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Sentiment analysis of coronavirus data with ensemble and machine learning methods

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Abstract

The coronavirus pandemic has distanced people from social life and increased the use of social media. People's emotions can be determined with text data collected from social media applications. This is used in many fields, especially in commerce. This study aims to predict people's sentiments about the pandemic by applying sentiment analysis to Twitter tweets about the pandemic using single machine learning classifiers (Decision Tree-DT, K-Nearest Neighbor-KNN, Logistic Regression-LR, Naïve Bayes-NB, Random Forest-RF) and ensemble learning methods (Majority Voting (MV), Probabilistic Voting (PV), and Stacking (STCK)). After vectorizing the tweets using two predictive methods, Word2Vec (W2V) and Doc2Vec, and two traditional word representation methods, Term Frequency-Inverse Document Frequency (TF-IDF) and Bag of Words (BOW), classification models built using single machine learning classifiers were compared to models built using ensemble learning methods (MV, PV and STCK) by heterogeneously combining single machine classifier algorithms. Accuracy (ACC), F-measure (F), precision (P), and recall (R) were used as performance measures, with training/test separation rates of 70%-30% and 80%-20%, respectively. Among these models, the ACC of ensemble learning models ranged from 89% to 73%, while the ACC of single classifier models ranged from 60% to 80%. Among the ensemble learning methods, STCK with Doc2Vec text representation/embedding method gave the best ACC result of 89%. According to the experimental results, ensemble models built with heterogeneous machine learning classifier algorithms gave better results than single machine learning classifier algorithms.

1. Introduction

The development of information technologies has had both negative and positive effects on people. The channels through which they express this situation are social media. With the development of smart devices that allow access to social media at any time, applications and websites on these devices have become the first resort in many areas, especially in the field of health.

During the pandemic, people could not go out of their environment. Working life turned into remote work. Most levels of education, especially universities, turned to distance education. Those infected with the disease were subjected to mandatory isolation. For these reasons that can be increased, people's first choice for socializing was social media such as Twitter [1].

Sentiment analysis was performed on the data collected and tagged on Twitter, a medium where people share their instant ideas and emotions. The fact that social media is an indispensable tool for people and that people constantly express opinions about concepts such as social, economic, health, product, brand, etc. has led to the emergence of the field of sentiment analysis. Natural language processing techniques are used in these studies. Emotions such as positive and negative are predicted from the texts people share. Sentiment analysis studies are carried out on movie and restaurant experiences as well as texts that give opinions about companies. These studies provide positive feedback to companies. For this purpose, in this study, DT, KNN, LR, NB, RF, Support Vector SVM (SVM) algorithms are used to provide diversity in a heterogeneous ensemble system. MV and PV ensemble learners and STCK are used as methods to fuse the ensemble decision.

In the first step of ensemble learning, which consists of two parts: ensemble formation and integration, different base classifiers are used. This step is called ensemble formation, and different sets of patterns are created. In the ensemble integration phase, the final decision of the system is determined by using various integration methods to combine the decisions of the base classifiers. In this process, two other factors are as important as classifier selection and integration methods: the single performance of the base learners and the independence of the ensemble learners' results. High diversity of base learners is usually achieved with traditional ensemble algorithms such as bagging, random subspaces, random forests and rotation forests. In heterogeneous systems, diversity is achieved using different learning algorithms and the results are combined with various decision-making methods such as voting, STCK and boosting. By combining these factors, the ensemble system can achieve a higher classification performance.

Models based on machine learning (SVM, DT, RF, LR, NB, KNN) and ensemble learning (MV, PV, STCK) tweet data were split into two separate training and test sets (70%-30% and 80%-20%). F, ACC, and performance metrics were used to evaluate these models. The contributions of this paper can be listed as:

- The performance of six single machine learning classifiers was compared to sentiment analysis in the same study,
- The performance of various ensemble learning methods was compared with sentiment analysis in the same study,
- The performance of single machine learning classifiers was compared to ensemble learning methods based on the same single learning classifiers in the same study,
- The effect of different text representation/embedding methods on sentiment analysis performance was compared in the same study.

This study used BOW, TF-IDF both of which are frequency-based text representation methods. In addition, the classification process performed using W2V, one of the word embedding methods, and the Doc2Vec method, which allows direct vectorization of documents. Two methods of W2V word embedding (CBOW and Skip-gram) and two methods of Doc2vec embedding (PV-DM, PV-DBOW) were used. The flowchart is shown in Figure 1.

In the second section, information about the literature is given. In the third section, the methodology section, the data set and its types, word embedding and text representation methods are available. In the fourth section, which is the experimental settings section, information is given about the environment in which the experiments are carried out, the language, the performance evaluation metric of the models created, and the separation method of the data set used in the experiments. In the fifth section, experimental results are given. In the last section, the conclusion and discussion section, comparison with the literature and general evaluation are included.

