparing topological spaces but also serves as a foundation for more advanced results in both pure and applied topology. This paper defines FBS separation axioms, namely FBS-Ti spaces (for, i=0,1, 2, 3,4), and their properties are studied, as studied FBS connectedness. The results of this paper will help the researcher enhance and promote further studies on FBS compactness, continuity, etc.

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