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Research Articles / Araştırma Makaleleri

Building A Keystroke Dynamic Recognition System Using An Improved Accelerated Method

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Keywords

Deep Learning, Keystroke Dynamic, Residual CNN, Parallel Computing, Authentication System

Abstract

A trustworthy security application in the actual world uses the keystroke capability of typing recognition software. Despite being straightforward, it requires a quick and precise method of character analysis. In this manuscript, a keystroke dynamic recognition method to identify and block illegal users is proposed by using deep learning of convolutional neural networks (CNNs) which can efficiently distinguish legitimate users from illegitimate users. Where, two proposed networks are built based on 1D-CNN to increase and accelerate the recognition abilities. The first network improves the system performance by modifying the kind of activation function utilized, whereas the second network improves the system performance by employing the residual scheme. The findings display that the suggested CNN model with the swish function can deny all illegitimate users with an average equal error rate (EER) of 0.0066. Furthermore, by Graphic Processing Unit (GPU), the model performance is accelerated by approximately 2 times. Based on the outcomes, the suggested CNN model with swish function significantly outperforms other models in the literature.

Research Article
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1. INTRODUCTION

The advancement of digital information systems and the usage of biometrics today have significantly improved how to handle the variety of user data and analyze it quickly and efficiently* for many enterprises. Keystroke dynamic is one of the categories of behavioral measurements for users, and it relies on identifying the user based on how they behave when

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using a keyboard. To do this, it specifies a set of temporal characteristics that correspond to the user's behavior when using the keyboard, such as dwell time, flight time, or the time taken for keys to transition between each other, as well as their typing speed. Because this technique relies heavily on software, it may be used as a different approach to assessing user data in a variety of contexts, such as the identification of mental weariness (Maheshwary, Ganguly & Pudi, 2017; Kim & Kang, 2020). Although it would appear that there are very few distinctions between people's typing styles, this is not the case. When typing using the keyboard, users may have varied typing patterns. These patterns, which may include using the left or right shift keys or varying the duration between two key presses, make typing more unique. One can identify between authorized and unauthorized users by making use of such distinctive behaviors. These biological traits, however, are not likely to be discernible with the human eye or with standard programmed decision-making methods (Lin, Liu & Lee, 2018). As a result, in this paper, deep learning's potent capabilities are utilized. Through a variety of learning processes, the suggested system may finally discriminate between authorized and unauthorized users.

Artificial intelligence in the form of deep learning identifies a preliminary answer to a problem using induction and reasoning, then updates the solution based on learning experiences so that it eventually approaches the proper value (Lemley, Bazrafkan & Corcoran, 2017). The deep learning model has been examined in this paper: Convolutional Neural Networks (CNNs). Because CNN cascades several features to allow features to associate with one another while doing feature analysis, which can considerably improve the accuracy of the prediction or analysis. The authentication system based on the proposed CNN model can be used in multiple applications like Electronic Health Record Systems (EHR) (Wesołowski, Porwik & Doroz, 2016), Online Learning Environments (OLE) (Muniasamy, 2019), etc.

A keystroke dynamic recognition method is proposed by using convolutional neural networks (CNNs) which can efficiently distinguish legitimate users from illegitimate users. The contributions of this paper are as follows:

- A CNN architecture is built by replacing the Rectified Linear Unit (ReLU) with Swish activation to increase the propagation of a few negative weights across the CNN architecture.
- One-layer residual CNN design is developed to aid in assisting the Graphic Processing Unit (GPU) in expediting training. process.

The structure of this paper is as follows: In section 2, several previous works concerning deep learning are presented. The next section displays the methodology used to build the proposed system. In section 4, the results of the proposed system are analyzed, discussed, and compared with related works. Finally, the conclusions and future works are mentioned in section 5.

2. RELATED WORKS

This section offers an overview of the studies applying keystroke dynamics as a biometric technique for the verification and identification of users, emphasizing the work by Killourhy and Maxion, conducted on the CMU dataset (Killourhy & Maxion, 2009).

In this research (Çeker & Upadhyaya, 2017), the convolutional neural network and the Gaussian data augmentation approach are used to look at efficacy of the deep learning when applied on three different datasets. Authors revised up the precision of previous approaches with 10%. They also reduced the equal error rate (EER) by 7.3%, which is 10% better than the one proposed earlier. Because of that, the analysis suggests that the crucial part of a network which learned a keyboard input is a fully connected layer conjugated by a convolution operation as they are the one that mainly affect the network's accuracy and speed of learning.

The research (Andrean, Jayabalan & Thiruchelvam, 2020) applied to the model using the CMU benchmark dataset a deep learning model based on Multilayer Perceptron (MLP) for keystroke typing dynamics for the purpose of user verificiation. With regard to the other reference classifiers, the MLP`s optimal EER was only 4.45%, while the outlier count`s result was 9.96%, Mahalanobis Nearest Neighbor`s was 9.96%, and for the scaled Manhattan`s it was even 9.6%. We could also say that the results of the Outlier Count classifier (Altwaijry, 2020) took it one step further by introducing CNN-Detect, a convolutional neural network that processes characteristics of typical human typing patterns in an attempt to recognize culprits. Having evaluated the data with appropriate feature engineering, CMU keystroke dynamics dataset which can be accessed publicly, the suggested model was tested with an average EER of 0.009 and ZM-FAR of 0.027 being found.

In this study (Sahu & Banavar, 2021), the authors enrich the model that counts the users and assigns their place in the queue to those who had similar typing rhythms. Therefore, an idea about eliminating outliers was a quantile transformation that was supposed to turn unprocessed keystroke characteristics to a uniform distribution. Last, the rotated feature space is recreated using projects on the lower-dimensional space through principal component analysis and other methods. Using the k-means clustering to examine the number of people utilizing the system in a smaller feature space was the algorithm selected for this experiment. Our findings were served mathematically through the vector search approach and the labeling of tightness clusters. The method was verified to be more than 93% accurate and were validated through the use of two standards datasets namely MobiKey and the CMU keystroke benchmark dataset.

The research (Mao, Wang & Ji, 2022) described the development of a key stroke dynamics authentication mechanism for identifying users based on deep learning. Bi-directional LSTM-based model (BI-LSTM), CNN, and the attention mechanism become an interlaced structure. This model embraces both character's typing speed and writing context. First of all, the CNN conducts the operations with the characteristic vectors that comprise data. The normalized sequence goes into the bi-LSTM network to be trained. Through the use of the Buffalo Open Data Collection to judge, the model is assessed. The findings demonstrate that the False Accept Rate (FAR), Equal Error Rate (EER), and False Reject Rate (FRR) are correspondingly 3.03%, 4.23%, and 3.09%.

3. METHODOLOGY

This section includes the experimental settings and details of the two suggested networks. The two proposed networks are built based on 1D-CNN to increase and accelerate the recognition abilities. The first network improves the system performance by modifying the kind of activation function utilized, as given in Figure 1, whereas the second network improves the system performance by employing the residual scheme, as given in Figure 2.

The CMU Keystroke Dynamics Dataset (Killourhy, 2009) was used for the tests to assess the performance of the suggested network topologies. The 50 people are utilized as illegitimate users while one person is chosen to be a legitimate user. The dataset is divided into training samples (80%) and testing samples (20%). The two networks receive a series of 50 user samples (N) and 31 feature vectors (Vi), and they output either legal or illegal users as two outcomes.

The first network's proposed structure (as given in Figure 1) consists of four convolutional blocks: a pair of 1D-convolution layers, an activation function, and a layer for batch normalization. A 1D-convolution layer extracts the features from input data using a collection of filters that perform a convolution operation with a stride of 1 and the same padding. The first and second convolutional blocks apply 16 and 32 filters, respectively, to the data. The network is training two times, one employing the Swish activation function and another using the ReLU activation function. To improve classification accuracy and speed up the training process, batch normalization adds a transformation to the network.

The findings are then sent to a one-dimensional average pooling layout with a stride of two to reduce memory usage and improve network translation, distortion, and scaling robustness. The network employed the dropout and early stopping regularization techniques to lessen system overfitting. The probability values for the needed two classes were then produced using two fully connected (FC) layers and a softmax classifier. On the other hand, the second suggested network is made up of two fully connected layers, a SoftMax classifier, one residual convolutional block, and 1D-average pooling strided with two. The convolutional block's structural components include a layer of 1D-convolution strung together in a stack, 64 filters of the same padding, a layer of ELU activation function, and a layer of batch normalization with the residual connection. In this study, residual connections enable features information to pass from the convolutional layer as the input layer to the batch normalization layer as the output layer and apply addition operation, as given in Figure 2. For knowledge, the type of the penultimate FC layer in the three methods is the ReLU type. The suggested networks are learned using the following parameters: 32-batch size, Adam optimizer, learning rate = 0.001, momentums = 0.9 and 0.99, categorical cross entropy as loss function, 100 epochs, and EarlyStopping to halt training when the parameter updates do not improve performance on the validation set.

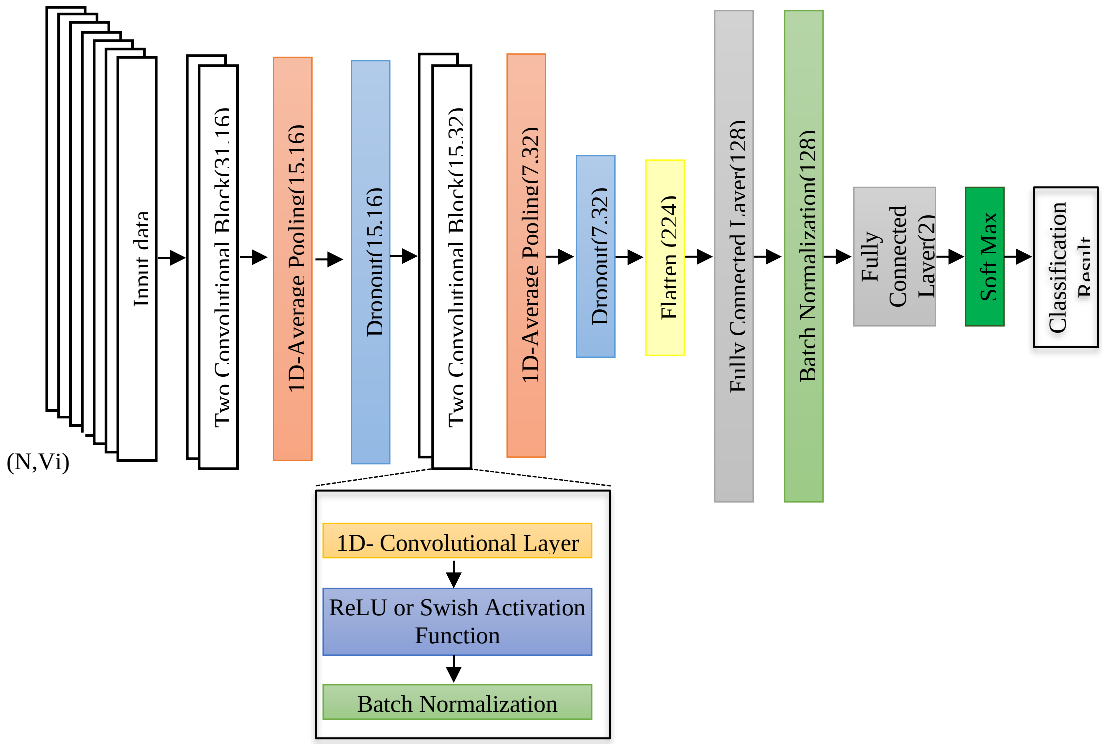

Figure 1. The proposed architecture of CNN

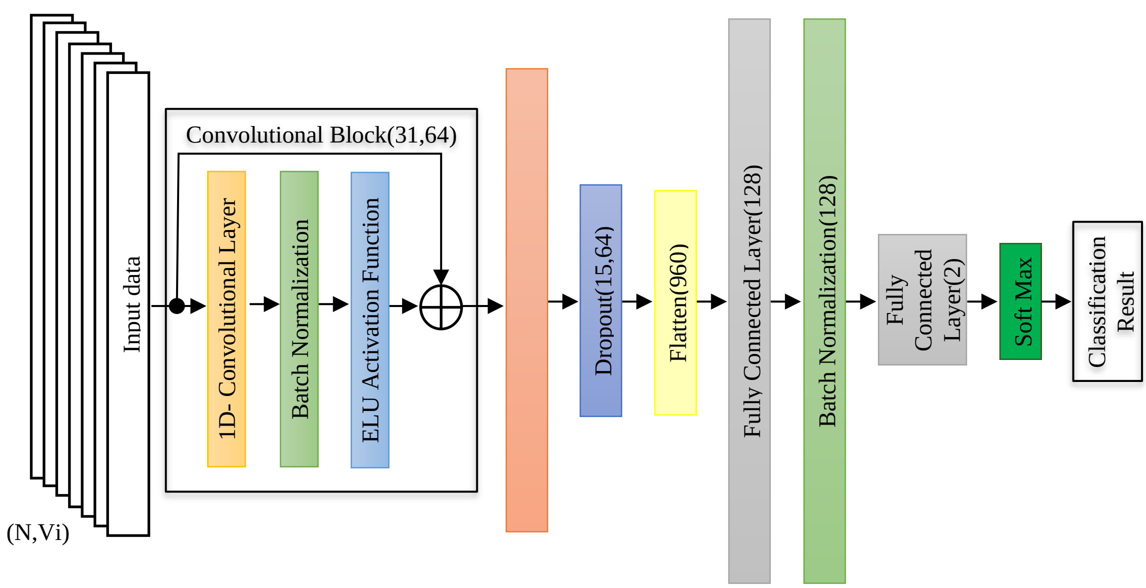

Figure 2. The proposed architecture of one-layer Residual CNN

4. RESULTS AND DISCUSSION

The recognition findings with their discussion are presented in this section. The proposed networks are implemented on two computers with the characteristics listed in Table 1 and constructed in Python software using the frameworks of TensorFlow and Keras.

Table 2 provides a summary of many average findings after modifying numerous different hyperparameters for the suggested CNN and the residual CNN models. The proposed CNN architecture with the Swish activation function produces the best EER value. This is because the Swish function has a smoothness feature that allows a relatively small number of negative weights to get through, whereas ReLU limits all negative weights to zero. Nevertheless, despite being, the architecture-based Residual connection produces an adequate performance.

Table 1. Machines specifications

	Equipment	Machine 1	Machine 2
CPU	Computing name	Intel i7-7500U	Intel i7-10700
	#core	2	2
	#thread	4	4
	Clock frequency	2.7GHz	2.9GHz
GPU	Architecture	Maxwell	Turing
	Computing name	940MX	RTX 2060 super
	CUDA Driver Version	10.2	11.2
	CUDA Capability	5.0	7.5
	# Multiprocessors	3	34
	# CUDA Cores	384	2176
	Clock frequency	1.242GHz	1.68GHz
	Memory bandwidth	14.4 GB/s	448 GB/s

Table 2. Average results of recognition

Evaluation measure	Architecture based ReLU	Architecture based Swish	Architecture based Residual connection
Accuracy	99.3%	99.3%	99.1%
Recall	98.6%	98.7%	98.3%
Precision	100%	99.9%	99.9%
F1	99.3%	99.4%	99.1%
EER	0.0070	0.0066	0.0091

Table 3 displays the training time (per epoche) and testing time when applied on two distinct machines. Because GPUs parallel computing has a greater number of cores, the implementation is faster than using CPUs and is suited for the suggested designs. Furthermore, because of the distinct network architectural design process and its confinement on one layer, the residual network was faster than other networks.

Table 4 shows a comparison of the number of parameters and FLOPs for the proposed models, where the residual model requires a higher design cost than the two proposed architectures (Architecture-based ReLU and Architecture-based Swish function) because it contains more filters as well as the use of residual connections.

Table 3. Time of different equipment of GPU and CPU

Machine	Equipment	ReLU-model		Swish-model		Residual-model	
		Training (ms)	Testing (ms)	Training (ms)	Testing (ms)	Training (ms)	Testing (ms)
Machine 1	Intel i7-7500U	4060	281	4184	301	3286	230
	940MX	3330	190	4105	200	3130	160
Machine 2	Intel i7-10700	1953	170	2093	284	1162	124
	RTX 2060 super	1876	125	1969	126	960	78

Table 4. The architectural and computational complexities of the proposed models

Model	Architecture based ReLU	Architecture based Swish	Architecture based Residual connection
Parameters	35,474	35,474	124,290
FLOPs	255 K	257 K	270 K

The average EER result of the best proposed architectural design was compared to several recent works and outperformed them, as given in Table 5, because of building the suggested network differently and using the swish function.