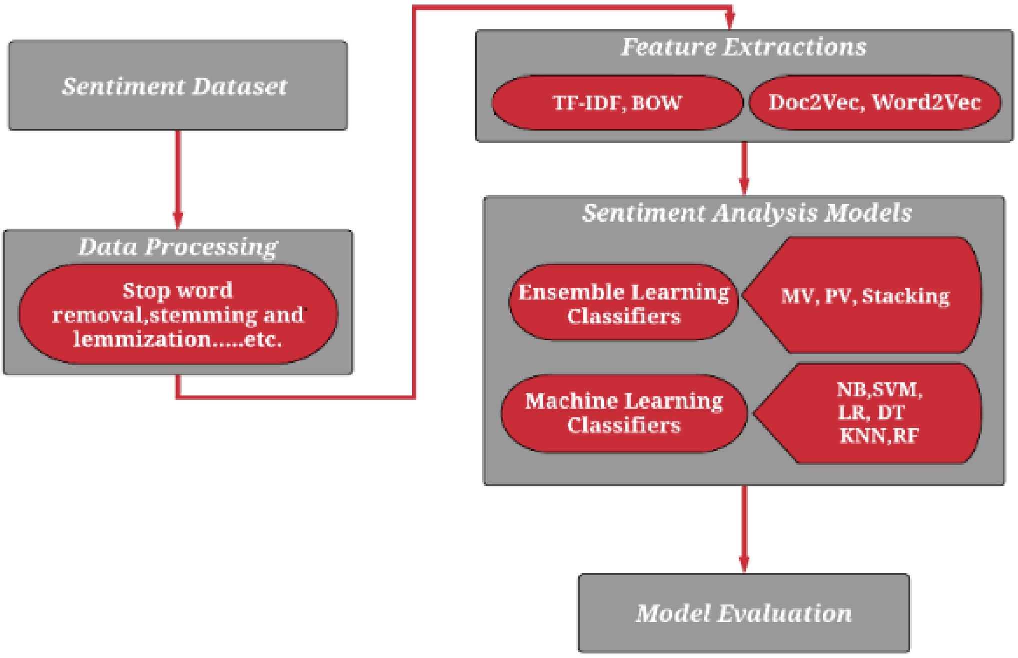

Figure 1. Study flowchart diagram.

After the text representation methods on Coronavirus made with Twitter data during the pandemic period, models and details on sentiment analysis with various Machine Learning methods will be explained in this section.

After TF-IDF and BOW, 65% ACC result was obtained in the model created with Long short-term memory (LSTM) [2]. In another study with TF-IDF, 65% ACC value was obtained in the model created with stochastic gradient descent (SGD) [3]. After word representation with TF-IDF method, 78.5% ACC was obtained as a result of emotion classification with LR machine learning [4]. The first study [5] obtained 74.29% ACC and the second [6] obtained 84% ACC in the model created with TF-IDF and ngrams before NB machine learning. In their experimental study on sentiment analysis using SVM and NB methods together with MV ensemble learning on Twitter data, they achieved the best result with 87.7%

accuracy [7]. In another study, 84.38 ACC results were obtained in the model created with SVM after TF-IDF and W2V [8]. Among the models they created using different ensemble learning methods for sentiment analysis on tweet data during the pandemic period, they obtained 83.3% with voting and 83.2% with STCK [9]. TF IDF on 40,000 coronavirus tweets with Bi-gram Among the models created with NB, RF, and SVM, the best results were obtained with SVM with 87.80% ACC [10].

Classification Performance achieved using TF-IDF feature extraction and SGD is 85.141% ACC [11]. In another study, they obtained an ACC value of 70.6% with TDF-IDF and artificial neural networks (ANN) [12]. Models were created with KNN, SVM, DT, and NB after TF-IDF and BOW with Covid data, and they got better results than other models with 63% ACC with SVM [13]. In sentiment analysis models made with DT, LR, SVM, NB models and BOW, LR gave better results with 81.8% ACC [14]. In the models built with Arabic tweet data and RF, LR, NB, Voting, and BOW word representations, Voting performed better with a 74% ACC [15].

In this section, we describe sentiment analysis studies based on different machine learning classifiers using different text representation and word embedding methods on Twitter tweets about coronavirus. Popular studies have used ensemble learning to improve the performance of machine learning algorithms. In this study, we compare the performance of models generated by single machine learning methods and different ensemble methods according to TF-IDF and W2V in different vector dimensions.

2. Method

This section describes the ensemble and machine learning algorithms, the text representations, and the data set. Before classification, 44955 tweets were preprocessed. Symbols, punctuation, numbers and stop words were removed. All characters were converted to lower case. Lemmization was performed. Removed usernames and hashtags. NLTK was used in the preprocessing steps.

2.1. Dataset

The study used open-source data. [16]. The data set contains 44955 data and 6 attributes as shown in Table 2. In the study, only the label attribute with tweet and sentiment class was used. Table 1 gives information about the Twitter data.

As shown in Table 2, the emotion class distribution of the tweet data consists of 3 classes: positive, negative, and neutral.

The percentage distribution of the coronavirus tweet data is shown in Figure 2.

Figure 3 shows word clouds according to the sentiment classes of the posted tweets. As can be seen in all three sentiment classes, words for basic needs such as "supermarket", "pandemic", "grocery", "store", "shopping" are used. In addition to protecting health, this situation has revealed feelings about the places where he and his family meet their needs such as hygiene, especially food. This situation is another research topic that needs to be studied.

Table 1. Data set information.

Attribute	Definition of attribute
Username	Twitter Users integer type name
Screen Name	The name of the query that everyone on Twitter sees in integer type
Location	Tweet location
Tweet At	When the tweet was posted
Tweet	Content of the tweet

Table 2. Sentiment class distribution.

Sentiment class	Text
Positive	19592
Negative	17031
Neutral	8332

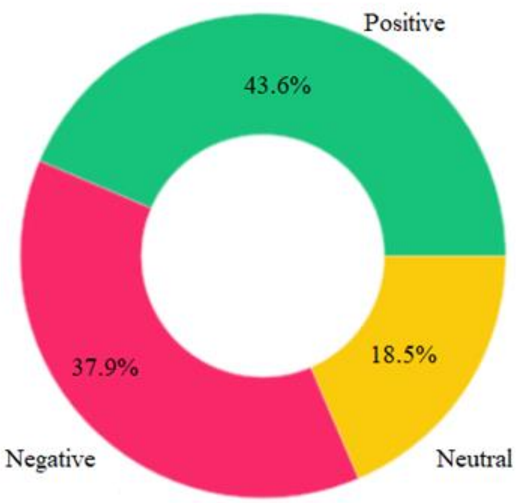

Figure 2. Class distribution.

