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Research Article

A CASE STUDY: FUZZY LOGIC BASED DECISION-MAKING SYSTEM FOR ELECTRIC VEHICLE CHARGING

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Abstract: *Recently, the use of environmentally friendly electric vehicles instead of traditional internal combustion engine vehicles continues to be widespread due to threats to world life such as global warming and climate change. However, the biggest disadvantages of this technology are the limited range of electric vehicles, long charging times, low number of charging stations, and different charging costs. There is a need for more studies on the problem of finding charging stations, especially for long-distance traveling with electric vehicles. In this paper, a fuzzy logic based decision making system is designed for electric vehicle users to find the most suitable one among the charging stations on a long travelling route. In this study, a traveling route of 1779 km between Izmir and Van provinces in Turkey is selected. The current charging station locations obtained from different charging station companies on this route were processed on Google Earth, and charging stations that were too far from the route were not taken into consideration. A fuzzy logic model was created for 56 charging stations on the route, which performs weight calculation according to the current charging cost and the distance of the station to the normal route. The fuzzy control system is expected to decide on the most appropriate charging station in accordance with the specified rule table, and the results are evaluated.*

Keywords*: Charging, Charging Stations, Electric Vehicles, Fuzzy Logic.*

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1. Introduction

Today, environmental and economic problems such as global warming, climate change, and the rapid depletion of fossil fuels necessitate a shift towards sustainable energy sources in the transport sector. The limited availability of fossil fuels and the environmental damage caused by carbon emissions from their use have increased the demand for new-generation energy solutions. Electric vehicles have emerged as an environmentally friendly and energy-efficient transport alternative in this context. Electric vehicles operate without producing emissions thanks to their battery systems, which play an important role in achieving environmental sustainability goals [1-2].

Despite the popularisation of electric vehicles, fundamental problems prevent the widespread use of this technology. In particular, limited battery capacities, long charging times, and deficiencies in charging station infrastructure are among the main challenges electric vehicle users face during intercity journeys. Inadequate and inappropriate positioning of charging stations limit the use of electric vehicles over long distances. Therefore, there is a critical need to develop solutions that will facilitate the access of electric vehicle users to charging stations and optimize factors such as cost and distance [3-4].

In this study, a fuzzy logic based decision making system is proposed for electric vehicle users to select the most suitable charging stations in their long distance journeys by evaluating the charging stations in terms of distance and cost. In the study, a decision-making system is developed to determine which charging station would be the most suitable for the user to charge the electric vehicle according to the cost and distance criteria of the charging stations selected on a 1779 km route between Izmir and

Van provinces of Turkey. In this context, it is foreseen that the study will provide essential progress to popularise the use of electric vehicles and increase the charging stations' efficiency.

2. Materials and Methods

In the digitalizing world, one of the most critical problems is the rapid depletion of high-energy and non-renewable energy resources, especially petroleum products, due to rapidly developing technology and the increasing population. Due to the limited amount of fossil fuels and the damage caused to the environment by motor vehicles using fossil fuels, the search for new-generation energy sources continues rapidly. Electrification of transport can potentially reduce carbon emissions and environmental pollution [5-6].

There are some obstacles for electric vehicles to replace conventional vehicles. The biggest obstacles are the limited driving range of electric vehicles, long charging times, low number of charging stations, and ineffective charging station locations. Although electric vehicles are considered to be more suitable for urban use due to reasons such as battery capacities, long charging times, and limited number of charging stations, they are also becoming suitable for intercity use by increasing battery capacities and improving charging station infrastructure with technological developments [7-8].

With the development of electric vehicle charging technology, charging station investments are made. With charging station investments, companies make different tariffs and pricing. Fast charging stations save time but increase the cost of charging. This paper aims to make the traveling of electric vehicles less costly with their current battery capacities between current charging stations. For this purpose, electric vehicle users will be able to have information about the charging stations on their routes. The problem of finding the most suitable charging station among the charging stations on the route with the current charging status of the electric vehicle is tried to be solved. For this purpose, a fuzzy logic control-based charging station algorithm was created by evaluating the multiple requirements of electric vehicles at the same time. Charging stations of different brands with different tariffs on the determined route were detected and processed on Google Earth. It is aimed to determine the most suitable charging station by calculating the current charging status of the electric vehicle and the distances and charging costs to these charging stations while traveling on its route. For this case, a route between Izmir and Van in Turkey was determined, and 56 charging stations on this route were evaluated according to these criteria. A weight value was calculated for each charging station using fuzzy logic. The fuzzy logic system designed in MATLAB environment for 56 stations in total is simulated to determine the accuracy of the system. Figure 1 shows the travel route between Izmir and Van and the charging stations of different companies whose locations are marked on the route.