Table 5. Comparative average EER of the proposed system with the related works methods over CMU dataset.

Ref.	Method	EER	Accuracy
(Killourhy and Maxion 2009)	Manhattan (scaled)	0.096	N/A
(Çeker and Upadhyaya 2017)	CNN	0.065	94%
(Andrean, Jayabalan et al. 2020)	MLP	N/A	96.7%
(Altwaijry 2020)	CNN-Detect	0.009	N/A
(Sahu and Banavar 2021)	Nearest neighbor rule	N/A	93%
(Mao, Wang et al. 2022)	ACBM	0.0423	N/A
Our Work	Proposed method	0.0066	99.3%

5. CONCLUSION

The field of keystroke dynamics biometrics has developed in recent years. The primary motivation for most works is how easily and affordably keystroke dynamics biometrics may be included in prevailing computer security systems without user involvement. Numerous studies on data collection techniques, feature representations, classification algorithms, and experimental approaches have been conducted. The experimental technique has been emphasized in this paper. By altering the kind of activation function used, the first networgivenk enhances system performance, whereas the second network enhances system performance by utilizing the residual scheme. The experimental findings demonstrate that the suggested CNN model is capable of blocking all unauthorized users with an average EER of 0.0066. Moreover, parallel processing (GPU) enhances system performance by a factor of two. The suggested CNN model with the swish function greatly outperforms other models in the literature based on the experimental results. More parallel architectures will be used to implement the model in the future work.

Conflict of Interest

The authors declare no conflict of interest

Contribution of Authors

All authors contributed to the conception, design, examination, resource allocation, data collection, literature review, and analysis and interpretation aspects of the research.

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Fuzzy VIKOR Method for Dynamic MADM Problem Solution in ESI 5-Level Triage System

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Keywords
Dynamic MCDM, Uncertainty, Fuzzy Theory, Emergency Severity Index, Triage Patients.

Abstract
Multiple Attribute Decision Making (MADM) tools make preference decisions over multiple attributes' alternatives available, which in most cases conflict among themselves. The classic MADM includes techniques that consider a set of fixed and predefined attributes when making a decision. However, the majority of real-world decisions occur in dynamic and unstable scenarios. Therefore, classic MADM will not be the answer to our problems in the real world and uncertainty. This paper addresses a flexible framework for dynamic MADM, based on the concept of fuzzy sets theory and the VIKOR method to provide a rational, scientific and systematic process for prioritizing patients in the Emergency Department (ED), under a fuzzy environment where the uncertainty, subjectivity, and vagueness are addressed with linguistic variables parameterized by triangular fuzzy numbers. Finally, the computational results are discussed in detail. Dynamic decisions arise in many applications, including military, medical, management, sports and emergency situations. Therefore, this study can affect a wide range of applied fields.

Research Article
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1. INTRODUCTION

As existing systems become more complex, the importance of dynamic systems has become much wider than in the past. Decision making in dynamic systems can cause growth, survival and even destruction of systems. Today, most real-world decisions are made in a dynamic environment (Jassbi et al., 2014). Therefore, it is necessary to create a suitable framework for these types of decisions. In this paper, we seek to find a framework for this type of decision making. In classical models of multiple criteria decision making (MCDM), it is assumed that when making a decision, the decision maker has predefined a fixed set of criteria and presented fixed alternatives with a clear picture of all available alternatives (Peng & Tzeng, 2013). In dynamic situations, the problem is that decisions are made in a constantly changing (dynamic) environment (Alinezhad & Taherinezhad, 2020), and the available alternatives can change over time. In most studies conducted in the field of multiple attribute decision making (MADM), the

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decision-making matrices in them are static (Alinezhad et al., 2023; İşler & Çalık, 2022; Norouziyan, 2022; Amini et al., 2016). That is, the weight of attributes and the value of alternatives for each attribute belong to a period of time, and the change of these items during the past or future periods was less considered. While it is quite evident that all the information related to MADM matrices can change over time and their values are not necessarily constant during several time periods. Therefore, these items can be seriously effective in the decision-making process and ranking of alternatives. Decision-making with the above conditions, which we call dynamic decision-making under uncertainty, is used in many fields, including military, medical, management, sports, and emergency situations. In hospitals and medical centers, the triage system refers to the process of prioritizing patients based on the severity of the disease in order to perform the best treatment measures in the shortest possible time (Sabry et al., 2023). Our main problem is to provide a framework for decision-making in one of the common types of triages (American 5-level triage). The proper triage will increase the quality of patient care services, increase satisfaction, reduce the waiting time and stay of patients, reduce deaths, and increase the efficiency of emergency departments in parallel with reducing related costs (Sabry et al., 2023).

The term triage was first used in 1800 by one of Napoleon's army doctors named Doctor Dominique Jean Larry to prioritize and treat wounded soldiers in war. From the early 1990s, several countries started designing and providing triage systems until the five-level triage systems were created and introduced in the late 1990s and early 2000s (Travers et al., 2002). Among these systems, the triage system of Australia, Canada, Manchester and the emergency severity index (ESI) gained the most acceptance. The triage process becomes meaningful when, firstly, there are resources for providing services, secondly, the relative balance between the supply and demand of resources is not established, and thirdly, a specific plan for prioritizing patients is defined (Sabry et al., 2023). The ESI system is an American 5-level triage system that was invented in 1999 by two emergency medicine specialists named Richard Warez and David Eitel. The ESI triage structure is one of the 5-level triage methods in which patients are divided based on the two criteria of disease severity and the facilities required by the patient. Currently, ESI triage seems to be the most appropriate triage system. This system has been revised three times and currently the fourth edition is available (Gilboy et al., 2012).

In the ESI algorithm, there are four decision points as shown in Figure 1 (Gilboy et al., 2012):

- Decision point A: "Is the patient dying or does he need immediate and life-saving intervention?" In this case, it is placed at level 1.
- Decision point B: "Shouldn't the patient wait?" (Including: high-risk symptoms, impaired consciousness, pain, severe distress), which in this case is placed at level 2.
- Decision point C: In the absence of conditions A and B, the facilities needed by the patient are estimated in the emergency room to determine the patient's task. The patient's need for two or more emergency facilities, if vital signs are not disturbed, puts the patient at level 3. The patient's need for one of the emergency facilities places the patient on level 4, and the patient who does not need to use emergency facilities is placed on level 5.

Decision point D: If the facilities needed by the patient are two or more according to the definition, at this stage, the patient's vital signs should be considered for classification. If there is a disturbance in the vital signs, the patient will return to level 2, and otherwise, the patient will be divided into level 3. In the following, after identifying the problem and its precise definition, the first step in conducting the research is to study the literature of the subject in order to gain knowledge and determine the place of the current research among the studies. The next step is problem modeling with the help of MADM techniques and modeling methods in fuzzy conditions. Then, the proposed model will be implemented in a case study that is an improvement in the way of prioritizing patients in the emergency department of the hospital to determine its efficiency and effectiveness. At the end, the obtained results are analyzed, and a final summary is made.

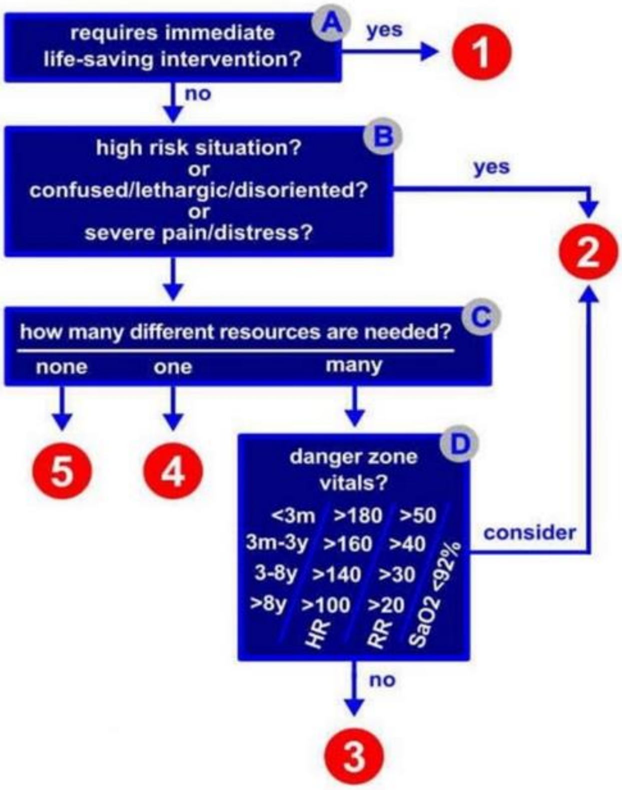

Figure 1. The ESI triage algorithm (Gilboy et al., 2012)

2. LITERATURE REVIEW

Decision making is a long-standing field that has been widely researched by various decision-making tools (Taherinezhad & Alinezhad, 2023; Taherinezhad & Alinezhad, 2022; Alinezhad & Taherinezhad, 2021; Khalili & Alinezhad, 2018; Sarrafha et al., 2014; Kiani Mavi et al., 2010; Alinezhad et al., 2007). For example, specifically in the area of decision making using non-dynamic MADM, we can refer to İşler and Çalık’s (2022) study. İşler and Çalık (2022) proposed the use of the WASPAS technique to select Islamic financial trades, focusing on the problem of "investment according to Islamic principles". In addition, they used the entropy method to determine the weights of criteria. In another research, Norouziyan (2022) focused on a petrochemical case study, using analytic hierarchy process (AHP) and VIKOR methods to determine the weights of criteria and ranking the alternatives, respectively. Also, Ramadan and Özdemir (2022) prioritized Istanbul rail system projects using Fuzzy AHP and PROMETHEE. The important point is that the criteria did not change in any of the decision-making stages in the mentioned studies and were constant. In other words, these MADM problems are non-dynamic. While this paper focuses on a dynamic problem. Therefore, in order to review the detailed and scientific literature, we limited the search for articles to the field of dynamic MADM (DMADM). For the first time, Brehmer (1992) examined decision-making under conditions in which decisions are not independent and the state of the surrounding world changes (dynamically), and presented a general method based on control theory as a means of organizing research in this field. Badiru et al., (1993) presented a decision support system based on the simulation and Analytic Hierarchy Process (AHP) method, which is called dynamic decision-making and can be used to implement dynamic decision-making scenarios. Lin et al., (2008) presented a dynamic decision-making model whose main structure is based on the

TOPSIS method. Also in it, integration and integration of the concepts of gray numbers and the Minkowski distance function have been done in order to deal with uncertain information. Wei (2009) investigated the problem of dynamic intuitionistic fuzzy MADM in which all attributes' values are expressed as intuitionistic fuzzy numbers or interval values of intuitionistic fuzzy numbers. In addition, he has presented some geometric cumulative operators such as the Dynamic Intuitionistic Fuzzy Weighted Geometric (DIFWG) operator and the Uncertain Dynamic Intuitionistic Fuzzy Weighted Geometric (UDIFWG) operator to collect uncertain dynamic intuitionistic fuzzy information. Chen and Li (2011) presented a dynamic MADM model based on Triangular Intuitionistic Fuzzy Numbers (TIFN) to solve DMADM problems, where all decision information was in TIFN form. Hu and Yang (2011) also proposed a method based on cumulative prospect theory and pair set analysis to solve stochastic dynamic decision-making problems in which the weight information of the criteria is completely unknown, and the values of the criteria are in the form of discrete random variables.

Campanella and Ribeiro (2011) introduced a flexible framework for solving the DMADM problem based on the classical model, which can be applied to any dynamic decision-making process. This framework aims to solve the above problem by expanding the classic MCDM model in a flexible way. Wang et al., (2015) presented an interval dynamic reference point-based method for Emergency Decision Making (EDM) problems. The above method uses a method similar to TOPSIS, which is a popular decision-making technique, to rank the alternatives. Lourenzutti and Krohling (2016) developed the TOPSIS technique and presented the Group Modular Random TOPSIS (GMo-RTOPSIS) method for group decision making with heterogeneous information and in a dynamic environment. In this method, each decision maker can independently define the set of attributes, the weight vector, and the basic factors effective in ranking the alternatives, as well as the type of information for each attribute.

In the following, we will review the research done on the problem of prioritizing emergency department patients through decision tools. Chen et al., (2010) presented an analytical framework for Dynamic Multiple Criteria Decision Analysis (DMCDA) problems as an extension of classical static MCDA. Their research process was such that an overview of MCDA was done and an introduction to DMCDA was stated. Then, various design aggregation strategies and an analytical framework of DMCDA were described in detail. Finally, an emergency management case study was provided using data from the Emergency Management Australia (EMA) database to demonstrate the feasibility of the proposed analysis method. Ashour and Okudan (2012) believe that the triage process relies on the interaction of the nurse with the patients and then classifying them based on the severity of the disease. They used the Fuzzy AHP algorithm and Multi-Attribute Utility Theory (MAUT) to rank patients according to their attributes including chief presenting complaint, age, sex, pain intensity and vital signs. Also, this algorithm has been applied to a sample of clinical data set from Susquehanna Health's William Sport. In addition, Chang (2014) also presented a scientific and systematic framework based on the concepts of fuzzy sets and using the VIKOR method to evaluate the quality of hospital services under conditions of uncertainty. By reviewing previous research, we find that none of them have focused on the evaluation of ESI triage systems in dynamic conditions, while considering the necessity of prioritizing patients and its widespread use in emergency departments, the need to conduct such a study is strongly felt. Therefore, according to this need and gap, the main contribution of this paper in the literature will be the use of the fuzzy VIKOR method in the dynamic environment of American 5-level triage (ESI).

3. MATERIAL AND METHODS

3.1. VIKOR Method

Opricovic and Tzeng (2004) developed the VIKOR method for optimizing MCDM problems in complex systems. This method focuses on ranking and selecting from a set of alternatives and determines compromise solutions to the problem with conflicting attributes, so that it is able to help decision makers to reach a final decision. Following previous research, Opricovic and Tzeng (2007) presented an extension of the VIKOR method to solve decision problems with conflicting and disproportional criteria (different measurement units). In this paper, the combination of the VIKOR method with the theory of fuzzy sets and linguistic variables is used to overcome the uncertainty in the ranking of alternatives. In addition, the group opinions of the decision-makers are used in such a way that the weights of the importance of each of the decision-makers in the final choice are different.

3.2. Triangular Fuzzy Numbers & Linguistic Variables

The basic theory of triangular fuzzy numbers is described by Dubois (1980), Klir and Folger (1988), and Klir and Yuan (1995), where a fuzzy number is considered as a normalized and convex fuzzy set. The triangular fuzzy number $\tilde{n}$ is represented as a triplet set $\tilde{n} = (n_1, n_2, n_3)$ and shown as in Figure 2.

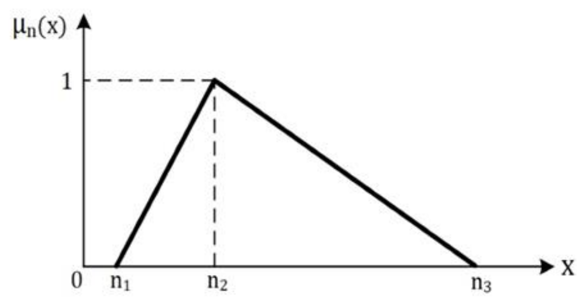

Figure 2. View of triangular fuzzy number $\tilde{n}$ (Chen, 2000)

The membership function of triangular fuzzy numbers is defined as Equation 1:

$$\mu_{\tilde{n}}(x) = \begin{cases} \dfrac{x - n_1}{n_2 - n_1} & , \quad n_1 \le x \le n_2 \\ \dfrac{x - n_3}{n_2 - n_3} & , \quad n_2 \le x \le n_3 \\ 0 & , \quad otherwise \end{cases} \tag{1}$$

Where n_1 and n_3 are the lower and upper limits of the fuzzy number $\tilde{n}$, respectively, and n_2 is the middle limit of $\tilde{n}$. Fuzzy numbers play an important role in quantitatively formulating fuzzy variables, and fuzzy variables can be linguistic variables. Figure 3 shows an example of linguistic variables in fuzzy form. In determining the membership function of linguistic variables, one of the variables is assumed as the base variable and the membership function is determined for it. Then the membership function of other linguistic variables is obtained using special relations based on the base variable.