Figure 3. Class word cloud.

2.2. Text representation

In text classification, text representation and embedding improve classification performance. A distinction can be made between frequency-based and estimation-based methods. In frequency-based methods, vectorization is performed according to the word frequency during the classification process, while in embedding, vectorization is performed based on the neural network. In this study, TF-IDF and W2V were used [17].

2.2.1. Term frequency inverse document frequency

TF-IDF is calculated by taking into account the words present in the document, including all the words associated with that particular document. This method facilitates the identification of the target word in the context of the document. Specifically, TF (Term Frequency) is determined by counting the occurrences of the target word within the document, providing insight into its frequency in that specific context. Conversely, IDF (Inverse Document Frequency) is derived by locating the relevant records within the entire set of word records, highlighting the importance of the term in relation to the broader corpus [17].

2.2.2. Word2Vec

W2V is a prediction-based text representation method. It is an unattended neural network model consisting of an input, an output, and a hidden layer. Mikolov and his team have proposed two new model architectures. W2V is performed by two different methods as Skip-Gram and CBOW. These two approaches are based on different application of input and output variables, but they basically use the same neural network [18]. The CBOW model tries to predict the central word from the words around the central word. The CBOW model makes better predictions on small data sets. On the other hand, it is difficult to understand words that have more than one meaning. The representation of the model is shown in Figure 4 [18-19].

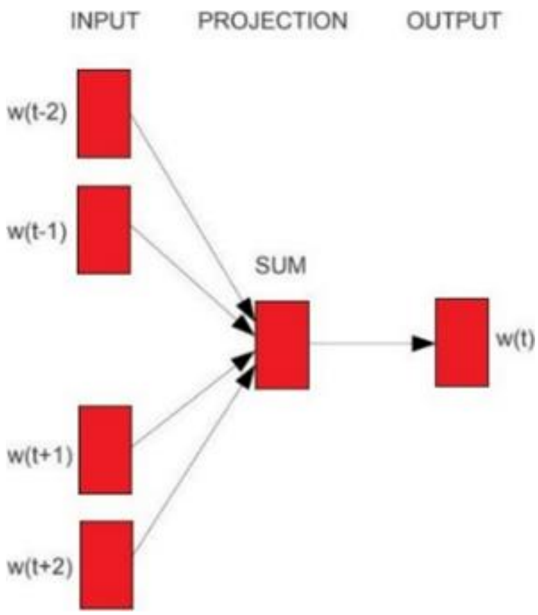

Figure 4. CBOW model [13].

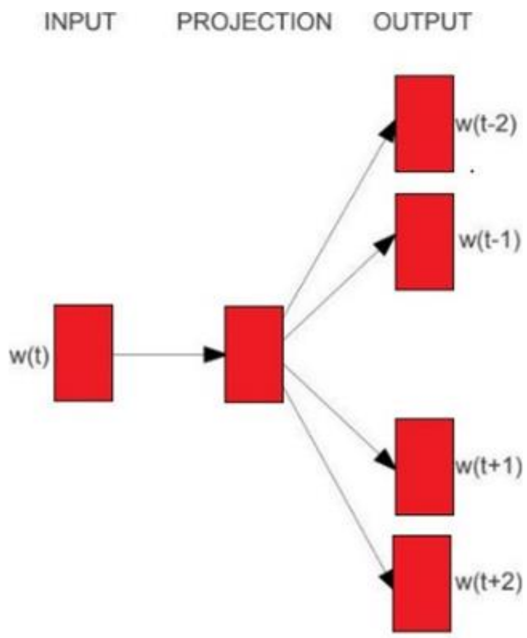

Figure 5. Skip-gram model [13].

The skip-gram model tries to predict the words found around a word. The skip-gram model works better with larger amounts of data. At the same time, the skip-gram model is better at understanding words that have 2 or more meanings than the CBOW. The representation of the model is shown in Figure 5 [19].

In the study, vector sizes of 100 and 200 and window size of 5 were taken.

2.2.3. Doc2Vec

Based on the W2V architecture, each document is created by adding a separate document vector. These document vectors are represented by numerical values in vector space. The Doc2Vec model has two methods, the distributed memory version of the paragraph vector (PV-DM) and the distributed bag-of-words version of the paragraph vector (PV-DBOW), which are shown in Figure 6 and Figure 7, respectively [20]. The PV-DM in the Doc2Vec model corresponds to the CBOW in the W2V model, while the PV-DBOW method is implemented as a skip-gram method [21]. In the study, the hyperparameter settings for Doc2Vec were taken as vector size 100 and 200, window size 5, min-count 5.

2.3. Machine learning

Machine learning is a mathematical approach to modeling decision making in the human brain and neural networks. It compares each neuron in the human brain to a simple digital processor and the brain to a computing machine. In 1950, Alan Turing introduced the idea of machines thinking like humans. The emergence of machine learning as we know it today dates back to the 1980s [21]. In this study, SVM, NB, KNN, LR from machine learning methods are used. These classifiers are explained in this section.