2.1. Battery Electric Vehicles

Battery electric vehicles operate with a completely different energy generation system than internal combustion engine vehicles. Instead of fossil fuels, they realize vehicle movement by storing energy through rechargeable batteries and transmitting it to electric motors. These batteries convert the stored electrical energy into mechanical energy and enable the vehicle to move. This design simplifies the structure of the vehicle and makes energy conversion more efficient by not requiring components such as fuel tanks and exhaust systems found in internal combustion engine vehicles [9-10].

This operating principle makes electric vehicles an environmentally friendly transport option. Unlike internal combustion engine vehicles, electric vehicles do not cause emissions during use. This feature helps to reduce air pollution and contributes to the fight against global warming and sustainable environmental goals. The fact that they run on electrical energy makes it possible to utilize renewable energy sources, creating the potential further to reduce the carbon footprint [11-12].

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Despite these advantages, there are some significant challenges to the widespread adoption of battery electric vehicles. In particular, the lack of charging station infrastructure is still a major disadvantage for electric vehicle users on long-distance journeys. The low number of charging stations and their lack of availability in suitable locations increase users' concerns about being stranded on the road, making it difficult to adopt this technology. This problem is one of the main factors limiting the use of electric vehicles, especially in intercity journeys [13].

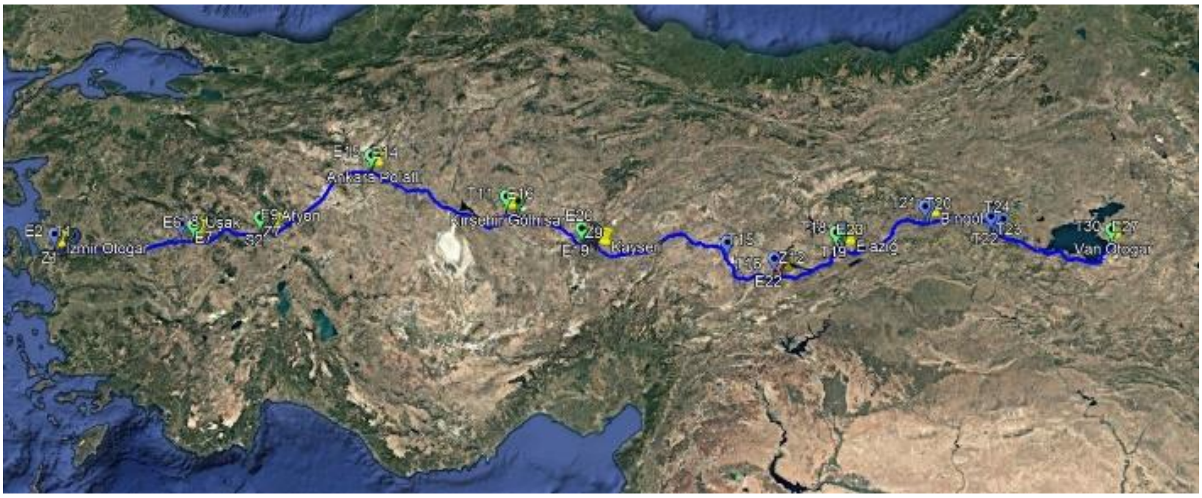

Figure 1. Selected travel routes between Izmir and Van and different brands of charging stations

2.2. Charging Stations

Electric vehicle charging stations are critical infrastructure elements used to meet the energy needs of battery electric vehicles. These stations perform the charging process by transmitting electrical energy to the batteries of the vehicles. Effective positioning and increasing the number of charging stations play an important role in the wider use of electric vehicles [14-15].