Each base variable is defined based on physical variables or numerical variables (Zadeh, 1983).

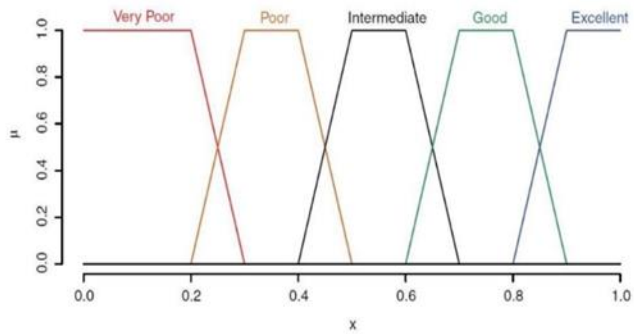

Figure 3. An example of linguistic variables in the form of trapezoidal fuzzy numbers (Zadeh, 1983)

3.3. Proposed Model

In this part, the problem is modeled with the VIKOR method, which is the basis of this research. Appropriate common functions have also been used to calculate scores in modeling. The modeling is the same for the five different levels of triage (ESI) and they differ only in the shared functions. Supposedly, for the first level, which is the level of emergency patients, we have used a stronger sharing function than other levels to calculate scores. In the fifth level, which is related to outpatients and is more crowded than other levels, weaker sharing functions can be used. Figure 4 shows the dynamic decision-making diagram in the ESI system. The dynamics of the problem is determined using a maintenance policy, which we will talk about later.

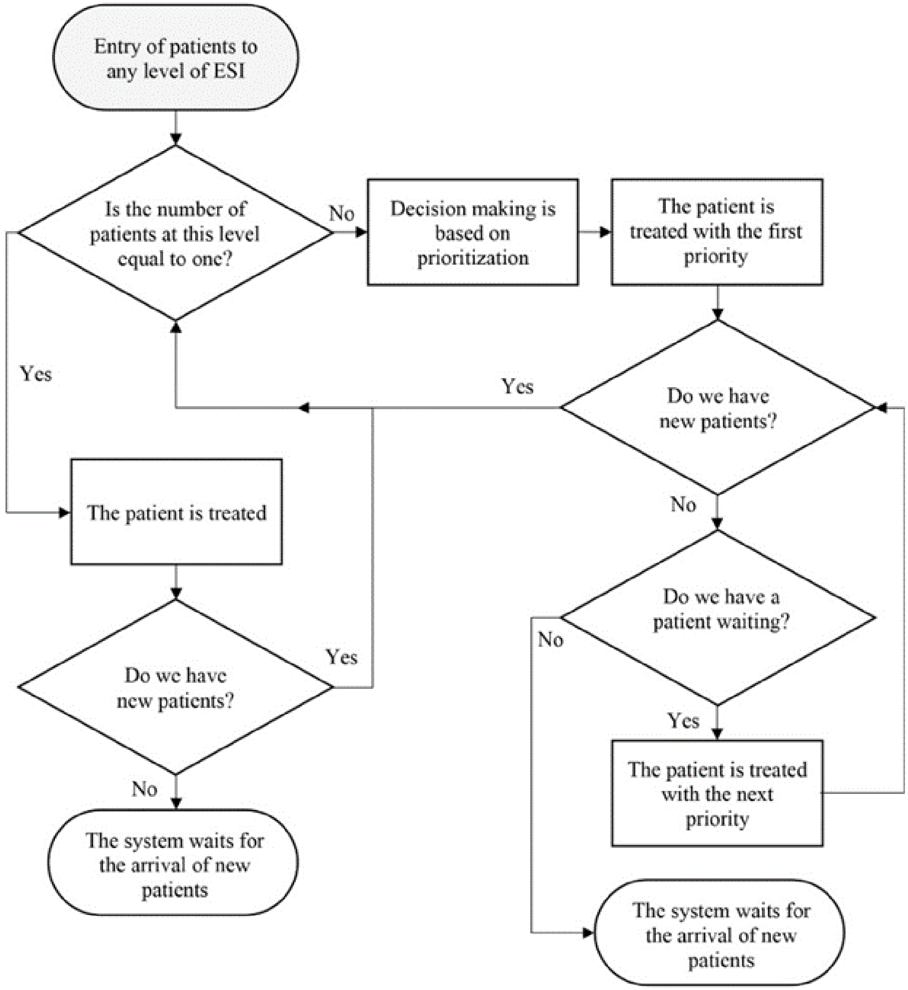

Figure 4. Prioritizing patients according to the dynamic cycle in the ESI system

3.3.1. Symbols Definition

Before stating the proposed model, we will introduce the symbols and some policies considered in it:

P_t: The set of patients available at the moment t
C_t: The set of criteria available at moment t
$\widetilde{W}_c$: Weight vector of criteria (considered as fuzzy numbers)
t_{ij}: The time of entering the ith patient from the jth level for treatment ($j = 1, 2, 3, 4, 5$)
p_{ij}: Patient i of the level j ($j = 1, 2, 3, 4, 5$)
t_n: Time of next patient arrival (new arrival)
H_t: The set kept to the next iteration in the tth iteration
U_t: The performance function in the tth iteration
R_t: Ranking of alternatives in the tth iteration in the first stage of decision-making (VIKOR method ranking)
E_t: Evaluation function in the tth iteration
O_t: Ranking of the alternatives in the tth iteration in the second stage of decision-making (final ranking)

D_E: Shared function considered in the second stage of decision making

3.3.2. Maintenance Policy

Because the current research model is implemented in a dynamic environment, it is necessary to define a maintenance policy. That is, a criterion for selecting a subset of current and past alternatives that are taken to the next iteration. The set maintained by the next iteration can be defined in different ways. One of these definitions is given in Equation 2:

$$H_t = \begin{cases} p_{ij} \notin H & , \quad if \ : \ t_{ij} \leq t_n \\ p_{ij} \in H & , \ otherwise \end{cases} \tag{2}$$

Where t_{ij} is the time of entry of the ith patient from the jth level (the level means the same 5 levels of ESI triage) for treatment and t_n is the time of arrival of a new patient. As long as t_{ij} is smaller than t_n, the patient p_{ij} is directed for treatment, otherwise, it will be a member of the maintained set and will be evaluated again for prioritization with new patients. According to the above definition, the patients who were not treated in the tth iteration will be members of the H set in the $(t + 1)$th iteration.

3.3.3. Dynamic Decision-Making Process

In this research, the end is not considered for the decision-making process. It means that the patient can enter the emergency department at any moment. So, the system will always be in a decision cycle. Usually, the task of prioritization is carried out by an experienced triage nurse. The iterations consist of two main stages, which can be seen in Figure 5.

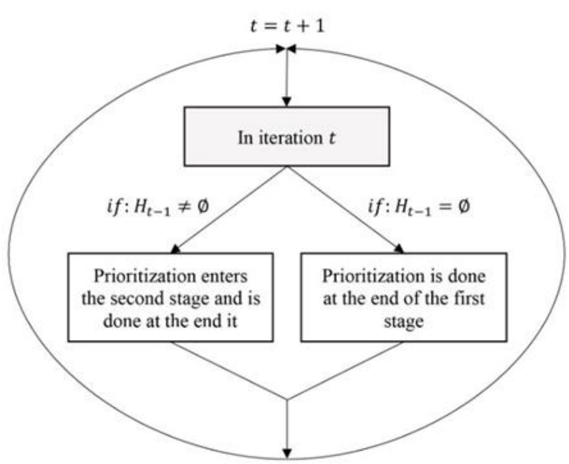

Figure 5. The cycle of iterations in the dynamic decision-making process

t stands for iterations in the dynamic decision process. In each iteration, the first stage is performed first. Then, if the maintenance set is empty in the previous iteration, prioritization is formed at the end of the first stage. Otherwise (if the maintenance set is not empty in the previous iteration), we enter the second stage and then perform the prioritization. Now, according to the above definitions and Figure 5, we describe the dynamic decision-making process. The first stage consists of 7 steps:

- Step 1: In this step, the decision-maker must express his opinion about the patients according to the measures that have been specified in advance and assign a score to the patient according to the tables in step 2. It should be noted that the evaluation criteria must also be specified in advance.
- Step 2: In this step, we convert the qualitative variables selected in the previous step into quantitative variables using the following tables. Using Table 1, the importance of the weight of each criterion can be converted into quantitative variables in the fuzzy environment.

Table 1. Linguistic labels for the weight importance of each criterion

Linguistic labels	Fuzzy equivalent
Very low	$(0, 0, 0.1)$
Low	$(0, 0.1, 0.3)$
Medium low	$(0.1, 0.3, 0.5)$
Medium	$(0.3, 0.5, 0.7)$
Medium high	$(0.5, 0.7, 0.9)$
high	$(0.7, 0.9, 1)$
Very high	$(0.9, 1, 1)$

Blood pressure, respiration, temperature and pulse ranges are different for different ages (Stewart, 2003). By using Tables 2 to 7, the qualitative variables of the alternatives can be converted into quantitative variables in the fuzzy environment.

Table 2. Linguistic labels for ranking alternatives based on measures of blood pressure and respiratory status

Linguistic labels	Linguistic variables in short	Fuzzy equivalent
Normal	N	$(0, 1, 3)$
Low	L	$(1, 3, 5)$
Medium low and Medium high	$ML - MH$	$(3, 5, 7)$
Low and High	$L - H$	$(5, 7, 9)$
Very low and very high	$VL - VH$	$(7, 9, 10)$

Table 3. Linguistic labels for ranking alternatives based on degree of consciousness criteria

Linguistic labels	Linguistic variables in short	Fuzzy equivalent
Very low	VL	$(0, 1, 3)$
Low	L	$(1, 3, 5)$
Medium	M	$(3, 5, 7)$
High	H	$(5, 7, 9)$
Very High	VH	$(7, 9, 10)$

Table 4. Explanation of linguistic labels based on the level of consciousness

Level of consciousness	Description
Alert	The patient is fully awake.

Pain & Voice	The patient responds to sound or painful stimulation.
Voice	The patient's eyes open while talking.
Pain	The patient does not respond to sound stimulation but responds to painful stimulation.
Unresponsive	The patient is unresponsive and does not respond to sound or painful stimulation.

Table 5. Linguistic labels for ranking alternatives based on criteria of pain intensity and required patient actions

Linguistic labels	Linguistic variables in short	Fuzzy equivalent
Alert	A	$(0,1,3)$
Pain & Voice	$P-V$	$(1,3,5)$
Voice	V	$(3,5,7)$
Pain	P	$(5,7,9)$
Unresponsive	U	$(7,9,10)$

Table 6. Linguistic labels for ranking alternatives based on fracture degree criteria

Linguistic labels	Linguistic variables in short	Fuzzy equivalent
Degree 0	D_0	$(0,1,3)$
Degree 1	D_1	$(1,3,5)$
Degree 2	D_2	$(3,5,7)$
Degree 3	D_3	$(5,7,9)$
Degree 4	D_4	$(7,9,10)$

Table 7. Explanation of linguistic labels based on the criterion of degree of fracture

Degree of fracture	Description
Degree 0	Fracture can be seen only as a crack.
Degree 1	Despite the fracture, the skin remains healthy and does not get injured.
Degree 2	A fracture causes the skin to tear, but it is not associated with a wound.
Degree 3	A fracture causes the skin to tear, but it is associated with a wound.
Degree 4	A fracture causes damage to other organs such as veins and nerves.

- Step 3: According to the previous two steps, the weight matrix of the criteria and the fuzzy decision matrix are in the form of Equation 3:

$$\widetilde{W}_c = \{\widetilde{w}_1, \widetilde{w}_2, \widetilde{w}_3, \dots, \widetilde{w}_n\} \quad \approx \quad \forall\, \widetilde{W}_i = (\widetilde{w}_{i1}, \widetilde{w}_{i2}, \widetilde{w}_{i3}) \tag{3}$$

Where $\widetilde{W}_c$ is the weight of the nth criterion in the form of a triangular fuzzy number, and the elements of the decision-making matrix in Equation 4 are also triangular fuzzy numbers:

$$\widetilde{D}_t = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad \Longrightarrow \quad \forall\, \tilde{x}_{ij} = (\tilde{a}_{ij}, \tilde{b}_{ij}, c_{ij}) \tag{4}$$

$\tilde{x}_{mn}$ is the *m*th alternative score according to the *n*th criterion.

- Step 4: In this step, the largest and smallest number of each column is determined from Equation 5:

$$\tilde{f}^{*} = \max_i\{x_{ij}\} \quad , \quad \tilde{f}^{-} = \min_i\{x_{ij}\} \tag{5}$$

- Step 5: Average level of regret (S) and maximum regret (R) for each patient are calculated from Equation 6:

$$S_i = \sum_{j}^{n}\left(w_j \times \frac{(f_j^{*} - f_{ij})}{(f_j^{*} - f_j^{-})}\right) \quad , \quad R_i = Max_j\left(w_j \times \frac{(f_j^{*} - f_{ij})}{(f_j^{*} - f_j^{-})}\right) \tag{6}$$

Where S_i represents the relative distance of the ith alternative from the positive ideal solution (the best combination) and R_i represents the maximum regret of the ith alternative from the positive ideal solution.

- Step 6: Now, for the final evaluation of patients, the VIKOR index (Q) is calculated from Equation 7:

$$Q_i = \left(\nu \times \frac{(S^{*} - S_i)}{(S^{*} - S^{-})}\right) + \left((1-\nu) \times \frac{(R^{*} - R_i)}{(R^{*} - R^{-})}\right)$$

$$S^{*} = Min\ \{S_i\} \quad , \quad S^{-} = Max\ \{S_i\}$$

$$R^{*} = Min\ \{R_i\} \quad , \quad R^{-} = Max\ \{R_i\} \tag{7}$$

ν is a number between zero and one and it is usually considered 0.5. The closer the value of ν is to one, it indicates that the decision maker is more interested in using the weighted value of utility and the involvement of all criteria than the maximum utility (Opricovic & Tzeng, 2007).

- Step 7: Any alternative that has a lower value of Q_i will have a higher priority for selection. At the end of these 7 steps, an efficiency matrix according to Equation 8 will be obtained and a VIKOR index (Q) will be obtained for each alternative.

$$U_t = \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_m \end{bmatrix} \tag{8}$$

At the end of this stage, the set H_{t-1} is decisive. If the set H_{t-1} is empty, the evaluation function for each patient will be equal to the efficiency function of that patient. By defining the evaluation function, the ranking (R_t) is created and the maintained collection is also determined in the next iteration (H_t). If the set H_{t-1} is not empty, we go to the second step.

At this step, due to the fact that the maintenance set is not empty, we use Equation 9 to calculate the evaluation function:

$$E_t(p) = \begin{cases} U_t(p) & , p \in P_t \\ D_E\big(E_{t-1}\ (p)\,, U_t(p)\big) & , p \in H_{t-1} \end{cases} \tag{9}$$

Where if the patient is a member of the P_t set and not a member of the H_{t-1} set, the same efficiency function is used to calculate the evaluation function, and if the patient is a member of the H_{t-1} set, we will use the shared function D_E. In order to calculate the shared function D_E, we have described various functions from the family of t-norms as follows (Equation 10 to 15). t-norms are introduced as an operator to combine distribution functions on statistical metric spaces (Schweizer & Sklar, 2005).