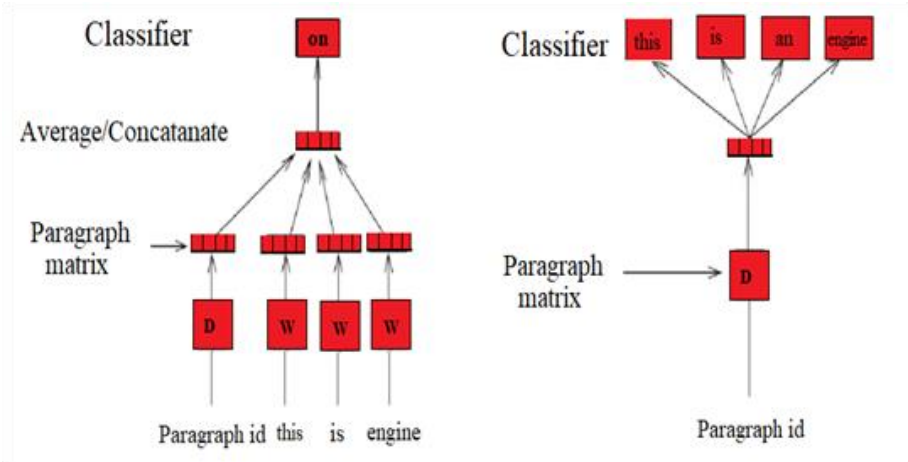

Figure 6. PV-DM model and PV-DBOW model [20].

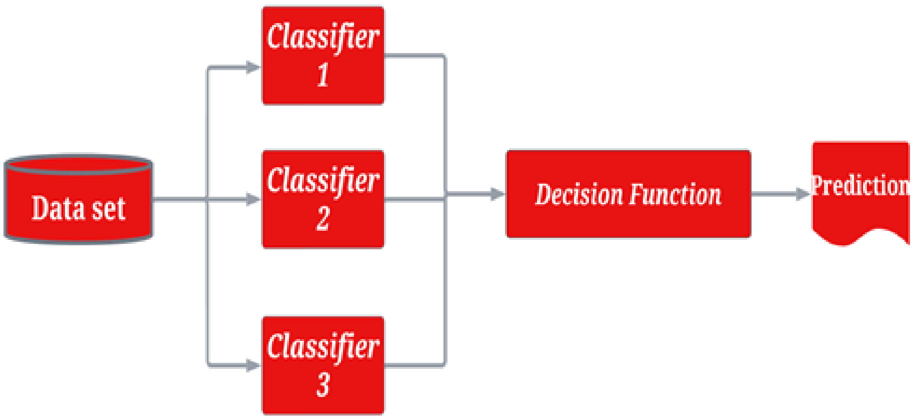

Figure 7. Ensemble learning.

2.3.1. Naïve bayes

Named in honor of the English mathematician Edmund Bayes, the algorithm belongs to the class of statistical classification methods. The Bayesian classifier is based on Bayes' theorem [21].

The above formula is used to decide whether a given x $(x = [x(1), x(2), \ldots, x(L)]^T \in r^L)$ belongs to class S_i When the independence proposition is used statistically in the Bayes decision theorem, this type of classification is called NB classification. In a mathematical expression (Equation 1) [22].

$$P(x|S_i)P(S_i) > P(x|S_j)P(S_j), \forall j \neq i \tag{1}$$

The term $P(x|S_i)$ in Equation (1) is rewritten as in Equation (2).

$$P(x|S_i) \approx \prod_{k=1}^{L} P(x_k|S_i) \tag{2}$$

In this way, Bayes' theorem takes the form of Equation (3).

$$P(S_i)\prod_{k=1}^{L} P(x_k|S_i)\,P(S_j)\prod_{k=1}^{L} P(x_k|S_j) \quad (3)$$

$P(S_i)$ and $P(S_j)$ is the prior probability of classes I and j. Their values can be easily calculated from the studied data set [22]. The NB classifier is used in many fields in artificial intelligence studies, including disease diagnosis [23-24].

2.3.2. Support vector machine

In classification studies based on the principle of least intrinsic risk, it creates a hyperplane for the separation between classes. In the hyperplane determines in which class the new sample will be placed [25]. SVM excel at both linear and nonlinear classification tasks [22].

2.3.3. K-nearest neighbor

KNN, one of the supervised learning methods, is used for classification and regression. It determines the k nearest neighbors by looking at the distances between the data set and the problem-specific data and includes that data in that class. Methods such as Euclidean Manhattan and Minkowski distance are used to calculate the distance [26].

2.3.4. Logistic regression

It was first introduced in 1958 by statistician David Cox. Logistic regression uses the "maximum likelihood" method. Logistic regression uses the sigmoid function to classify, the sigmoid function is an "S" shaped curve [22].

2.3.5. Decision tree

Tree-based learning algorithms are widely employed in supervised machine learning. At the core of these algorithms is the decision tree, a hierarchical structure designed to partition a data set with numerous records into smaller subsets through a series of decision rules. Essentially, a decision tree is a tool that, through sequential decision steps, segments substantial data sets into more manageable groups of records [27].

2.4. Ensemble learning

It is a type of learning designed to use different classifiers together to solve classification and regression problems, or to improve the performance of a classifier. Ensemble learning optimizes efficiency by strategically combining multiple expert or machine learning models to improve the performance of a single inferior model [28]. In addition to the distinction between homogeneous and heterogeneous, ensemble learning differs according to the decision function, such as voting, averaging, etc., and is classified as such. However, it is usually classified as bagging, boosting, STCK. Figure 7 shows an illustration of this classification of the ensemble process.

2.4.1. Voting

Voting is an ensemble learning method for classification problems. It makes predictions based on the creation of two or more sub-models and voting the result with the mean or mode of the predictions of these sub-models [29].

2.4.1.1. Majority voting

The same or different Base classifiers vote for a class and the majority with the MV wins. Statistically, the target label of the classes together can be said to be distributed by voting to guess. Equation (4), we estimate the $\hat{y}$ Class label through the majority (plurality) vote of each classification Cl.

$$\hat{y} = mode\{Cl_1(x), Cl_2(x), \ldots \ldots Cl_m(x)\} \quad (4)$$

If we combine the three-class results of an example of education as in Equation (5) [30].

$$\hat{y} = mode\{0,0,1\} = 0 \quad (5)$$

By MV, we would classify the sample into "Class 0". The MV process is shown in Figure 8 [31].