Since the study focuses on charging optimization in long-distance journeys, DC fast charging stations are taken into consideration. DC fast charging stations provide faster energy transfer, allowing electric vehicle users to charge more efficiently on long-distance journeys [16].

Reliable and accessible charging infrastructure for electric vehicle users directly affects the adoption rate of these vehicles. SAE (Society of Automotive Engineers), IEC (International Electromechanical Commission), and CHAdeMO standards are used worldwide [17]. Various specific charging standards, such as SAE J1772, IEC 61851, IEC 62196, and CHAdeMO, are widely used. However, IEC standards are widely accepted and applied in charging infrastructure in Turkey. Since this study focuses on the charging infrastructure in Turkey, the proposed fuzzy logic controller design is based on IEC standards. Accordingly, the technical specifications of IEC standards are presented in Table 1, and it is emphasized that the study is designed in accordance with the charging infrastructure of Turkey. This approach strengthens the suitability of the study for both local context and technical compatibility.

The IEC 61851 standard, widely used in Europe, includes both AC and DC charging modes. Table 1 presents the electrical parameters and technical specifications of each mode. For example, Mode 1 is a low-current charging method and requires a longer charging time, while Mode 4 provides ultra-fast DC charging, allowing users to cover a long range in a short time.

Table 1. Technical parameters of the IEC 61851 standard [18]

Source	Mode	Phase	Max. Voltage (V)	Max. Current (A)
AC	Mode 1	1	≤250	≤16
AC	Mode 1	3	≤480	≤16
AC	Mode 2	1	≤250	≤32
AC	Mode 2	3	≤480	≤32
AC	Mode 3	1	≤250	≤32
AC	Mode 3	3	≤480	≤32
DC	Mode 4	-	≤1000	≤400

Since the paper aims to optimize charging stations for long-distance journeys, it is important to provide details on charging station standards to implement the proposed solution and help select the most suitable charging method for different electric vehicle usage scenarios.

2.3. Fuzzy Logic Controller

Fuzzy logic is used in the development of non-linear systems, complex systems that lack clarity in their inputs or definitions. A fuzzy logic algorithm is a control approach that shows how the system will respond to multiple inputs according to predetermined rules [19].

In this study, the Fuzzy Logic Toolbox library in MATLAB was used to create the fuzzy logic controller selected as the decision-making algorithm. After the data from the variables are collected, it passes through the fuzzy logic controller and decides which charging station will be more logical to choose at what rate at the output.

The most suitable charging station is determined by calculating the charging cost of the charging stations on the travel route for the electric vehicle and the distance to the travel route. From this point of view, a fuzzy logic control based electric vehicle charging algorithm is proposed by reflecting multiple requirements of electric vehicles at the same time. The multiple requirements include the distance between the electric vehicle and the charging station and the charging cost of the charging station. The proposed scheduling algorithm focuses on finding the charging station preference priority for the electric vehicle. Considering the whole distance and total traveling cost, the fuzzy logic control generates a weight value as output, which is the concept of EV charging priority. Given the weight values, the proposed scheduling algorithm recommends the closest and most convenient scheduled charging stations to the EVs for charging [20].

Distance is the distance from the location of all charging stations on the route of the electric vehicle to its own location. The cost is found by calculating the charging tariffs of the charging stations of different brands on its route. As a result, distance and cost are used as inputs to the fuzzy logic control. Based on these inputs, the management system produces a weight matrix which is the output of the fuzzy logic control. The weight matrix is used in the charge scheduling algorithm operated by the management system. The management system focuses on recommending the closest and most cost-effective charging station for the electric vehicle to its route. In this study, fuzzy logic control is used in the management system to handle multiple parameters simultaneously. Fuzzy logic control inputs are distance and cost. Equation 1 is used to normalize these two factors in the range (0,1).

$$0 \leq x = \frac{x - x_{min}}{x_{max} - x_{min}} \leq 1 \tag{1}$$

This formula is used to normalize distance and cost. Here, x indicates distance or cost. While creating the scenarios to be given to the fuzzy system inputs, the average values are battery capacity 70