Each of these functions has its own characteristics, but their common characteristic is that they are a reduction function. The function of Equation 10 is the weakest, and the function of Equation 15 is the strongest. In the numerical example section, it is explained which common function will be suitable for which level.

$$Minimum: \quad D_E\left(E_{t-1}(p), U_t(p)\right) = min\{E_{t-1}(p), U_t(p)\} \tag{10}$$

$$Product: \quad D_E\left(E_{t-1}(p), U_t(p)\right) = E_{t-1}(p) \,.\, U_t(p) \tag{11}$$

$$Lukasiewicz: \quad D_E\left(E_{t-1}(p), U_t(p)\right) = \max\{0, E_{t-1}(p) + U_t(p) - 1\} \tag{12}$$

$Nilpotent\ Minimum:$

$$D_E\left(E_{t-1}(p), U_t(p)\right) = \begin{cases} \min\{E_{t-1}(p), U_t(p)\} & , \quad E_{t-1}(p) + U_t(p) > 1 \\ 0 & , \quad \text{otherwise} \end{cases} \tag{13}$$

$Hamacher\ Product:$

$$D_E\left(E_{t-1}(p), U_t(p)\right) = \begin{cases} 0 & , E_{t-1}(p) = U_t(p) = 0 \\ \dfrac{E_{t-1}(p) \,.\, U_t(p)}{E_{t-1}(p) + U_t(p) - E_{t-1}(p) \,.\, U_t(p)} & , otherwise \end{cases} \tag{14}$$

$$Drastic\ Product: \quad D_E\left(E_{t-1}(p), U_t(p)\right) = \begin{cases} E_{t-1}(p) & , \quad U_t(p) = 1 \\ U_t(p) & , \quad E_{t-1}(p) = 1 \\ 0 & , \quad otherwise \end{cases} \tag{15}$$

Now, with the evaluation function specified, we rank the alternatives and determine the retention set for the next iteration. Figure 6 shows a summary of the important steps in the decision-making process.

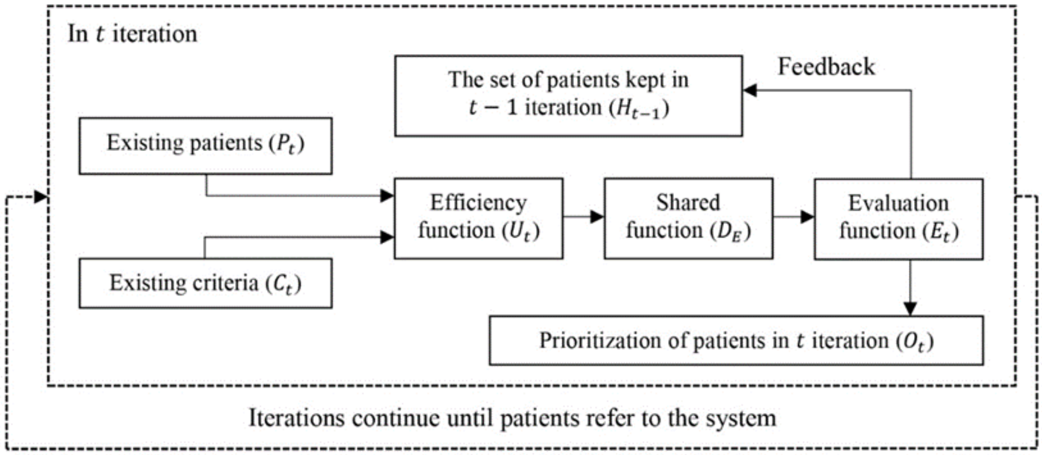

Figure 6. Operations performed in each iteration in the dynamic decision model

4. RESEARCH IMPLEMENTATION IN CASE STUDY

The investigation of this research is related to the prioritization of patients who visit the emergency department on a normal day. This problem is implemented in the Excel environment and prioritizes patients in each iteration. Patients of one of the ESI triage levels are considered and prioritized. Also, when prioritizing patients, the shared functions mentioned in the previous section are also compared and the best function is selected for the proposed model. The assumptions of the model are as follows:

- The arrival of patients is considered in time intervals. Here, patients are compared and prioritized in 15-minute intervals.
- The number of criteria and their weights can be changed in each iteration.
- Patients' conditions can be changed in each iteration.

The data of 20 studied patients are presented in Table 8. The prioritization of up to four iterations is checked as follows:

First iteration ($t = 1$): At time t_1, four patients have referred to the triage section in the emergency department. To evaluate patients, we have considered four criteria: blood pressure, respiratory status, level of consciousness and pain intensity. The weight of each of the criteria as well as the information related to the patients is given in the form of linguistic labels (triangular fuzzy numbers) in Tables 9 and 10. According to the calculations and prioritization, among the patients, patient P_3 is selected for treatment. It is assumed that no new patient has been referred to the triage system until the completion of the treatment of patient P_3. Therefore, patient P_4 is also treated. Until the completion of the treatment of patient P_4, no new patient has entered the system, so patient P_1 is also directed to the treatment department. During the treatment of patient P_1, two new patients refer to the system. Therefore, the patient with the fourth priority P_2 is considered as a member of the maintained set, and along with these two new patients, prioritization is done again.

Table 8. Data and information of patients in the study department

	Criteria				
	Blood pressure (C_1)	**Respiratory status (C_2)**	**level of consciousness (C_3)**	**Intensity of pain (C_4)**	**Actions required (C_5)**
W_j	H (0.7, 0.9, 1)	VH (0.9,1, 1)	MH (0.5, 0.7, 0.9)	M (0.3, 0.5 0.7)	MH (0.5, 0.7, 0.9)
P_1	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)	(9, 10, 10)	(5, 7, 9)
P_2	(9, 10, 10)	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)	(7, 9, 10)
P_3	(9, 10, 10)	(7, 9, 10)	(5, 7, 9)	(5, 7, 9)	(9, 10, 10)
P_4	(3, 5, 7)	(5, 7, 9)	(3, 5, 7)	(1, 3, 5)	(1, 3, 5)
P_5	(9, 10, 10)	(1, 3, 5)	(5, 7, 9)	(7, 9, 10)	(7, 9, 10)
P_6	(7, 9, 10)	(3, 5, 7)	(1, 3, 5)	(7, 9, 10)	(5, 7, 9)
P_7	(1, 3, 5)	(1, 3, 5)	(0, 1, 3)	(3, 5, 7)	(3, 5, 7)
P_8	(5, 7, 9)	(7, 9, 10)	(5, 7, 9)	(1, 3, 5)	(0, 1, 3)
P_9	(7, 9, 10)	(1, 3, 5)	(3, 5, 7)	(7, 9, 10)	(7, 9, 10)
P_{10}	(1, 3, 5)	(0, 1, 3)	(1, 3, 5)	(5, 7, 9)	(5, 7, 9)
P_{11}	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)	(0, 1, 3)	(3, 5, 7)
P_{12}	(3, 5, 7)	(0, 1, 3)	(1, 3, 5)	(1, 3, 5)	(3, 5, 7)
P_{13}	(1, 3, 5)	(3, 5, 7)	(7, 9, 10)	(5, 7, 9)	(9, 10, 10)
P_{14}	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)	(7, 9, 10)	(7, 9, 10)
P_{15}	(3, 5, 7)	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)	(1, 3, 5)
P_{16}	(1, 3, 5)	(3, 5, 7)	(3, 5, 7)	(9, 10, 10)	(5, 7, 9)
P_{17}	(7, 9, 10)	(1, 3, 5)	(9, 10, 10)	(5, 7, 9)	(0, 1, 3)
P_{18}	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)	(3, 5, 7)	(0, 1, 3)
P_{19}	(7, 9, 10)	(0, 1, 3)	(1, 3, 5)	(7, 9, 10)	(3, 5, 7)
P_{20}	(1, 3, 5)	(7, 9, 10)	(5, 7, 9)	(9, 10, 10)	(5, 7, 9)

Table 9. Fuzzy weight values of criteria and patients' information in the first iteration

	C_1	C_2	C_3	C_4
W_j	H (0.7, 0.9, 1)	VH (0.9,1, 1)	MH (0.5, 0.7, 0.9)	M (0.3, 0.5 0.7)
P_1	(1, 3, 5)	(7, 9, 10)	(1, 3, 5)	(5, 7, 9)
P_2	(5, 7, 9)	(3, 5, 7)	(0, 1, 3)	(1, 3, 5)
P_3	(3, 5, 7)	(5, 7, 9)	(3, 5, 7)	(0, 1, 3)
P_4	(7, 9, 10)	(1, 3, 5)	(7, 9, 10)	(9, 10, 10)

Table 10. Prioritizing patients in the first iteration

	S_i	R_i	Q_i	R
P_1	1.319	0.875	0.659	3
P_2	1.744	0.700	0.661	4
P_3	1.408	0.569	0.328	1
P_4	0.775	0.975	0.503	2

Second iteration ($t = 2$): Due to the dynamic nature of the system, a new criterion (C_5: Actions required) has been added to the other criteria. The fuzzy values of criteria weight and patients' information are presented in Table 11 and the prioritization of patients in the second iteration is presented in Table 12.

Table 11. Fuzzy weight values of criteria and patients' information in the second iteration

	C_1	C_2	C_3	C_4	C_5
W_j	H (0.7, 0.9, 1)	VH (0.9,1, 1)	MH (0.5, 0.7, 0.9)	M (0.3, 0.5 0.7)	MH (0.5, 0.7, 0.9)
P_1/P_2	(5, 7, 9)	(3, 5, 7)	(0, 1, 3)	(1, 3, 5)	(5, 7, 9)
P_2	(3, 5, 7)	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)	(1, 3, 5)
P_3	(5, 7, 9)	(1, 3, 5)	(9, 10, 10)	(7, 9, 10)	(7, 9, 10)

Table 12. Prioritizing patients in the second iteration

	S_i	R_i	Q_i	R	E_1	E_2	E_3	E_4	E_5	E_6	O_1	O_2	O_3	O_4	O_5	O_6
P_1	2.361	0.925	0.738	3	0.661	0.488	0.399	0.661	0.535	0	3	2	1	3	2	1
P_2	1.852	0.875	0.479	1	0.479	0.479	0.479	0.479	0.479	0.479	1	1	2	1	1	2
P_3	1.326	1.100	0.607	2	0.607	0.607	0.607	0.607	0.607	0.607	2	3	3	2	3	3

In this iteration, in order to better compare the results, we have used the mentioned six shared functions (Equations 10 to 15, respectively). By using functions one and four, patient P_1 will become a member of the maintained set, and by using functions two, three, five and six, patient P_3 will become a member of the maintained set. According to the obtained results, evaluation functions one and four are not suitable functions for evaluating the most urgent level of the ESI standard, because this level requires a stronger common (descending) function to reduce the VIKOR index (Q) of patients. Patients who have been waiting for previous courses. It is assumed that no new patient will come to the system until the treatment of the patient with the first priority is completed, and two new patients will be admitted during the treatment of the patient with the second priority. Therefore, evaluation functions one and four have been removed, and the patient with the third priority of this iteration (P_3) along with two newly arrived patients will go to the third iteration and will be evaluated using functions two, three, five and six.

The third iteration ($t = 3$): In this iteration, another criterion is added to the criteria of the evaluation system (C_6: Degree of fracture). The fuzzy values of criteria weight and patient information are presented in Table 13 and the prioritization of patients in the third iteration is presented in Table 14.

According to the calculations, using functions two and five, patient P_1 (patient P_3 in the previous iteration) is considered a member of the maintained set, and using functions three and six, patient P_2 is a member of the maintained set. Therefore, due to the reasons stated in the previous section, functions two and five are not suitable functions for evaluation and are removed. Assuming that when treating the patient with the second priority (P_3), we have a newly arrived patient, the patient with the third priority (P_2) goes to the next iteration together with the new patient, and they are evaluated by using functions three and six.

Table 13. Fuzzy weight values of criteria and patients' information in the third iteration

	C_1	C_2	C_3	C_4	C_5	C_6
W_j	H (0.7, 0.9, 1)	VH (0.9,1, 1)	MH (0.5, 0.7, 0.9)	M (0.3, 0.5 0.7)	MH (0.5, 0.7, 0.9)	ML (0.1, 0.3, 0.5)
P_1/P_3	(5, 7, 9)	(1, 3, 5)	(7, 9, 10)	(7, 9, 10)	(7, 9, 10)	(3, 5, 7)
P_2	(7, 9, 10)	(3, 5, 7)	(1, 3, 5)	(7, 9, 10)	(5, 7, 9)	(7, 9, 10)
P_3	(5, 7, 9)	(7, 9, 10)	(3, 5, 7)	(1, 3, 5)	(7, 9, 10)	(0, 1, 3)

Table 14. Prioritizing patients in the third iteration

	S_i	R_i	Q_i	R	E_2	E_3	E_5	E_6	O_2	O_3	O_5	O_6
P_1	2.404	0.925	0.765	3	0.465	0.372	0.512	0	3	1	3	1
P_2	2.359	0.838	0.451	2	0.451	0.451	0.451	0.451	2	3	2	3
P_3	2.230	0.888	0.434	1	0.434	0.434	0.434	0.434	1	2	1	2

The fourth iteration ($t = 4$): According to the dynamics of the system, in this iteration, the weight of the second criterion (respiratory status) and the third criterion (level of consciousness) has decreased compared to the previous period. The fuzzy weight values of criteria and patients' information are presented in Table 15 and the prioritization of patients in the fourth iteration is presented in Table 16.

Table 15. Fuzzy weight values of criteria and patients' information in the fourth iteration

	C_1	C_2	C_3	C_4	C_5	C_6
W_j	H (0.7, 0.9, 1)	MH (0.5, 0.7, 0.9)	M (0.3, 0.5, 0.7)	M (0.3, 0.5 0.7)	MH (0.5, 0.7, 0.9)	ML (0.1, 0.3, 0.5)
P_1/P_2	(7, 9, 10)	(3, 5, 7)	(1, 3, 5)	(7, 9, 10)	(5, 7, 9)	(7, 9, 10)
P_2	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)	(3, 5, 7)	(7, 9, 10)	(1, 3, 5)

Table 16. Prioritizing patients in the fourth iteration

	S_i	R_i	Q_i	R	E_3	E_6	O_3	O_6
P_1	2.766	0.875	0.756	2	0.341	0	2	1
P_2	2.047	0.675	0.244	1	0.244	0.244	1	2

Based on the results obtained from functions three and six, function six is more suitable. Since level one is the most sensitive and urgent level, therefore, the strongest shared function (namely function six) is chosen for evaluating patients. In the next iterations, patients are prioritized and treated using this function. For the way of prioritizing patients at other ESI triage levels, it is possible to use other weaker shared functions that were introduced in the previous section, based on the amount of urgency and the sensitivity of the patients' waiting time. The proposed framework for solving dynamic decision-making problems is implemented as a case study in the Emergency Department (ED) of Edalatian in Mashhad city in Iran. Figure 7 shows the flow process diagram of patients in Edalatian emergency center.

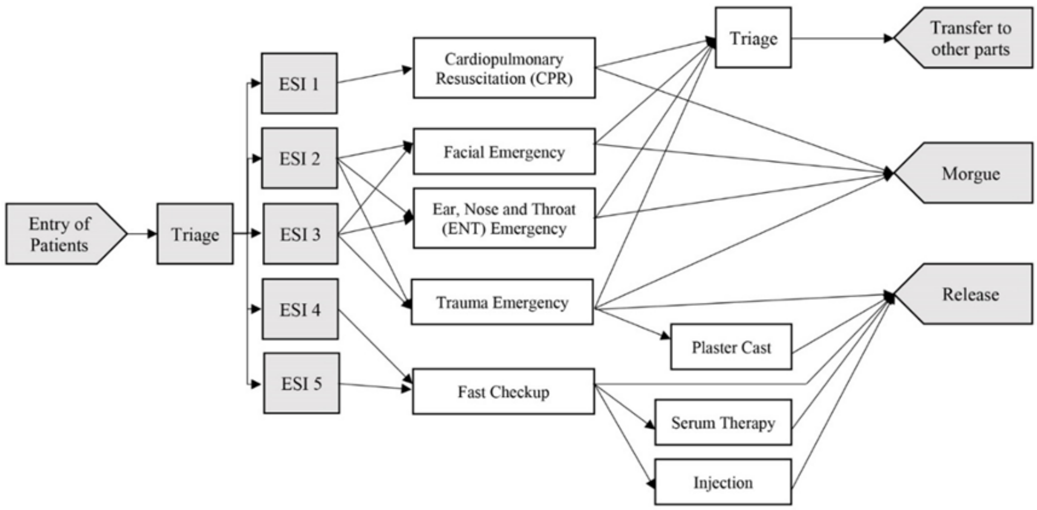

Figure 7. Flow chart of patients in Edalatian emergency center

In order to calculate the waiting time of patients in the normal state and compare it with the state where we use the proposed framework, a computer simulation has been done using Arena software. In order to determine the necessary statistical distributions, information has been collected from the documentation office of the nursing unit of the triage department. This information includes times between patient arrivals as well as service time in different emergency departments for 100 patients. Using the data input analyzer menu in the Arena software, the corresponding statistical distributions have been obtained, which are mentioned below. The process of entering patients has a beta distribution with different parameters for each level, which is presented in Table 17. The distribution of service time to patients in different parts of the emergency department is also presented in Table 18.