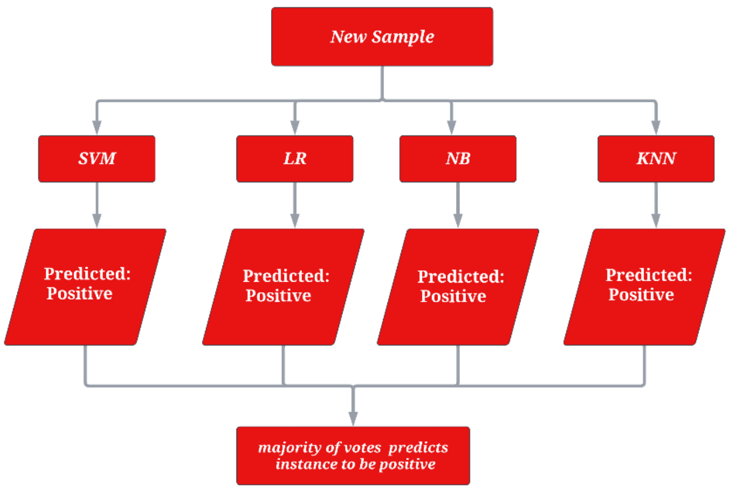

Figure 8. MV process.

2.4.1.2. Probabilistic voting

In the PV scheme, each base classifier provides a probability estimate indicating the likelihood that a given data point belongs to a particular target class. These probability predictions are assigned weights proportional to the size of the classifier and aggregated. The final prediction is determined by selecting the target label associated with the highest sum of weighted probabilities.

Soft voting, on the other hand, involves predicting class labels by considering the expected probabilities (p) provided by each classifier. It's important to note that this approach is only advisable if the classifiers are appropriately calibrated [30].

$$\hat{y} = arg\,\underset{i}{max} \sum_{j=1}^{m} w_j p_{ij} \tag{6}$$

w_j is the weight that can be assigned to the j th classifier in Equation (6) [31]. The PV procedure is shown in Figure 9.

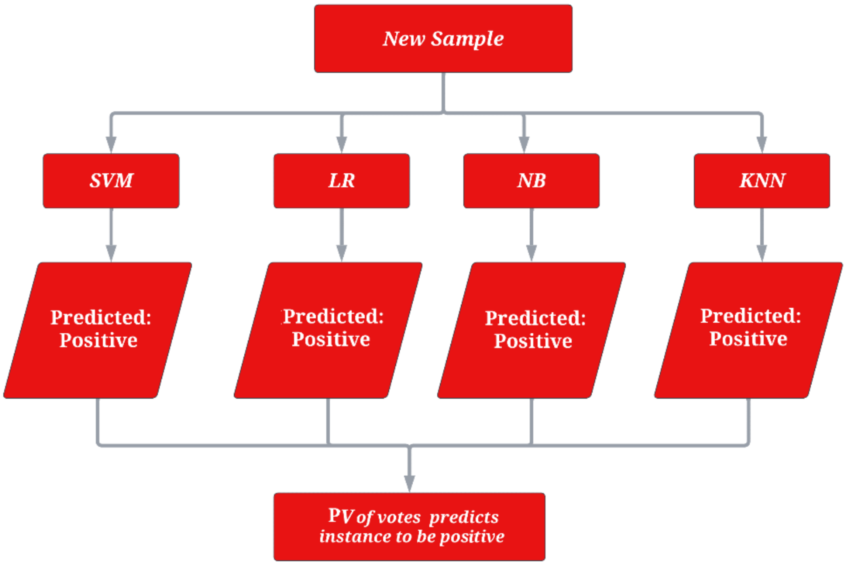

Figure 9. PV process.

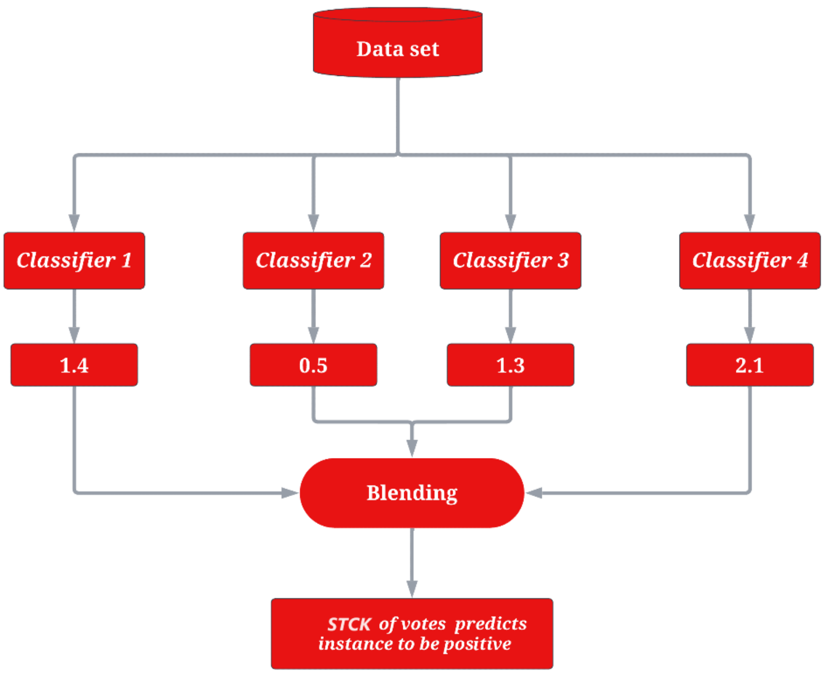

Figure 10. STCK process.