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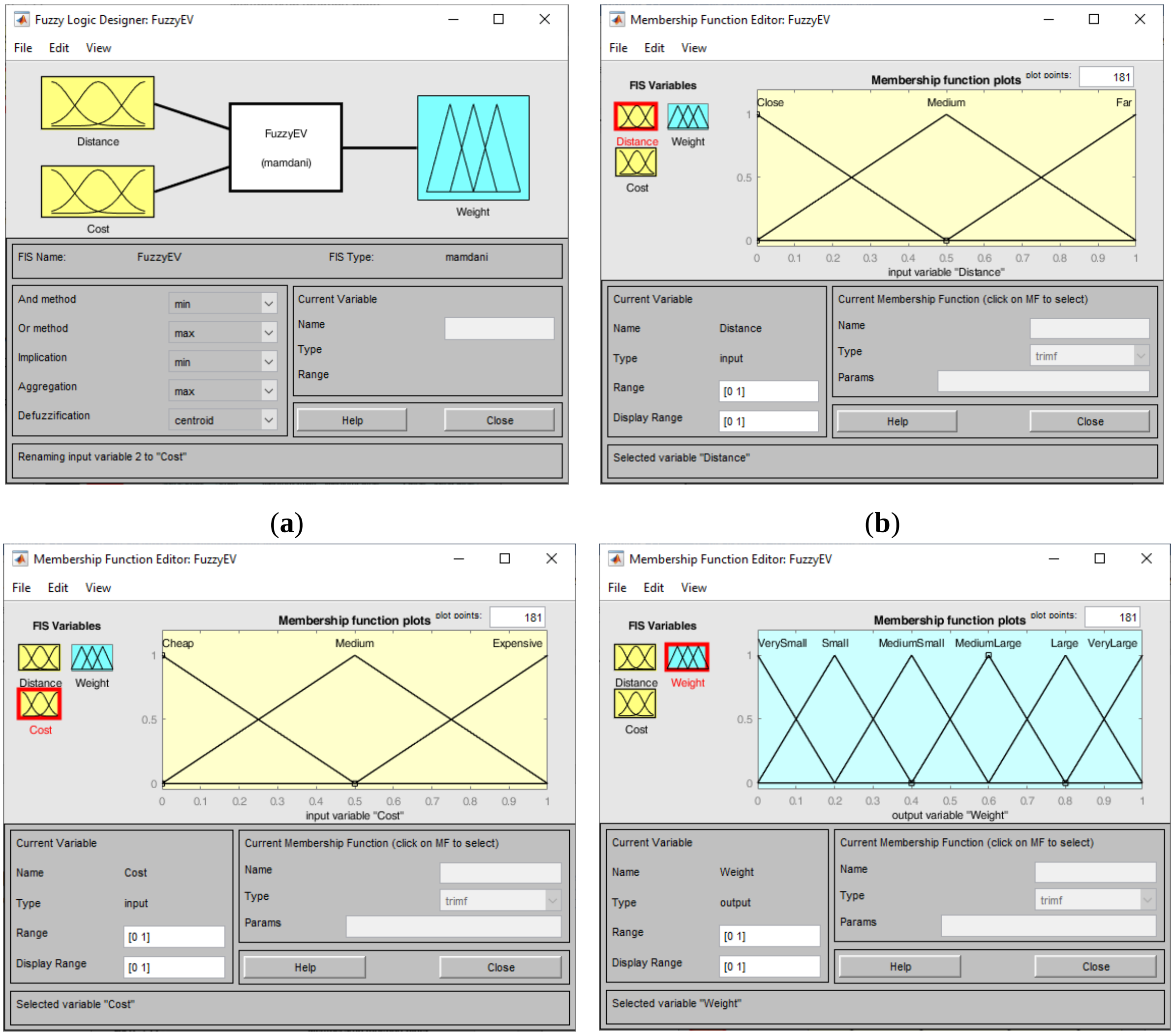
kwh, E brand charging station unit price 9,48 tl/kwh, T and Z brand charging stations 7,99 tl/kWh, and S brand charging stations 7,50 tl/kWh. It is assumed that 18 kWh of energy is spent per 100 km.