Table 17. Statistical distribution of triage levels (Time in minutes)

ESI Levels	Distribution	Description
ESI 1	BETA	$270 + 297 * BETA(0.866, 0.889)$
ESI 2	BETA	$84.5 + 184 * BETA(0.721, 0.785)$
ESI 3	BETA	$64.5 + 57 * BETA(0.955, 0.987)$
ESI 4	BETA	$51 + 39 * BETA(0.931, 0.961)$
ESI 5	BETA	$29 + 46 * BETA(1.08, 1.25)$

Table 18. Statistical distribution of service in different parts of the emergency (Time in minutes)

Part	Distribution	Description
CPR	BETA	$4.5 + 5 * BETA(0.851, 0.952)$
Triage	BETA	$0.5 + 6 * BETA(1.08, 0.977)$
Facial Emergency	BETA	$14.5 + 16 * BETA(1.17, 1.09)$
ENT Emergency	BETA	$20.5 + 16 * BETA(1.09, 1.13)$
Trauma Emergency	BETA	$14.5 + 31 * BETA(1.07, 1.04)$
Plaster Cast	BETA	$12.5 + 9 * BETA(1.09, 1.18)$
Fast Checkup	BETA	$2.5 + 5 * BETA(0.998, 1.06)$
Serum Therapy	BETA	$41.5 + 20 * BETA(0.854, 0.867)$
Injection	BETA	$2.5 + 4 * BETA(1.28, 1.13)$

5. DISCUSSION ON RESULTS

The aim of the simulation performed in this research is to estimate the waiting time of patients in different parts of the emergency department. Here is the Cardiopulmonary Resuscitation (CPR) part for comparison and analysis. The results of the simulation can be seen in Table 19.

Table 19. Arena software outputs

Part of Emergency	Waiting time (minutes)
CPR	12.11
Triage	1.73
Facial Emergency	17.90
ENT Emergency	8.59
Trauma Emergency	14.96
Plaster Cast	4.09
Fast Checkup	24.83
Serum Therapy	0.08
Injection	0.19

As the results show, patients will wait for an average of 12.11 minutes in the CPR part. In the static model where the queue type is FIFO (First In, First Out), the patient who is in serious condition must also wait in the queue and has no priority over other patients in the queue. While in the dynamic model, based on the presented prioritization, critical patients are treated sooner and their waiting time should naturally be reduced compared to the static state. Table 20 shows the average waiting time of patients in the CPR part along with their prioritization.

The first part of the table, which includes the arrival and service times of the patients, is obtained in such a way that we have reduced the simulation execution speed in the Arena software so that these times can be determined. The second part, which is related to iterations and prioritization of patients, is obtained from the implementation of the VIKOR method in Excel software. As it can be seen, decision-making has been done in 15-minute intervals and 9 iterations have occurred, and the output of the program presents 9 priorities. The obtained results show that the average waiting time of patients in the CPR part is 8.31 minutes, which has significantly decreased compared to the static state.

6. CONCLUSION AND FUTURE STUDIES

A proper triage system is a system that can perform the process of prioritizing patients in the best way in the shortest possible time. Although the type of triage system has a special effect on its performance, sometimes even the best systems are confused in prioritization. This is due to the inherent nature of triage. In the real world, the criteria at each decision point of the triage process are unstable and dynamic and can change constantly. If a scientific method for dynamic triage management is not developed, this issue will show its first effect on patients' waiting time.

Table 20. Waiting time (minutes) of patients in CPR part in dynamic mode

Patients	Arrival Time	Start of Service	End of Service	Waiting Time	t_1		t_2		t_3		t_4		t_5		t_6		t_7		t_8		t_9	
					E	O	E	O	E	O	E	O	E	O	E	O	E	O	E	O	E	O
P_1	6:04:22	6:16:01	6:21:03	11:39	0.77	**2**	0.00	**1**														

P_2	6:09:15	6:09:15	6:16:01	0:00	0.23 **1**								
P_3	6:16:29	6:21:03	6:29:40	4:34		0.10 **2**							
P_4	6:21:09	6:36:50	6:42:35	15:41		0.89 **4**	0.00 **1**						
P_5	6:25:50	6:29:40	6:36:50	3:50		0.74 **3**							
P_6	6:34:13	6:42:35	6:48:48	8:22			0.04 **2**						
P_7	6:38:58	6:59:43	7:05:11	20:45			1.00 **4**	0.83 **3**					
P_8	6:43:48	6:48:48	6:53:03	5:00			0.28 **3**	0.00 **1**					
P_9	6:49:24	6:53:03	6:59:43	3:39				0.04 **2**					
P_{10}	6:55:13	7:05:11	7:10:10	9:58				0.91 **4**	0.00 **1**				
P_{11}	7:03:11	7:10:10	7:18:46	6:59					0.08 **2**				
P_{12}	7:08:23	7:29:51	7:35:53	14:46					1.00 **4**	1.00 **3**			
P_{13}	7:14:41	7:18:46	7:23:09	4:05					0.33 **3**	0.00 **1**			
P_{14}	7:18:01	7:23:09	7:29:51	5:00						0.56 **2**			
P_{15}	7:33:01	7:35:53	7:44:54	2:52							0.09 **1**		
P_{16}	7:38:28	7:53:48	8:01:16	15:20							0.84 **3**	0 **1**	
P_{17}	7:44:25	7:44:54	7:53:48	0:29							0.78 **2**		
P_{18}	7:50:54	8:01:16	8:07:33	10:22								0.10 **2**	0.00 **1**
P_{19}	7:57:35	8:15:46	8:20:10	18:11								1.00 **3**	0.99 **3**
P_{20}	8:05:33	8:07:33	8:15:46	2:00									0.32 **2**

Due to the importance of this problem in hospitals, many algorithms have been presented to reduce the waiting time. In the present study, a dynamic algorithm based on MADM techniques and mathematical modeling of the problem was presented in order to prioritize patients in the emergency department. Also, in order to reduce the VIKOR index (Q) values of the patients belonging to the maintenance set, appropriate shared functions were used in the modeling of the problem.

By simulating the Mashhad Edalatian emergency center and estimating the average waiting time, the results of the proposed dynamic model were compared and analyzed with static models. The results showed that the waiting time in the dynamic algorithm was significantly reduced compared to the static algorithm. Therefore, the presented dynamic algorithm has a better capability and ability to reduce waiting time than static algorithms. Considering the extent of the subject of this research, it is suggested for future studies that by using other shared (cumulative) functions, the waiting time in dynamic mode and other static modes should be investigated. Specifically, the ideas that can be considered as future contributions in the literature of this field are as follows:

- Focusing on other types of triage systems and selecting appropriate emergency departments as a case study.
- Using dynamic group decision-making methods with a focus on solving other problems of triage systems such as: Increasing patient satisfaction, proper accommodation for patients, reducing costs.
- Using uncertainty methods (including neutrosophic, grey, probabilistic planning, robust optimization, etc.) for more realistic simulation of triage systems in order to more scientifically match the models with the real world.

Conflicts of Interests

The authors declared that there is no conflict of interest.

Contribution of Authors

The authors involved in this study are Ali Taherinezhad*, Alireza Alinezhad, and Saber Gholami; All authors contributed to the idea, design, resources, data collection, literature review, methods implementation and analysis and interpretation sections of the study.

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Overall Survival Prediction Of NSCLC Using Radiomics And Machine Learning Methods

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Keywords

Cancer, NSCLC, Radiomics, KNN, SVM

Abstract

Cancer is one of the most fatal diseases. Millions of people all around the world die due to this illness as a result of abnormal cell growth. Billions of dollars are spent to cure and analyze it. Non-small cell lung cancer (NSCLC) is the most diagnosed type of lung cancer, which is a trending type of cancer. Accurate prognostic strategies are important for treating cancer patients. By this aim, radiomics is used to diagnose and prognose the disease in a non-invasive, budget-friendly, smart and fast way. In this study, 2-year survival prediction of NSCLC is performed by using radiomics and machine learning methods. Lung CT-scan images belonging to 422 patients retrieved from TCIA public DICOM archive are processed to detect meaningful features using open-source radiomics feature extractor, PyRadiomics. For classification step, K-Nearest Neighbor (KNN) and Support Vector Machines (SVM), Random Forest (RF) and Neural Network (NN) classifier methods are utilized with 10-fold cross validation. To achieve the best performance, the hyperparameters of machine learning methods are tuned using grid search method. Experimental results present that the NN achieves the best performance with an AUC score of 0.87, an accuracy of 0.81, a recall of 0.79 and an F-measure of 0.76.

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1. INTRODUCTION

Lung cancer is one of the most severe and common diseases in the world. 2-year average survival predictions of stage-1, stage-2 and stage-3 lung cancer are %70, %45 and %10-30, respectively (R. L. Siegel , 2018). Lung cancer has two types of tumors, NSCLC and SCLC having 80-85% and 15- 20% frequency, respectively (Baek et al, 2019). The most frequent types of NSCLC are adenocarcinoma, squamous cell carcinoma and large cell carcinoma having frequency of %40, %30 and %15 respectively. The major causes of the illness are irregular lifestyle, e.g. lack of exercise, alcohol, diet, obesity; exposure to radiation; exposure

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to chemical agents, e.g. smoking, exposure to dangerous gases; genetic tendency. Staging is vital for cancers to categorize the tumor. The TNM system is the most used and well-known method to stage tumors. In TNM system, T refers to the size and extent of the main tumor. TX, T1, T2, T3, T4 are stages for sizing main tumor volume. TX means main tumor cannot be measured and the higher the number, larger the tumor. N refers to regional lymph nodes near the main tumor. NX, N1, N2, N3, N4 are stages for regional lymph nodes. NX means nearby lymph nodes cannot be measured and the higher the number, the more lymph node cancerous. M refers to distant metastasis. MX, M0, M1 are stages to distance of cancer. MX means metastasis cannot be measured. M0 means cancer has not spread to other parts of the body. M1 means cancer has spread to other parts of the body. Radiomics is a field of science that utilizes medical images to cultivate quantitative information about tumors. It processes radiological images, extracts, and analyzes quantitative features of a Region of Interest (ROI) to build predictive models to predictive histological results, survival time, staging or fatality of tumor. Processed features are handcrafted features and deep features. Radiomics emerged with the study by Aerts et al. in which they built prognostic model for lung and head & neck cancer by utilizing LUNG1 dataset in TCIA archive.

LUNG1 dataset is a collection of medical images. It has 52073 CT scan images of 422 patients having NSCLC. This dataset includes both DICOM images and segmentation volume performed by experienced radiologists. It includes not only DICOM and segmentation data, but also clinical data including tumor stages, patient age, survival time. There are many studies utilizing LUNG1 public dataset. One of such studies is done by Parmar et al (Parmar et al., 2015). They utilized fourteen feature selection methods and twelve classification methods on 440 features of 464 lung cancer patients. They compared all methods based on performance. They found that Wilcoxon test-based feature selection and random forest-based classifier show the best performance. Other study by Parmar et al again utilizes LUNG1 and LUNG2 dataset for training and validation (Parmar et al., 2015). They analyzed Head & Neck and Lung cancer cohorts. They built consensus clustering maps for features to correlate features. Another study utilized LUNG1 dataset is done by Wu et al (Wu et al., 2016). They classified tumor histologic subtypes based on extracted 440 features. They utilized 24 feature selection methods and 3 classification methods in their study. The best model shown with the highest performance is Naïve Bayes with AUC of 0.72. In this work, 2-year survival prediction of NSCLC lung cancer patients are predicted via radiomics and machine learning. To obtain more reliable results, 10-fold cross validation is performed. To obtain the best performance from machine learning models, hyperparameter optimization is performed.

This paper comprises of four sections: Introduction, materials and method, results and discussion, conclusion. In the introduction part, introductory information about radiomics and lung cancer is given. The dataset utilized in the study is explained. In the materials method part, the methodology of study is explained. Machine learning methods utilized in the study and techniques to obtain more reliable results and better performance from the models are given. In the results and discussion part, experimental results and discussion on results are given. In conclusion part, inferences about the study is given.

2. MATERIALS AND METHOD

Dataset

The collection used in this study is NSCLC-Radiomics of TCIA archive. It contains 422 non-small lung cancer (NSCLC) patients' lung CT scans. It includes 52073 images of 422 studies. The size of this collection is 33 GB. It includes RTSTRUCT and SEG files that are generated based on manual delineation by a radiation oncologist. This collection is generated in MAASTRO Clinic, The Netherlands. It includes not only segmentation and DICOM images but also clinical data of each patient. For each patient, lung CT scan acquired for radiological purposes and segmentation of Gross Tumor Volume (GTV) region of interest (ROI) are utilized in this work. They used SIEMENS Biograph 40 CT scanner having slice thickness of 3, KVP of 120, convolution kernel of B19f, row and column of 512 by 512, pixel spacing of 0.9765625, allocated bit of 16, window center of 40, -600, window width of 400, 1200, Rescale Intercept value of -1024. Clinical feature instances of LUNG1 dataset are given in the table in Table 1.

Table 1. Histological features of LUNG1

Histology	LUNG1
Adenocarcinoma	16
Large Cell Carcinoma	60
Squamous Cell Carcinoma	54
Total Number of Instance	130

Table 2. Tumor *s*taging of LUNG1

Overall Stage	LUNG1
I	16
II	60
III	54

Radiomics Process

Radiomics workflow is composed of multiple steps. It starts with DICOM imaging and ends with prediction. The workflow of the process is depicted in the Figure 1. Each building block of the process is expressed in detail as below.

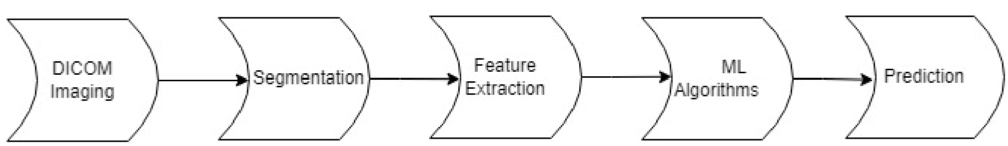

Figure 1. Radiomics workflow

Segmentation

For each instance of the collection segmentation of Gross Tumor Volume (GTV) is drawn by a professional experienced radiotherapist.

Feature extraction

Quantitative knowledge from LUNG1 dataset is extracted from PyRadiomics open-source feature extractor. Extracted features include First-order Statistics, 2D Shape-based, 3D Shape-based, GLCM, GLRM, GLSZM, Neighboring Gray tone difference matrix and GLDM image related features. This extractor can cultivate radiomics features from any imaging modalities, CT, MRI, PET or US. In this work, DICOM images from CT scanner is processed without pre-processing in PyRadiomics 3.0.1.

Machine Learning Algorithms

Radiomics workflow is built which contains successive processing steps in which each output of a step is input of next step. As the fourth step, machine learning algorithms are applied to extracted feature set. In this study, there are four machine learning methods applied to predict 2-year prediction for overall survival of NSCLC lung cancer patients: K-Nearest Neighbor (KNN), Support Vector Machine (SVM), Random Forest (RF) and Neural Network (NN). In order to improve the performance of the models, hyperparameter optimization is performed for the models. The number of Neighbors in KNN, kernel in SVM and max depth in RF are tuned to obtain the best performance. Performance of the models are compared.

3. RESULT AND DISCUSSION

Results obtained from the dataset is given in this part of the paper. LUNG1 data, the dataset utilized in this study, is linearly non-separable. Visualization of dataset is given below. It can be seen that the points of two classes are extremely intertwined. Therefore, to classify the dataset wisely is difficult work. In this study, four classification methods are utilized: KNN, SVM, RF and NN. For each machine learning method, 10-fold cross validation is performed.