2.4.1.3. Stacking

This voting is similar to the voting used in classification problems. In addition to the selection of multiple sub-models, STCK allows you to specify an additional model to learn how to best combine the predictions of the sub-models. Because a metamodel is used to best combine the predictions of the sub-models, this method is sometimes referred to as mixture, as is mixture of predictions [32]. The STCK process is illustrated in Figure 10.

3. Experimental settings

In the experimental results, the preprocessing and feature extraction is completed and the performance of the data set is evaluated ACC, F by classifying it with ensemble and machine learning classifiers after hold-out test training separation. The experiments were coded using the Python sci-kit learn library. The experiments were performed on an AMD Ryzen CPU computer.

3.1. Performance metrics

ACC is the ratio of the true negative (T_N) and true positive (T_P) fields correctly predicted by the model to the sum of the false negative (F_N), and false positive (F_P) values contained in these fields. The ACC value is given by Equation (7) [27].

$$Acc = \frac{T_N + T_P}{T_P + T_N + F_N + F_P} \quad (7)$$

P is the ratio of (T_P) to (T_P) and (F_P) as given in Equation (8) [32].

$$P = \frac{T_P}{T_P + F_P} \quad (8)$$

R refers to the ratio of (T_P) to (F_P) and (T_P) given by Equation (9) [33].

$$R = \frac{T_P}{T_P + F_N} \quad (9)$$

F has values between 0 and 1. It is the harmonic mean of P and R defined by Equation (10) [33].

$$F = \frac{2 * Precision * Recall}{Precision + Recall} \quad (10)$$

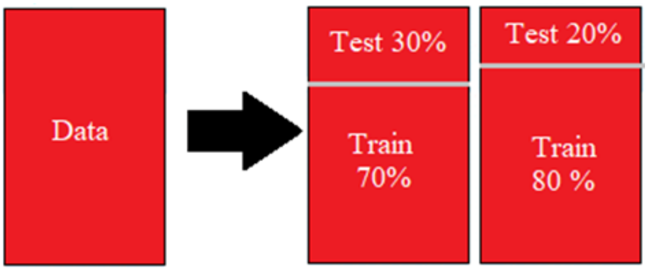

Figure 11. Train and test set separations.

Data sets were divided into training and test sets to develop models using classifier algorithms, followed by evaluation of model performance. Holdout was preferred in this research. Figure 11 shows the separation of training and test sets used in the study.

4. Results

In the Coronavirus data set, text representation methods and word embedding methods, then STCK and Voting (MV, PV) ensemble learning (background is blue) hold created using DT, KNN, NB, LR, RF, SVM machine learning methods (background is green) 70%-30% and 80%-20% ACC (Table 3, Table 4), F (Table 5, Table 6), shows the results.

Table 3 shows the ACC results of the sentiment analysis models generated by 80%-20% train-test separation after frequency-based text representation (TF-IDF, BOW) and word embedding in 100 and 200 vector sizes (Word2Vec and Doc2Vec). MV showed better classification performance after BOW and TF-IDF methods. STCK performed better on both Word2vec and Doc2vec methods and all vector sizes.

Table 4 shows the ACC results of the generated sentiment analysis models with 70-30% train-test separation after frequency-based text representation (TF-IDF, Bow) and vector sizes of 100 and 200 words (Word2Vec, Doc2Vec). STCK ensemble learning performed better in all models created after word embedding and text representation methods. But MV and PV also gave results close to STCK.

As shown in Table 5, the STCK ensemble learning model, which was developed after all text representation methods, performed better than the other models. Among the machine learning models, although SVM has given the best results, DT, KNN, which came after LR and SVM, gave the worst results. Ensemble learning methods outperform machine learning methods.

Comparison of the 200-vector size CBOW Word2Vec model with STCK 80%-20% train-test separation, which gave the best results in the study, and similar studies on coronavirus are shown in Table 7.

Among the models created for sentiment analysis between Table 3 and Table 7, the ensemble models produced ACC ranging from 73% to 89%, while the ACC of the single classifier models ranged from 60% to 80%. In terms of F performance, the results ranged from 68% to 78% for the ensemble models and from 60% to 76% for the single classifiers. After all text representation methods, ensemble learning models built with STCK gave better results in all performance evaluation criteria. According to the experimental results, ensemble models built with heterogeneous machine learning algorithms gave better results than machine learning algorithms used as a single classifier.

5. Conclusion and Discussion

Sentiment analysis of various social media topic data is so popular today. In this study, an evaluation of six single machine learning classifiers (SVM, DT, RF, LR, NB, KNN) versus ensemble learning methods (MV, PV, STCK) based on listed single classifiers on Twitter data about coronavirus with frequency-based text representation and word embedding methods have been investigated with different experiments.

The experimental results obtained in the study are presented between Table 3 and Table 6. It has been observed that using machine learning algorithms in heterogeneous ensemble learning algorithms gives a significant advantage in terms of classification performance compared to single classifiers. And STCK with Skip-Gram gave the best performance among all the models.

In the study, we obtained the best model with STCK ensemble learning after Word2Vec CBOW at 100 and 200 vector size. Table 7 shows a comparison of the presented model with other coronavirus studies in the literature.

Table 3. ACC results of models (80:20 Train: Test).

Models	Text representation/Embedding methods									
	BOW	TF-IDF	W2V				Doc2Vec			
			CBOW		Skip-Gram		PV-DM		PV-DBOW	
			100	200	100	200	100	200	100	200
LR	78	75	67	69	67	68	62	64	61	67
SVM	77	77	67	69	66	68	62	64	61	66
RF	79	78	72	72	72	72	67	67	64	71
NB	77	77	72	74	65	75	64	65	63	66
KNN	63	69	67	68	69	69	62	62	59	67
DT	71	69	62	61	60	61	65	65	64	69
STCK	**83**	**82**	84	**89**	**84**	**85**	**79**	**81**	**83**	**83**
MV	82	80	83	84	82	84	75	76	73	79
PV	81	81	83	84	82	84	75	76	83	79

Table 4. ACC results of models (70:30 Train: Test).