(c) (d)

Figure 2. a) General representation of the designed model, b) Membership functions for Distance input, c) Membership functions for Cost input, d) Membership functions for Weight output

MATLAB/Simulink interface was used to design the controller and algorithm of the system. The general representation of the model designed with the Fuzzy Logic Designer Toolbox in MATLAB environment is given in Figure 2. a, the visualizations for the selection of membership functions are given in Figure 2. b for distance, Figure 2. c for cost and Figure 2.d for weight as output. The rule table of the fuzzy control system is shown in Table 2. The fuzzy logic controller operates according to the rules specified in the table, and all mappings and combinations of if/then rules are presented to calculate the weight value at the output. The weight value linguistic variables are defined as "Very Small, Small, Medium Small, Medium Large, Large, Very Large". Finally, the weight value is calculated by the fuzzification method. The charging station with the larger weight value calculated by this method has higher priority in terms of selection.

Table 2. Mapping and combination of if/then rules

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Rules	Distance	Cost	Weight
Rule 1	Close	Cheap	Very Large
Rule 2	Close	Medium	Large
Rule 3	Close	Expensive	Medium Large
Rule 4	Medium	Cheap	Large
Rule 5	Medium	Medium	Medium Large
Rule 6	Medium	Expensive	Medium Small
Rule 7	Far	Cheap	Medium Small
Rule 8	Far	Medium	Small
Rule 9	Far	Expensive	Very Small

In accordance with this rule table, 56 charging stations on the route were analyzed, and the fuel cost to be spent as a result of selecting these charging stations in terms of total travel cost was calculated. During this calculation, both the calculated total fuel cost, the distance of the charging station to the normal travel route, and the charging station tariff were normalized. The total fuel cost is calculated for a TOGG brand short-range electric vehicle manufactured in Turkey, where the vehicle user will be fully charged only once on the specified route, and the electric vehicle has a standard energy cost for each kilometer distance outside the route and is selected the same for all possibilities.

Table 3. Projected weight versus distance and charging costs of some sample charging stations on the route

Charge Station	Distance	Cost	Normalized Total Cost	Expected Weight
S1	0.55	0.01	0.94	Very Large
T15	0.17	0.25	0.78	Large
Z9	0.39	0.25	0.74	Medium Large
T2	0.56	0.25	0.71	Medium Large
Z11	0.56	0.25	0.71	Medium Large
T14	0.56	0.25	0.71	medium large
E3	0.14	1.00	0.11	Small
E4	0.24	1.00	0.09	Very Small

Here, S1 represents the 1st numbered charging station on the route of brand S. Similarly, charging stations belonging to E, Z, and T brands are numbered.

3. Results and Discussion

The designed Mamdani fuzzy logic decision making system with two inputs and one output is intended to be tested for 100 different scenarios generated randomly in MATLAB environment. For this reason, randomly generated distance and cost values are applied as input to the fuzzy logic controller as shown in Figure 3.

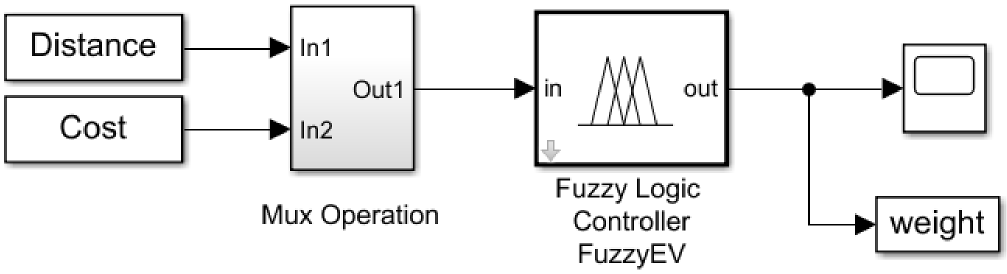

Figure 3. Simulation model of the designed fuzzy logic decision making system

The designed fuzzy logic decision making system generated output weight values according to the distance and cost values in the range of 0-1 randomly applied to its input. The change of weight values obtained from 100 different scenarios generated in the MATLAB environment is given in Figure 4.