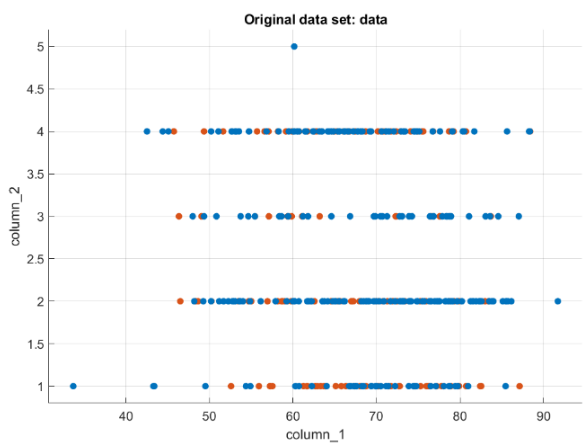

Figure 2. Dataset visualisation

KNN

As a simple algorithm, KNN classification is applied to the dataset. To increase classification performance, hyperparameter tuning is performed to tune the number of neighbors. Confusion matrix, AUC and hyperparameter optimization results are given in Figures 3,4 and respectively.

RF

As another supervised classifier, RF is utilized for classification process. To increase the performance of SVM, max depth is tuned. Confusion matrix, AUC-ROC and hyperparameter optimization results for RF are given in Figures 6,7 and 8 respectively.

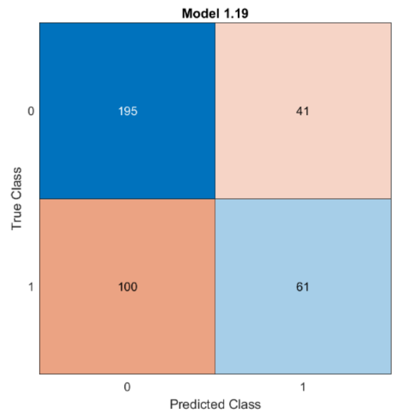

Figure 3. Confusion matrix of KNN

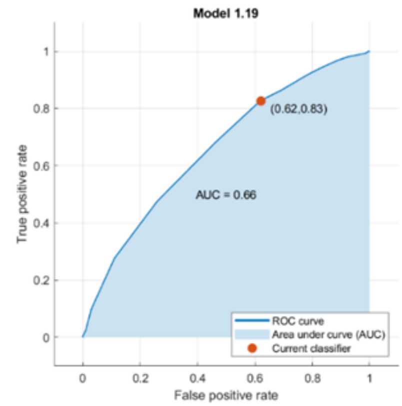

Figure 4. AUC-ROC for KNN

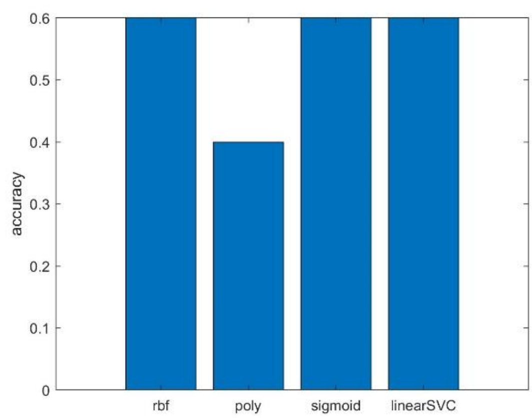

Figure 5. Hyperparameter tuning for SVM

RF

As another supervised classifier, RF is utilized for classification process. To increase the performance of SVM, max depth is tuned. Confusion matrix, AUC-ROC and hyperparameter optimization results for RF are given in Figures 6,7 and 8 respectively.

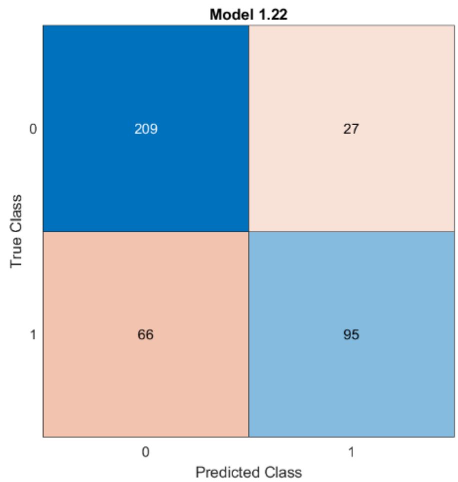

Figure 6. Confusion matrix of RF

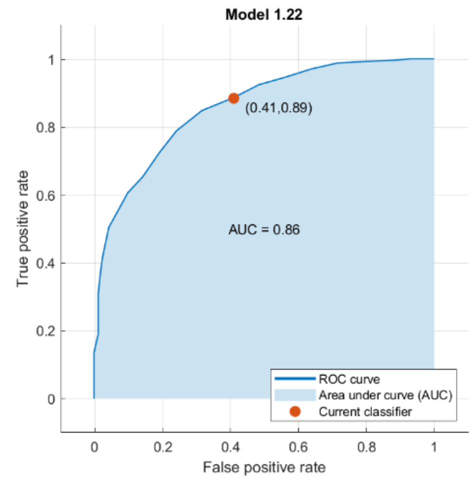

Figure 7. AUC-ROC for RF

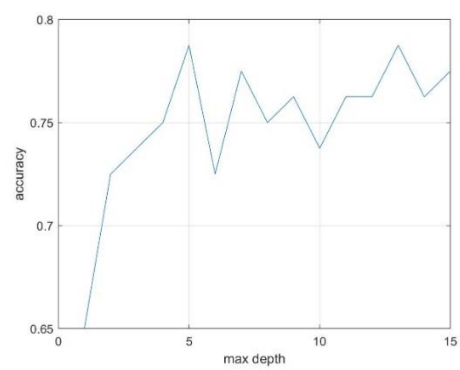

Figure 8. Hyperparameter tuning for RF

SVM

As other supervised classifier, SVM is utilized to classify 2-year overall survival. To increase the performance of SVM, kernel is tuned. Confusion matrix, AUC-ROC and hyperparameter optimization results for RF are given in Figures 9,10 and 11 respectively.

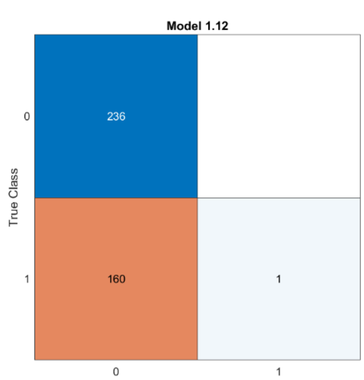

Figure 9. Confusion Matrix of SVM

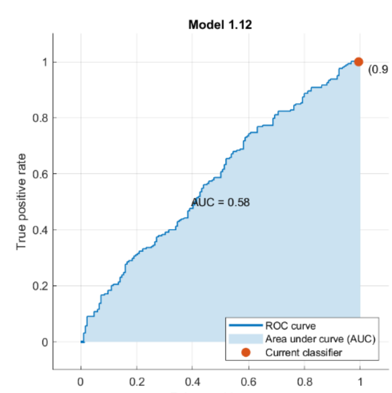

Figure 10. AUC-ROC for SVM

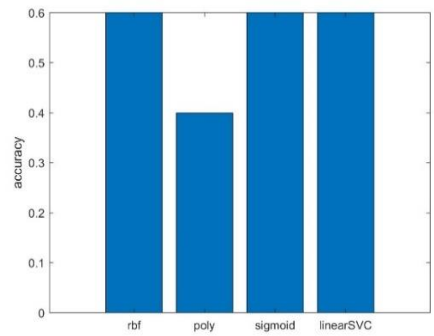

Figure 11. Confusion matrix of SVM

NN

As a next-generation algorithm, NN is utilized for this study. Confusion matrix and AUC-ROC are given in Figure 12 and 13.

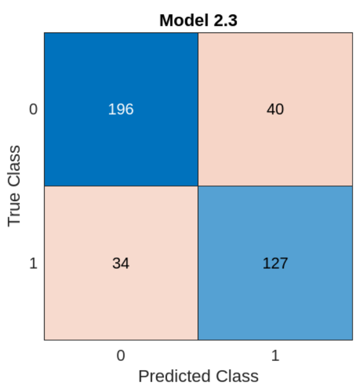

Figure 12. Confusion Matrix of NN

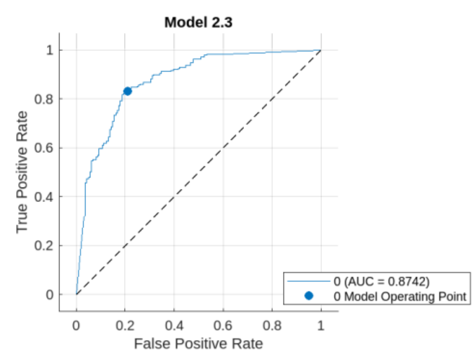

Figure 13. AUC-ROC for NN

To perform a complete performance comparison, classification performance results are tabulated as given in Table 3.

Table 3. Classification performance complete comparison

	KNN	SVM	RF	NN
ACCURACY	0.64	0.6	0.77	**0.81**
SPECIFICITY	0.82	1	0.83	**0.83**
SENSITIVITY	0.38	0.01	0.59	**0.79**

As can be seen from the results, Neural Network shows the best performance compared to methods. Although hyperparameter optimization is performed for KNN, SVM and RF, NN has the best classification performance. This shows that next generation classification algorithms are better than conventional algorithms that are hyper-tuned indeed. To build a correlation matrix for features of the dataset, feature selection is essential for this study.

3. CONCLUSION

To conclude, radiomics is becoming a popular field of study within the Medical Imaging community. Image processing and machine learning skills gain importance. In this paper, various methods and approaches are utilized to predict 2-year overall survival prediction of NSCLC lung cancer patients by using LUNG1 public dataset. PyRadiomics open source radiomics feature extractor is utilized. NN shows the best classification performance compared to other methods. In future work, feature selection algorithms will be used to select primary features in the dataset.

Conflict of Interest
There was no conflict of interest between the authors during the creation of this study. No financial support has been received and there are no conditions that provide financial or personal benefit.

Contribution of Authors
The authors involved in this study are Muhammed Selman Erel*, Hilal Arslan, Esra Şengün Ermeydan, İlyas Çankaya; contributed to all aspects of the study. All authors contributed to the idea, design, inspection, resources, data collection, literature review, critical review and analysis and interpretation sections of the study.

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Benefit And Cost Analysis of Network and Service Connection Renewal In Distribution Systems For Sustainable Water Loss Management

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Keywords
Water distribution network, Network renewal, Cost analysis, Benefit analysis

Abstract
Reducing the rate of non-revenue water (NRW) in water distribution systems (WDSs) has become one of the most important goals for utilities. Increasing water losses bring along social, economic and technical difficulties, which accelerates the work to be done to reduce water losses. Although water losses are managed by applying active and passive leakage methods, in some cases it may not be economical for the utilities to manage the network under current conditions and to continue the efforts to reduce water losses. The aging network and its equipment can now make it difficult to manage this system. In these cases, the method of rehabilitating the whole or partial parts of the network is applied. Due to the high level of pipe material, labor and construction costs, a detailed cost-benefit analysis and alternative solutions should be evaluated before the network renewal approach is preferred. The main purpose of this study is to define the cost benefit structure of the main line and service connection renewal in WDSs. For this aim, current failure rates, the cost components of the operation, maintenance and repair, water supply and energy, initial investment is considered. The current costs and benefits that will be encountered in case of renewal of the entire network (network + service connection), only subscriber lines or only network lines for a sample network are discussed. The results show that it is that the rehabilitation method to be chosen for different network conditions has a serious effect on increasing the planned benefit.

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1. INTRODUCTION

In distribution systems (WDS), leaks are observed at different rates depending on physical, operational, environmental and hydraulic factors (Yilmaz et al., 2022). Depending on the

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malfunction and water losses, the operation of the network deteriorates and service quality decreases. Annual leakage rates in WDSs are between 25 and 30% (EU Commission, 2014), and the non-revenue water ratio is approximately 30% (Liemberger & Wyatt, 2019). A significant part of water resources is lost due to leaks in WDSs. In developed countries, the volume of these leaks is seen to be between 3 and 7% of the water provided, while in developing countries there is more than 50% leakage (Moslehi et al., 2021). In our country, the average water loss ratio is 42% (SUEN, 2020). Preventing and managing physical losses provides significant contributions in terms of water and energy efficiency, postponing the search for new resources, efficient use of energy and water resources, and reducing malfunction repair activities and costs. In the literature, it can be seen that many different methods are generally applied to monitor, prevent and control physical losses. These methods or tools have generally high costs including the equipment and labor, and require technical, technological and personnel infrastructure to be implemented in the field (Lambert et al., 1999; Haider et al., 2019; Salehi et al., 2017; Firat et al., 2021). Dighade et al. (2014) made an evaluation within the framework of the problems faced by developing countries in leakage management, inadequate infrastructure, metering policy, water delivery hours and operation pressure. It was stated that, first of all, the physical and operating characteristics of the existing network should be evaluated. The "network renewal" method, which involves replacing pipes and other fittings in the network and generally costs more than other active leak control methods, is preferred in many cases. However, failure rates under current network conditions, operation, failure repair costs, new resource and energy costs should be taken into consideration, and in case of network renewal, the initial investment and medium and long-term operating costs should be considered (Mamo et al., 2013; Al-Zahrani et al., 2016). Before choosing the network renewal method, a detailed cost-benefit analysis should be made, and alternative solutions should be evaluated. The impact of environmental and operational factors that cause leakage should be reduced. It is emphasized that if the expected benefits cannot be obtained from these methods, determining priority regions in grid renewal will make significant contributions in terms of resource efficiency (Park & Loganathan, 2002; Suribabu & Neelakantan, 2012; Venkatesh, 2012; Mondaca et al., 2015; Francisque et al., 2017). Pipe material management and network renewal should be considered with extending the economic life of pipes and postponing renewals.

Analyzing the factors that cause pipe damage in the network, reducing their effects and identifying the areas where damage occurs despite all prevention methods are important for efficiency. Tee et al. (2014) proposed an operation plan with budget, maintenance and renewal options, and the service life of the network. The best fit renewal option was defined by minimizing the risk of failure and the life cycle cost of the pipe with the help of genetic algorithm. Loganathan et al. (2002) aimed to define an economically sustainable fault rate threshold value for economical operation of the system and management of faults in network management. Maintenance, repair and renewal costs and the inflation rate were considered. There is a significant relationship between pipe diameter and failure rate threshold value. Zangenehmadar (2016) developed an estimation model for analyzing economic life of the pipes in drinking water networks according to the available budget. A statistical model has been proposed to predict the current state of a pipeline. Carriço et al. (2021) presents a MCDA support methodology for the selection and prioritization of the region and network to be rehabilitated in a WDS. It is suggested that before the network renewal and rehabilitation works, the current status of the network should be taken into consideration and a benefit/cost analysis should be carried out. Hu et al. (2021) emphasized that due to rapid urbanization, drinking water networks are often created without planning. For this reason, a very serious planning and project phase should be carried out before the drinking WDS is physically implemented in the field. While the network is applied to the field, the network life is shorter and the operating cost increases due to reasons such as inadequate engineering services, lack of control, and incorrect manufacturing. The main purpose of this study is to define the cost benefit structure of the main line and service connection renewal in WDSs. The current failure rates, the costs of the operation, maintenance and repair, water supply and energy, initial investment is considered. The current costs and benefits that will be encountered in case of renewal of the entire network, only subscriber lines or only mains for a sample network are discussed. The results show that the rehabilitation method to be chosen for different network conditions has a serious effect on increasing the planned benefit.

2. WATER LOSSES and COMPONENTS

Water losses including the real and apparent losses refer to the loss given to the WDS. While some of the water supplied to the system is consumed by legal users, the remaining part constitutes water losses. Water losses cause loss of income for the administration and constitute the most important component of water resource inefficiency. The "standard water balance" was recommended by the International Water Association to determine the amount and rate of water loss (Table 1). Water loss volume is obtained by subtracting the legal consumption volume from the system inlet volume. Apparent losses refer to the water supplied to the system and consumed by legally registered subscribers and/or unregistered users, but for which no fee is collected.