Models	Text representation/Embedding methods									
	BOW	TF-IDF	Word2Vec				Doc2Vec			
			CBOW		Skip-Gram		PV-DM		PV-DBOW	
			100	200	100	200	100	200	100	200
LR	79	76	69	70	67	69	62	64	61	67
SVM	78	78	68	70	67	69	62	63	61	66
RF	80	80	72	72	73	73	67	67	72	71
NB	77	77	73	74	67	74	65	66	63	66
KNN	62	69	67	67	68	67	60	69	69	67
DT	71	70	61	61	61	61	64	66	64	69
STCK	83	82	84	85	84	85	81	80	83	83
MV	82	81	83	84	83	84	76	77	73	79
PV	82	80	82	83	80	83	75	77	73	79

Table 5. F results of models (80:20 Train: Test).

Models	Text representation/Embedding methods									
	BOW	TF-IDF	W2V				Doc2Vec			
			CBOW		Skip-Gram		PV-DM		PV-DBOW	
			100	200	100	200	100	200	100	200
LR	72	71	73	76	73	71	71	70	68	67
SVM	72	72	76	76	73	73	69	71	70	68
RF	72	72	74	75	74	72	70	65	67	65
NB	67	66	76	74	77	72	64	65	63	66
KNN	63	63	67	68	68	69	62	62	61	64
DT	61	64	62	61	60	61	60	60	60	65
STCK	72	72	76	77	76	78	74	75	73	75
MV	71	71	74	76	74	75	73	74	72	73
PV	70	71	73	73	72	73	72	72	71	72

Table 6. F results of models (70:30 Train: Test).

Models	Text representation/Embedding methods									
	BOW	TF-IDF	W2V				Doc2Vec			
			CBOW		Skip-Gram		PV-DM		PV-DBOW	
			100	200	100	200	100	200	100	200
LR	72	71	71	72	70	71	72	73	68	72
SVM	72	72	72	74	71	72	72	73	69	73
RF	71	71	70	73	70	71	71	71	64	71
NB	67	67	69	68	69	70	65	66	62	66
KNN	71	69	67	67	68	67	60	61	60	66
DT	70	70	61	61	61	60	60	60	60	60
STCK	73	72	77	77	76	76	76	75	72	74
MV	72	71	73	74	73	74	75	74	70	68
PV	71	71	73	74	73	74	75	74	71	72

In Table 7, it is seen that the proposed method can compete with the literature when compared with other coronavirus studies in the literature.

As future work, we plan to improve the performance of sentiment analysis by using various deep learning algorithms in hybrid forms after feature selection on social media data along with text representation methods. Also, performance analysis of models based on transfer learning can be investigated on different data sets.

Table 7. Presented model versus literature.

References	Model	ACC (%)
[2]	LSTM	65
[3]	SGD	65
[4]	LR	78.5
[5]	NB	74.29
[6]	Trigram NB	84
[7]	MV (SVM, NB)	87.7
[8]	SVM	84.38
[9]	MV	83.3
	STCK	83.5
[10]	SVM	87.8
[11]	SGD	85.141
[12]	ANN	70.6
[13]	SVM	63
[14]	LR	81.8
[15]	Voting	74
The Presented model	STCK with CBOW	89

Author contributions

Muhammet Sinan Başarslan: Data preprocessing, data analysis, drafting the manuscript. **Fatih Kayaalp:** Defining the methodology, evaluating the results and editing the draft.

Conflicts of interest

The authors declare no conflicts of interest.

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Investment technique for ensuring energy supply continuity in ring grids

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Abstract

The importance of energy supply for both end-users and electricity distribution entities, as well as the need for reliable energy quality parameters, is significant. This study delves into scenarios where these parameters cannot be met, outlining formulas for calculating compensation and other financial obligations that distribution companies may incur. The study highlights various types of interruptions that disrupt energy supply continuity within electricity distribution networks and elucidates their impacts on the network infrastructure. The establishment of alternative energy sources and the enhancement of the network infrastructure through coupling are recommended to mitigate the consequences of these interruptions. Investments in alternative energy sources and network improvements are compared to penalty amounts incurred when the quality parameters for energy supply continuity cannot be met. The F13/F14 Ring Network, a proposed coupling approach that can improve energy supply, is identified and its installation costs are compared with the existing conditions. Additionally, the magnitude of fines that distribution companies may potentially face is estimated. As a result, a comprehensive cost-benefit analysis is conducted, integrating these comparisons to evaluate the economic sustainability and advantages associated with the proposed F13/F14 Ring Network coupling method.

1. Introduction

Voltage quality (also referred to as "power quality") encompasses topics related to the ideal voltage level and deviations in waveform. Voltage quality covers a wide range of issues including harmonics, voltage level fluctuations, voltage drops, and more. A comprehensive study has been conducted on regulations regarding voltage quality [1]. The fundamental purpose of electric power system design and operation is to provide all network users (consumers, producers, and both) with an acceptable level of energy supply continuity and voltage quality. In this context, the term "acceptable" can be assessed through various approaches. Traditionally, such decisions were often made by local energy providers, and customers were required to accept the outcome without question. However, this approach has been replaced by international standards or general requirements set at the national level. For instance, limitations for continuous events such as voltage level fluctuations and harmonics in Europe are defined in the EN 50160 standard [2, 3]. Limitations on interruption events such as the number and duration of outages are determined by regulatory bodies in some countries. Nevertheless, the ultimate decision on what is considered acceptable always rests with the customers, and in this context, requirements are becoming increasingly stringent. This is especially true for cases where prolonged outages take on political dimensions in certain situations. Similarly, a tightening of regulations is observed for issues affecting industrial customers, such as significant voltage drops [4, 5].