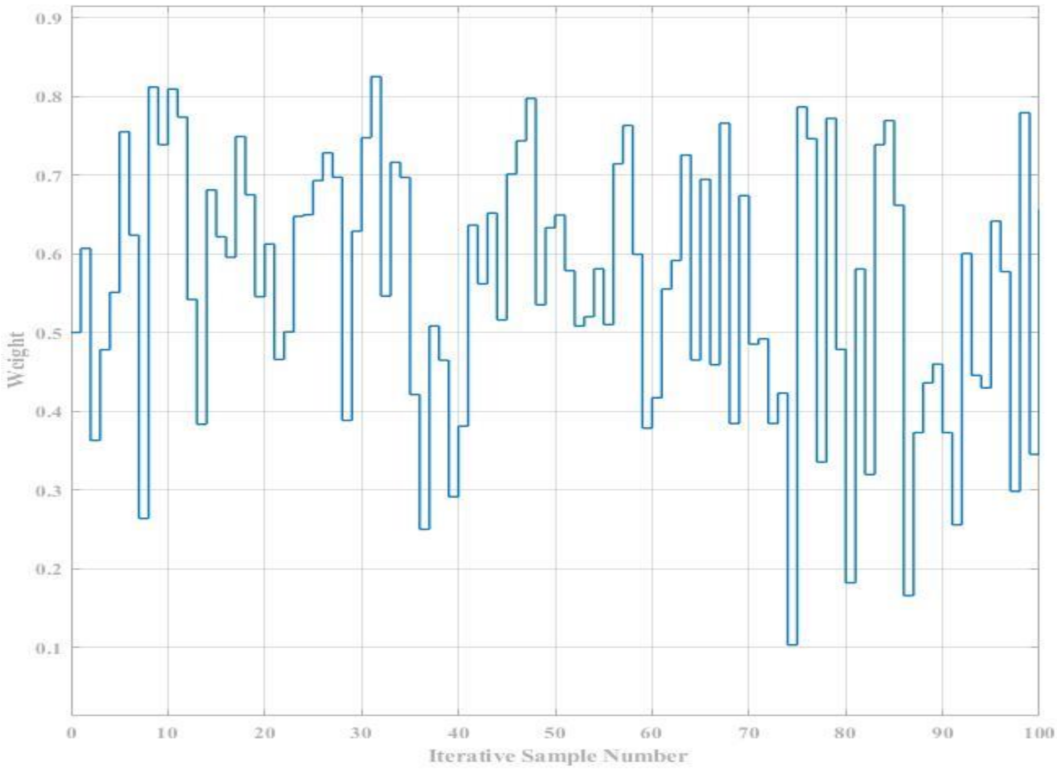

Figure 4. Variation of weight values calculated by the fuzzy logic decision making system for 100 different scenarios

As can be seen from the change, within the framework of the rules and inputs entered into the model, the scenario with the highest weight is the 32nd scenario, with a weight value of 0.8248. The input values are 0.2587 for Distance and 0.0909 for Cost. The lowest weight is obtained as 0.1030 in the 75th Scenario, and the input values are 0.0729 for Distance and 0.2229 for Cost.

4. Conclusion

In this paper, a fuzzy logic based decision making system is designed for electric vehicle users to select the most suitable charging station from the charging stations on their routes while travelling.

In order to demonstrate the real-time applicability of the study, an electric vehicle traveling between Izmir and Van in Turkey and 56 charging stations belonging to four different companies with known locations on the travel route are selected. While on the travel route, the distance between the electric vehicle and the charging station and the charging costs of the relevant charging station are normalized and given as fuzzy logic inputs. As a result of this sample data, a weight value was calculated for each charging station and a priority ranking was determined for electric vehicle drivers according to this value. The charging station with the highest weight value is the most suitable charging station. With this designed system, it is expected to solve the confusion in the charging station selection of electric vehicle users during their travels. In future studies, we will focus on the queuing problem at charging stations on any route determined by using current data from the charging station in Turkey.

Ethical statement

This study does not involve the use of human or animal subjects, nor does it involve hazardous chemicals, and therefore no ethical approval is required.

Acknowledgement

This study was derived from Melek Coşkun's Master's Thesis, titled "Determining the Optimal Charging Station for Electric Vehicles."

Conflict of interest

The authors declare no conflicts of interest.

Authors' Contributions

M.C: Conceptualization, Methodology, Formal analysis, Writing-Original draft preparation (%50)

B.K: Conceptualization, Methodology, Resources, Investigation, Writing-Original draft preparation (%50).

All authors read and approved the final manuscript.

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