Table 1. IWA standard water balance

<table>
<tr><td rowspan="10">System Input Volume</td><td rowspan="4">Authorized consumption</td><td rowspan="2">Billed authorized consumption</td><td>Billed metered consumption</td><td rowspan="2">Non-revenue water</td></tr>
<tr><td>Billed unmetered consumption</td></tr>
<tr><td rowspan="2">Unbilled authorized consumption</td><td>Unbilled metered consumption</td><td rowspan="8">Revenue water</td></tr>
<tr><td>Unbilled unmetered consumption</td></tr>
<tr><td rowspan="6">Water losses</td><td rowspan="3">Apparent losses</td><td>Illegal consumption</td></tr>
<tr><td>Losses due to meter inaccuracies</td></tr>
<tr><td>Losses due to reading errors</td></tr>
<tr><td rowspan="3">Real losses</td><td>Leakages in transmission and WDSs</td></tr>
<tr><td>Leakages in reservoirs</td></tr>
<tr><td>Leakages in service connections</td></tr>
</table>

Leakages express the volume (m^3/year) of leakage according to failures occurring due to various factors or overflows and cracks in tanks. This component constitutes a significant part of the volumetric water losses. Apparent and real losses are analyzed or estimated based on authorized consumptions and input volumes. In Türkiye, the "Control of Water Loss in Drinking Water Supply and Distribution Systems" regulation was published in 2014. This regulation aims to use water resources more effectively and efficiently and monitor the performance. Basic methods such as pressure management, pipe material management, fault repair speed and quality and active leakage control are applied. Fault repair speed and quality refers to the rapid and high-quality repair of faults after locating reported or unreported faults in WDSs. Repair quality prevents re-occurrence of faults at the point of fault in the future. Material management refers to the processes applied, and the strategy followed to minimize water losses occurring due to pipe material quality in WDSs. Material management includes choosing the most appropriate diameter and type of pipes according to the characteristics of the region, flow rate, and pressure conditions.

3. NETWORK RENEWAL

Network renewal refers to the replacement of network mains serving in WDSs. Since network renewal creates a high cost, it should be implemented as the last solution whenever possible. Valve renewal refers to the replacement of valves that have reached the end of their economic life. Since valve replacement creates costs, creating an asset management strategy and implementing a preventive maintenance program can extend the useful life. Service connection renewal refers to the replacement of subscriber connections serving between the mains and the building. Since a significant part of failures occur in service connections, the quality of materials and workmanship is quite important in the renewal. Network renewal generates high costs, and, it is preferred as a priority in many cases. It is possible to reduce losses by managing networks together with existing failures, operation, repair, new resource and energy costs (Mamo et al., 2013; Al-Zahrani et al., 2016).

Figure 1. Network renewal in the field

The pipe material should be selected by considering the climate and environmental, operating and hydraulic criteria. Since network renewal will result in very high costs for WLM, this method should be the last option. It is seen that the concept of useful life for networks comes to the fore in the literature. One of the important methods followed in determining the useful life is Loganathan et al. (2002). The failure coefficient (Brk) was calculated using the annual inflation rate (R), annual repair cost (C) and the network renewal cost (F). Firstly, the total renewal cost will be calculated. Unit repair costs will be calculated according to pipe diameter and type. The pipe type to be used in the renewal and the average pipe diameter of the existing network should be defined.

Figure 2. Service connection renewal in the field

4. COST BENEFIT ANALYSIS STANDARD AND RESULTS

The benefits and costs to be obtained in cases of renewal of only the mains, renewal of only service lines and renewal of network (service connection + main) were calculated. During these analyses, it was thought that if the entire network was rehabilitated, the loss level would decrease to the "Inevitable Loss" level. If the service connection and the mains are renewed individually, the benefit flow to be obtained when the existing faults are eliminated. Depending on the amount of leakage detected, the total number of faults and the resulting faults were differentiated by network and service connection type. A DMA was selected as study area (Table 2).

Table 2. Main data used for network rehabilitation

#	Parameters	Unit	Value
1	Total Network Length	m	15000
2	Total Number of Subscriber Connections	No.	300
3	Average Night Pressure	m	55
4	Unit Water Cost	TL/m^3	5
5	Annual Breakdown Amount (Service connection)	No.	80
6	Annual Breakdown Amount (Main)	No.	120
7	Average Fault Resolution Time	hour/No.	20
8	Physical Loss Volume	m^3/month	18000
9	Volume of Leakage from Tanks	m^3/month	150
10	Percentage of Ø 150 mm Small Pipe Lengths	%	80

11	Rate of Pipes (Ø 150 mm - 300 mm)	%	10
12	Rate of Pipes (Ø 300 mm - 500 mm)	%	0
13	Rate of Pipes (Ø 500 mm - 700 mm)	%	10
14	Rate of Pipes of Ø 700 mm	%	0

Kayseri is located in the Central Anatolia region. Active leakage control is applied in WDS. The DMAs were applied in the field. The data monitoring system are regularly worked. The network data, failure and customers are obtained. In network renewal costs, basic costs for different pipe types for different pipe diameters were considered and the rehabilitation costs were calculated (Tables 3 and 4). The failure rate of mains is approximately 38% (Nicolini et al., 2014; Aydoğdu & Fırat, 2015; Boztaş et al., 2019). In network renewal costs, basic costs for different pipe types for different pipe diameters were considered.

Table 3. Network rehabilitation benefit cost data

#	Parameters	Unit	Value
BM13a	Pipe Smaller than Ø150 mm in Network for PVC Pipe	TL/m	₺185,00
BM13b	Pipe Between Ø150 - Ø300 mm in Network for PVC Pipe	TL/m	₺580,00
BM13c	Pipe Between Ø300 - Ø500 mm in Network for PVC Pipe	TL/m	₺1.000,00
BM13d	Pipe Between Ø500 - Ø700 mm in Network for PVC Pipe	TL/m	₺1.600,00
BM13e	Pipe Larger than Ø700mm in Network for PVC Pipe	TL/m	₺2.250,00
BM14a	Pipe Smaller than Ø150 mm in the Network for Ductile Pipe	TL/m	₺420,00
BM14b	Pipe between Ø150-Ø300 mm in network for Ductile pipe	TL/m	₺775,00
BM14c	Pipe between Ø300 - Ø500 mm in Network for Ductile Pipe	TL/m	₺1.400,00
BM14d	Pipe between Ø500 - Ø700 mm in Network for Ductile Pipe	TL/m	₺2.100,00
BM14e	Pipes greater than Ø700mm in the Network for Ductile Pipe	TL/m	₺2.950,00
BM15a	Pipe Smaller than Ø150 mm in Network for HDPE Pipe	TL/m	₺210,00
BM15b	Pipe Between Ø150 - Ø300 mm in Network for HDPE Pipe	TL/m	₺610,00
BM15c	Pipe Between Ø300 - Ø500 mm in Network for HDPE Pipe	TL/m	₺1.100,00
BM15d	Pipe Between Ø500 - Ø700 mm in Network for HDPE Pipe	TL/m	₺1.600,00
BM15e	Pipe Larger than Ø700mm in Network for HDPE Pipe	TL/m	₺2.500,00
BM16a	Pipes Less than Ø150 mm in Network for Steel Pipe	TL/m	₺360,00
BM16b	Pipe Between Ø150 - Ø300 mm in Network for Steel Pipe	TL/m	₺720,00
BM16c	Pipe Between Ø300 - Ø500 mm in Network for Steel Pipe	TL/m	₺1.250,00
BM16d	Pipe Between Ø500 - Ø700 mm in Network for Steel Pipe	TL/m	₺190,00
BM16e	Pipes Greater than Ø700mm in Network for Steel Pipe	TL/m	₺2.750,00
BM17	Service connection	TL/No.	₺8.000,00

Table 4. Benefit cost calculation results

Parameters	Current	Main renewal	Service connection renewal	Main + Service connection renewal
Real loss volume (m^3/month)	18000	18000	18000	18000
Saved volume (m^3/month)	0	9105	2164	11269
Final Status (m^3/month)	18000	8895	15836	6731
Cost (TL/year)	₺0,00	₺870.000	₺88.000	₺958.000
Cost Reduction (TL/year)	₺0,00	₺546.300	₺129.840	₺676.140

+ / - (TL/year)	₺0,00	-₺323.700	₺41.840	-₺281.860

5. DISCUSSION

There is currently a monthly water loss of 18,000 cubic meters. It is seen that 9105 cubic meters of water can be obtained if the entire network is changed. The cost of this method is lower than the profit to be obtained. Therefore, it should not be preferred. It was seen that 2164 cubic meters of water would be saved if only the service connection lines were renewed. This method may be preferred because its cost is lower than its benefits. It is seen that if the entire water line is replaced, 11269 cubic meters of water will be saved. However, the cost of this method is lower than its gain. Therefore, it should not be preferred. Many variables such as the current network status, fault status, network lengths and number of subscribers are very important in the work to be done to reduce water losses. For this reason, it has been observed that the rehabilitation method to be chosen for different network conditions in water loss reduction studies has a serious impact on increasing the planned benefit.

6. CONCLUSIONS

In Turkey, utilities have become obliged to reduce the NRW rate to a maximum of 30% by 2023 and to a maximum of 25% by 2028. The average water loss of utilities is 40%. It is understood that the average may be much higher in the remaining provinces. Combating water losses in WDSs is of serious importance. Considering that all networks have their own characteristics and the countries they are connected to have different economic criteria, it will be seen that the economic leakage level is different for each network. For this reason, utilities need to manage the leakages by considering the current status of the networks. The methods to prevent water losses should be well understood. While every method to be used to reduce water losses will incur costs, it will also provide various benefits depending on the current status and characteristics of the network. Analysis and evaluations in detail should be made within the framework of economic components for the basic methods applied in leakage management in future studies.

However, considering both the costs of water loss reduction methods and their relationships with each other, the possible benefits to be obtained must be calculated before implementation. If the current network conditions are maintained, current failure rates, operation, repair costs, new water resource and energy costs, initial investment and medium and long-term operating costs in case of network renewal should be considered. Since pipe material, labor and construction costs are at very high levels, a detailed cost-benefit analysis must be made, and alternatives should be evaluated. The current characteristics of the network and factors that cause damage to the pipe should be analyzed.

Conflict of Interest

Authors declare that there is no conflict of interest.

Contribution of Authors

The authors involved in this study contributed to all the aspects of the study.

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Multi-Depot Vehicle Routing Problem with Drone Collaboration in Humanitarian Logistics

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Keywords

Drone-Truck Collaboration, Humanitarian Logistics, Multi-Depot Vehicle Routing Problem, Perishable Commodities

Abstract

Routing problems are used in many areas to obtain the most appropriate results in terms of time and cost. An attempt is made to address the issue by formulating mathematical models that incorporate multiple variables such as capacity, time, cost, and demand, tailored to the specific area of application. Natural disasters are one of these applications. In natural disasters, especially time management is a critical issue. For this reason, routing models play a crucial role in delivering aid to disaster victims and transporting disaster victims to hospitals. In this study, a mathematical model is proposed to be applied in post-disaster humanitarian aid logistics. The model, which aims to minimize the total distribution time, also considers the distribution of perishable commodities. Drones are integrated into this operational framework to facilitate the dissemination of perishable commodities. Thus, a new mathematical model for the multi-depot vehicle routing problem (MDVRP), which includes both truck-drone collaboration and perishable commodities, has been introduced to the literature. The proposed model was solved with a data set in the literature using Python software and the results were tested.

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1. INTRODUCTION

Disasters are tragic events that can cause great losses. Many people around the world lost their lives due to natural disasters in their region. When their effects on people and buildings are examined, earthquakes are among the disasters with the most potential impact (Mavrouli et al., 2023). According to EM-DAT (The International data Disaster Database-Center for Research on the Epidemiology of Disaster), 242,000 people lost their lives in the 1976 China earthquake, 222,570 in the 210 Haiti earthquake and 165,708 in the 2004 Indonesia earthquake.

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As a result of the tsunami disaster in the Indian Ocean, the number of people who died in the Indonesian earthquake increased to 226,408. Recently, 50,783 people lost their lives as a result of the earthquake that occurred in Turkey on February 6, 2023 (Walika et al., 2023). One of the vital points that increases the magnitude of the effects of disasters such as earthquakes is the distribution of humanitarian aid after the earthquake. Lack of supplies that do not arrive on time may increase the effects of the disaster by causing people to survive the disaster but die afterwards. Therefore, the post-disaster supply chain is very important to reduce post-disaster deaths and prevent the suffering of disaster victims from increasing (Diabat, Jabbarzadeh & Khosrojerdi, 2019). There are many difficulties in carrying out post-disaster humanitarian aid logistics activities. One of these difficulties is that blood and some food materials spoil in a short time. Considering the importance and perishability of these foods, the distribution of such perishable commodities becomes a vital issue (Rashidzadeh et al., 2021)

Routing is one of the most important parts of post-disaster humanitarian logistics. Routing is vital to manage the process and reduce distribution time. For this reason, many academic studies have been conducted on the delivery of supplies to disaster victims as soon as possible, including routing the distance between need points and warehouses. However, when the studies are examined, it is understood that there is a gap in the literature for a situation that includes multi-depot truck-drone collaboration in post-disaster humanitarian relief logistics and also takes perishable commodities into consideration. The aim of this study is to deliver the products to the disaster victims in the most effective way with truck-drone collaboration in vital post-disaster logistics. With a different perspective from the literature, a mathematical model is developed for the multi-depot vehicle routing problem with drones, which includes the safe delivery of perishable products to disaster victims. The mathematical model that had been developed was evaluated on the case study using Python software.

In this study, the following sections, Section 2, contain the literature that has been investigated. In the third section, the problem definition and the mathematical model that has been provided are presented. Testing the model with the illustrated case is covered in Section 4. The limitations of the study are discussed in Section 5, along with a conclusion section that discusses potential research subjects.

2. LITERATURE REVIEW

Vehicle routing problem (VRP), one of the most important problems in the field of disaster management, is delivery nodes starting from one or more warehouses (Laporte, 1992). The purpose of VRP in humanitarian logistics is to determine the most appropriate routing considering the constraints such as vehicle capacity, number of vehicles, demand and time. It is anticipated that the integration of drones into traditional VRP in humanitarian logistics will maximize immediate distribution. Hence, multi-depot vehicle routing problems with drone are presented in this section.

Stodola & Kutěj (2024) tackle the MDVRP-D in their study. Drones are paired with vehicles to make deliveries from warehouses to customers. They developed a mathematical model for this problem whose objective is to minimize the duration of the entire logistics operation. In addition, Adaptive Node Clustering Ant Colony Optimization with Node Clustering algorithm, a metaheuristic algorithm based on Ant Colony, is proposed as a solution. The multi-depot unmanned aerial vehicle (UAV) routing issue was addressed by Li et al. (2021). They suggested a mathematical model that does not impose restrictions on the depot where UAVs launch and land. The proposed model includes multiple objective functions to minimize the time and number of UAVs on the route. Hybrid large neighborhood search was suggested as a potential remedy. Rathinam & Sengupta (2006) paperwork deals with the issue of path selection for a number of UAVs traveling from various depots to particular terminals and locations. Each UAV starts from a depot and travels to at least one location as part of their proposed solution to the issue. For the multi-depot UAV routing problem, the authors additionally provide a 2-approximation approach and a lower bound algorithm. Manyam et al. (2017) focused on the persistent intelligence, surveillance, and reconnaissance routing problem. Their model aims to optimize the data collection and delivery tasks of multiple UAVs. As a solution methodology, they presented complex computational methods as well as heuristic approaches. Habib, Jamal & Khan (2013) studied a real-time optimization problem for UAV path planning in dynamic situations. They considered this problem as a variant of a multi-depot vehicle routing problem (MDVRP) and proposed a mixed integer linear programming (MILP) model for solving this problem. Kim et al., (2017) studied the distribution of drugs and test kits by drones for patients with chronic diseases who need to go to clinics for routine health examinations in rural areas. They proposed two models for this situation. In the first of these models, they used the closure approach to find the optimal number of drone centers. In the second model, they proposed a MDVRP model that minimizes the operating costs of drones. Haller (2021) worked on two models to optimize the US Marine Corps' use of UAVs. In the first model, the author aimed to find the optimal depot locations for the charging and supply of UAVs. In the second model, author proposed a model for the MDVRP for UAVs by improving a single depot model in the literature. Hamid, Nasiri & Rabbani (2023) worked on optimizing the homemade food delivery process. They used drones and crowdsourcing as two novel approaches for this process. To solve this problem, they developed a multi-warehouse vehicle routing model using transport costs, freshness of the delivered food and delivery date satisfaction as objective functions. Due to the complexity of the problem, they proposed a self-regulating hyper-heuristic method to obtain a solution. This method is based on genetic algorithm and modified particle swarm optimization and includes new selection and mutation mechanisms. Calamoneri, Corò & Mancini (2022) pointed out that autonomous operation of unmanned aerial vehicles (UAVs) is an effective method to identify people in need of assistance in natural disasters. They encourage the use of an interface between computer science, especially sensor networks and Operations Research. In their research, they modelled their topic as a graph theoretic problem called Multi-Depot Multi-Path Vehicle Routing Problem with Total Completion Time minimisation (MDMT-VRP-TCT). They proposed a mixed integer linear programming (MILP) formulation for small instances and developed a heuristic for large instances. Lu et al. (2024) conducted research on an issue aimed at reducing human contact during epidemics and minimizing the involvement of drones in the diagnosis and treatment procedures. The authors of the research utilized a heuristic that combines the single link (S-LINK) algorithm, greedy randomised adaptive search process (GRASP), and genetic algorithm (GA). The authors introduce a novel vehicle routing problem (VRP-mD_ER) that incorporates the usage of drones to minimize collision in specific scenarios. Liu et al. (2024) tackled the difficulties associated with last mile delivery by employing a diverse fleet of drones to transport big packages. Within this system, the primary drone is responsible for transporting heavy and sizable packages, whereas lesser drones are assigned to deliver lightweight and compact products. A two-stage optimization strategy was employed to address this problem. During the initial step, the process of task allocation involves the creation of multi-task allocation schemes. In the subsequent stage, known as single drone route planning, the routes for the drones are selected. The initial phase involves the introduction of a simulated annealing (SA) algorithm, which is subsequently followed by a variable neighborhood descent (VND) algorithm for the routing of the primary drone, and dynamic programming (DP) for the routing of the smaller drones. Tan et al. (2024) conducted research to enhance the efficiency of urban drone delivery operations with a focus on sustainability. This research highlighted the significance of noise optimization in sustainability methods within this domain. Within this particular scenario, a hybrid cost function was formulated by considering both the impact of noise and the length of the path. They suggested a three-stage heuristic technique to optimize this routing strategy. Lichau et al. (2024) conducted a study on the two-stage vehicle routing issue with drones (2E-VRP-D) and introduced a novel cluster partitioning model. This model efficiently enumerates partial routes that correspond to drone movements using a dynamic programming approach. The model was solved using a precise branch-and-cut-and-price approach and a labeling technique. Furthermore, they suggested modifying the well-recognized rounded capacity cuts for the specific problem and use preprocessing techniques to decrease the complexity of the challenge. Bhuiyan et al. (2024) emphasized the capacity of aerial drones to decrease delivery time and energy usage in the transportation of time-sensitive and small items. They examined the issue of optimizing drone deployment for the direct delivery of time-sensitive products. The researchers introduced a novel mixed integer programming model, along with fresh valid inequalities, a new greedy heuristic algorithm, and a Genetic algorithm. These tools aim to assist business owners in efficiently planning and managing their drone fleets by minimizing the fleet size, the need for additional batteries, and the overall energy consumption.

As a result of the research, there are very few studies of the multi-depot vehicle routing problem involving drone collaboration in disaster logistics. In this context, the consideration of the distribution of perishable commodities in drone collaborative studies of the multi-depot vehicle routing problem differs from other studies. Thus, the problem definition and mathematical model proposal of this study contribute to the literature.

3. PROBLEM DEFINITION and FORMULATION

There are numerous obstacles associated with humanitarian logistics following a disaster. The state of roads, uncertainty of demand, spoilage of products, and inaccessible areas for vehicles are among the challenges. Distribution in post-disaster humanitarian logistics is the issue that this study addresses. There is an emphasis on the most rapid and effective delivery of relief supplies, including perishable products, to disaster-affected regions. Transportation is particularly challenging due to road conditions, particularly for perishable product deliveries that require prompt delivery. Currently, drones are the favored method for the distribution of perishable commodities due to their superior speed and immunity to road conditions when compared to trucks.

Figure 1. Problem definition

In this paper, we suggest a mathematical model that accounts for the timely delivery of perishable products to demand points. The problem is regarded as an open form of the multi-depot vehicle routing problem (MDVRP), as illustrated in Figure 1. The classical vehicle routing problem is enhanced by the integration of a drone in the proposed model, which facilitates the cooperation between trucks and drones. The materials to be distributed are divided into 2 groups: other necessities (Type 1) and perishable commodities (Type 2). Type 1 materials include needs such as clothes, blankets, non-perishable products, while type 2 includes needs with the risk of spoilage. The model is designed to guarantee the safe delivery of perishable products and the rapid delivery of all supplies. The assumptions of the problem, which deals with post-disaster humanitarian aid in MDVRP open form for two different product types, are as follows.

- There are sufficient numbers of logistics vehicles and relief supplies in warehouses.
- Distribution points and demands are known.
- Only one product type is in demand at each distribution point.
- Perishable product demands for a single point cannot exceed the maximum drone capacity.
- The fleet of logistics vehicles used in distribution is homogeneous.

3.1 Mathematical Model

In this study, MDVRP-D model is proposed to be implemented in post-disaster humanitarian aid logistics. The notations of the proposed model are as shown in Table 1.

Table 1. Notations of MDVRP-D model

Indices	
i, j	Tasks and depots
v	Fleet of trucks
u	Fleet of drones
d	Depots
p	Product type
QV	Capacity of truck
QU	Capacity of drone
Takeoff	Time for the takeoff of the drone
Landing	Time for the landing of the drone

MF	Maximum flight time
Parameter	
R_{jp}	Demand for product p at point j $(j \in j-d)$
TU_{ij}	The time of reaching from point i to point j by drone
TV_{ij}	The time of reaching from point i to point j by truck
Variables	
S_{iv}	Arbitrary numbers
S_{iu}	Arbitrary numbers
Binary Variables	
X_{ijv}	1, if truck v arrives at point j after leaving point i (I≠j); otherwise, 0
Y_{iju}	1, if drone u arrives at point j after leaving point i (I≠j); otherwise, 0

Objective function (1) minimizes the time it takes logistics vehicles to deliver relief supplies.

$$Min \sum_{i}\sum_{j}\sum_{v}(TV_{ij} * X_{ijv}) + \sum_{i}\sum_{j}\sum_{u}(TU_{ij} * Y_{iju}) \quad (1)$$

Constraint (2-3) ensures the same number of trucks and drones leaving and returning to the depot

$$\sum_{i\in i-d}\sum_{j\in j\cap d} X_{jiv} = \sum_{i\in i-d}\sum_{j\in j\cap d} X_{ijv} \qquad \forall v \quad (2)$$

$$\sum_{i\in i-d}\sum_{j\in j\cap d} Y_{jiu} = \sum_{i\in i-d}\sum_{j\in j\cap d} Y_{iju} \qquad \forall u \quad (3)$$

Constraints (4-5) allow the same truck or drone to leave the depot only once.

$$\sum_{j\in j-d}\sum_{i\in i\cap d} X_{ijv} \leq 1 \qquad \forall v \quad (4)$$

$$\sum_{j\in j-d}\sum_{i\in i\cap d} Y_{iju} \leq 1 \qquad \forall u \quad (5)$$

Constraint (6-7) ensures that there is only one entry into a task by a drone or a truck.

$$\sum_{i}\sum_{v} X_{ijv} + \sum_{i}\sum_{u} Y_{iju} = 1 \qquad \forall j \in j-d, i \neq j \quad (6)$$

$$\sum_{j}\sum_{v} X_{ijv} + \sum_{j}\sum_{u} Y_{iju} = 1 \qquad \forall i \in i-d, i \neq j \quad (7)$$

Constraint (8-9) ensures that the truck or drone entering the same point leaves that node.

$$\sum_{j} X_{ijv} = \sum_{j} X_{jiv} \qquad \forall v, i \in i-d, i \neq j \quad (8)$$

$$\sum_j Y_{iju} = \sum_j Y_{jiu} \qquad \forall u, i \in i-d, i \neq j \quad (9)$$

Constraint (10-11) provides that the payload carried by each truck and each drone along its route does not exceed its capacity.

$$\sum_p \sum_{j\in j-d} \sum_i R_{jp} * X_{ijv} \leq QV \qquad \forall v \qquad (10)$$

$$\sum_p \sum_{j\in j-d} \sum_i R_{jp} * Y_{iju} \leq QU \qquad \forall u \qquad (11)$$

Constraint (12) ensures that perishable commodities can only be delivered by drones.

$$\sum_i \sum_u Y_{iju} = 1 \qquad \forall j \in j-d, i \neq j: eğer\ R_{j2} \neq 0 \quad (12)$$

Constraint (13) ensures that the time required by each drone along its route, including landing and takeoff time, does not exceed the maximum flight time.

$$\sum_{j\in j-d} \sum_{i\in i\cap d} Y_{iju} * \left(TU_{ij} + takeoff\right) + \sum_{j\in j-d} \sum_{i\in i-d} Y_{iju} * \left(TU_{ij} + take-off + landing\right) + \sum_{i\in i-d} \sum_{j\in j\cap d} Y_{iju} * \left(TU_{ij} + landing\right) \leq MF \qquad \forall u \qquad (13)$$

Constraint (14-15) prevents routes that do not start and end at the depot.

$$S_{iv} - S_{jv} + QV * X_{ijv} \leq QV - \sum_p R_{jp} \qquad \forall i \in i-d, j \in j-d, v, i \neq j \quad (14)$$

$$S_{iu} - S_{ju} + QU * Y_{iju} \leq QU - \sum_p R_{jp} \qquad \forall i \in i-d, j \in j-d, u, \neq j, \quad : if\ R_{j1} \leq QU, R_{j2} \leq QU \qquad (15)$$

Constraints (16-17) provide upper and lower bounds for logistic vehicles.

$$\sum_p R_{ip} \leq S_{iv} \leq QV \qquad \forall i, v \qquad (16)$$

$$\sum_p R_{ip} \leq S_{iu} \leq QU \qquad \forall i, u: if\ R_{j1} \leq QU\ and\ R_{j2} \leq QU \quad (17)$$

3.1 Implementation of Case

The proposed model was tested by applying the mathematical model to the case in the article by Song & Ko (2016). As stated in Table 3 from the data with 50 demand points, the data set was made suitable for the developed model by determining temporary warehouses with the p-median method, increasing the amount of demand in the data by 150 times and randomizing the product types at the demand points.

Initially, the p-median approach was employed to identify temporary warehouse locations based on 50 demand points. Subsequently, the model's solution is evaluated using the logistics tools whose features are given in Table 2 and the data set provided in the case study. The results demonstrate the model's efficacy in a comprehensive case study with 50 demand points, since it consistently produces achievable outcomes within the specified time limit. Nevertheless, the approach necessitates the use of a heuristic algorithm to achieve optimal outcomes within a limited timeframe and to generate quicker and more effective solutions when dealing with larger datasets.

Table 2. Features of logistic vehicles

	Capacity (kg)	Max. Flight time (min)	Velocity (km/h)
Truck	800	-	60
Drone	200	30	80

Table 3. Data set taken and organized from the literature

Customer Index	X	Y	Demand (kg)	Product Type	Customer Index	X	Y	Demand (kg)	Product Type
1	1109	1490	60	2	26	3403	1368	225	1
2	2765	2179	75	2	27	2042	699	270	1
3	975	2998	135	1	28	1598	2151	105	1
4	90	842	240	1	29	933	58	15	2
5	938	1208	255	1	30	2792	811	105	1
6	3908	1005	135	1	31	3378	1073	15	2
7	1223	1590	60	2	32	4980	3935	90	1
8	4654	3092	210	1	33	161	1906	75	2
9	2930	208	270	1	34	3293	2871	60	2
10	1675	2458	180	1	35	2763	3169	255	1
11	425	2213	135	1	36	3366	1493	120	1
12	1947	3108	60	2	37	2839	4964	60	2
13	4307	1275	165	1	38	2870	4650	90	1
14	3627	4873	165	1	39	4583	2600	135	1
15	1666	4325	135	1	40	1436	4002	240	1
16	2021	1984	165	1	41	4782	1486	270	1
17	1235	466	225	1	42	23	3866	180	1
18	3437	2020	120	1	43	3030	1489	255	1
19	2480	2877	105	1	44	4092	4156	15	2
20	1898	3563	120	1	45	4020	2598	165	1
21	1126	199	210	1	46	942	691	75	2
22	112	4397	75	2	47	1647	4798	105	2
23	362	1860	90	1	48	4812	1674	210	1
24	1137	2712	150	1	49	4332	3428	270	1
25	1203	1789	240	1	50	4952	2609	240	1

The results obtained from the proposed mathematical model for the multi-depot vehicle routing problem with drone collaboration in post-disaster humanitarian aid logistics demonstrate the applicability of the concept in minimizing the overall distribution time. Table 4 indicates the achievable outcome obtained within a time frame of 10800 seconds utilizing the dataset mentioned in the literature. The routes were established with a combined fleet of 16 logistics vehicles, consisting of 7 trucks and 9 drones. The distribution of humanitarian aid supplies to the designated locations was successfully completed within 377 minutes through the collaborative efforts of trucks and drones. Trucks were mostly employed for delivering large quantities of supplies to demand points, while drones were utilized for swift delivery of perishable commodities to demand points. This collaborative strategy aims to enhance the efficiency of the post-disaster humanitarian aid logistics process by using the benefits of various logistics vehicles.

Table 4. Result of data set

Logistics Vehicles	Routes	Objective Function
Truck	10-24-3-42-40-15; 5-17-21-4-5; 5-23-11-25-28-16-10; 26-48-41-13-6-26; 49-8-50-39-45-49; 26-30-9-27-5; 10-19-35-18-43-26	377 min
Drone	5-33-7-1-5; 26-31-2-34-49; 5-29-46-5;15-20-12-10;49-14-44-49; 15-22-47-15;15-37-38-15; 26-36-26; 49-32-49	

4. CONCLUSION

Over the past few years, the significance of humanitarian logistics in mitigating the consequences of post-disaster situations has become increasingly apparent in the aftermath of natural calamities. Scientists have carried out several investigations to enhance and streamline this process. This work presents a novel model (MDVRP) for the open-form multi-point vehicle routing problem, specifically addressing the distribution of perishable items. This effort adds to the existing body of knowledge in the field of humanitarian logistics. An exceptional feature of this study is the integration of truck-drone collaboration. Although trucks have the advantage of more capacity, drones are more favorable in terms of efficiency and accessibility to challenging locations, which is particularly crucial for perishable commodities. The model findings clearly demonstrate that the combination of these two logistical methods has produced successful outcomes for solving vehicle routing difficulties in humanitarian logistics.

Given its NP-hard complexity, the mathematical model that was created underwent testing using a case study from the literature consisting of 50 data points. It was determined that the ideal outcome could not be achieved within a time frame of 10800 seconds. This constraint of the model implies that the utilization of heuristic methods will be a focus of future research. Furthermore, a potential avenue for future research involves enhancing the model through the utilization of diverse logistics vehicles. In addition, demand uncertainty of distribution points and weather conditions may be future studies that add value to the literature by dynamizing the model.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this paper.

Contribution of Authors

[1st Author Zeynep Yuksel]: Editing the introduction, general design, preparation of visuals and tables, arrangement of data, literature review, mathematical model development, coding and solution of the model, discussion and improvement of the results, revision of the manuscript according to the requests of the advisor and editor.

[2nd Author Dursun Emre Epcim]: Literature review, developed a mathematical model, coded and solved the model, discussed and enhanced the results, and revised the work based on the feedback from the adviser and editor.

[3rd Author Suleyman Mete]: The study supervisor is responsible for designing the study framework, assessing its suitability, establishing the study's boundaries and main areas of focus, and reviewing and editing the paper.

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