Electric distribution companies conduct grid improvement projects to enhance energy continuity and quality. The importance of these initiatives in ensuring supply continuity is emphasized. Through operational enhancements or additional investments within the existing grid, efforts are made to achieve customer satisfaction with energy supply. In this paper, a cost-benefit analysis of a method aimed at improving energy supply continuity in a city grid is conducted using the F13/F14 Ring Grid model. Compensation penalties to be levied on distribution companies for prolonged or frequent outages exceeding a certain threshold value are calculated within the electric distribution network. The study examines the costs incurred by the distribution company due to outages in the absence of the F13/F14 ring grid and compares these with the situation after implementing the ring grid, taking compensation penalties into account. The paper compares the establishment cost of the ring grid with the benefits through cost-benefit analysis. In the ring network model proposed in this study, estimating the quality of supply continuity allows taking into account all potential factors, both interconnected and independent, including not only reliability factors but also investment costs. Thus, this study presents a new approach that proposes to use the benefit-cost analysis model to calculate the continuity quality of the power supply [6]. This method allows estimating continuity of supply by taking into account various factors, including investment costs.

The methodology used involves conducting a cost-benefit analysis of a method aimed at improving energy supply continuity using the F13/F14 Ring Grid model. This analysis is used to calculate the compensation penalties to be imposed on distribution companies and to compare the costs incurred due to outages in the absence of the F13/F14 ring network with the post-implementation situation. Additionally, the cost of establishing the ring network is compared with the benefits achieved through cost-benefit analysis.

This analysis proposes to use different feeders to calculate compensation penalties imposed on distribution companies and compare them with the situation after the implementation of the costs incurred due to interruptions in the absence of the F13/F14 Ring Grid. In addition, the installation cost of the ring grid is compared with the benefits obtained through cost-benefit analysis, presenting a new approach for connection between two feeders. The coupling system used in the methodology aims to improve energy supply continuity by integrating the F13/F14 Ring Grid model and performing cost-benefit analysis.

2. Reliability and supply continuity in power systems

Electrical energy service quality is basically; It consists of three main components: supply continuity, voltage quality and commercial quality. Supply continuity defines interruptions in energy supply by analyzing the number and duration of disruptions, assessing the reliability of the electrical system. Voltage quality focuses on specific characteristics of voltage waveform, including frequency, RMS value, fluctuations, flicker, imbalance, and harmonic distortion. Commercial quality evaluates the relationship between electric companies and customers. The main aim of this study is to contribute to a better understanding of the concept of supply continuity.

Outages can be classified based on their nature or duration. According to their nature, outages are defined as follows [7]:

- Planned Outages: In most cases, these outges occur as a result of deliberate circuit breaker opening by the system operator to de-energize a portion of the network, affecting one or more customers. Customers are informed in advance. Such measures are usually used for maintenance operations or construction of new parts of the network. Generally, these types of outages lead to an improvement in network reliability.
- Unplanned Outages: These outages occur due to unforeseen events, such as component failures, lightning strikes, excavation activities, or incorrect switching operations.
- Extraordinary Events: Events associated with natural disasters.

According to their duration, outages are defined as follows:

- Long-Term Outages: Lasting more than three minutes.
- Short-Term Outages: (In most European countries) lasting three minutes or less.

2.1. Reliability in power systems

The primary objective of an electrical energy system is to provide consumers with economical, high-quality, acceptable, reliable, and uninterrupted energy supply. The ability of the system to fulfill this inherent expectation throughout its operational period is referred to as reliability. Electrical energy system reliability analysis is conducted at three levels. The reliability analysis performed at the production zone level determines whether the generated energy can meet the total system load [8]. Enhancing the reliability of electrical distribution systems is currently of increasing interest and importance because power outages caused by any errors affect both energy providers and end-users. Closed-ring operation mode ensures high reliability by reducing the duration and frequency of faults [9].

To date, reliability indicators used in the design of power systems have limitations as they do not consider all possible factors influencing the continuity of power supply [10-12]. These reliability indicators often only account for the reliability of devices and components in the system [13, 14]. As an alternative, the Dempster-Shafer (DS) mathematical evidence theory-based method derived from Dempster and Shafer's names may include series modeling to predict signals from sequentially connected sensors [15-17]. Other uncertainty prediction methods are available for modeling dependent and independent elements (both series and parallel). The CF-based method is sometimes used to model system quality to predict uncertainty. This method has been successfully applied to estimate information quality [18-20] and also in the authors' publications [21]. In summary, the method presented in this paper for determining the continuity quality of power supply represents an approach based on cost-benefit analysis, distinct from the multi-layer prediction method described in [22, 23] for uncertainty prediction.

In a modern electrical distribution network, providing uninterrupted energy supply is technically and economically challenging. However, as consumers' dependence on electrical energy grows, better performance in energy supply continuity is expected [24].

Some indicators exist that measure and evaluate the costs or losses incurred in the service schedule and on the consumer side as a result of power interruptions, and these should be considered in planning and operations. Network reliability analysis produces load point and system indicators. These indicators are divided into energy indicators and frequency/expectancy indicators. In this study, Load point indicators [25];

- System Average Interruption Duration Index (SAIDI)
- System Average Interruption Frequency Index (SAIFI)
- Average Service Availability Index (ASAI)
- Customer Average Interruption Duration Index (CAIDI)
- Customer Interruption Index per Interrupt (CIII),

These indices have been evaluated as for a part of a Distribution Company's network. All service providers need to have the necessary data to calculate all reliability indicators.

2.2. Continuity quality

The quality of energy supply continuity refers to the capacity of an electrical distribution network system to provide the electricity service that consumers should receive, at an acceptable cost and without disrupting vital activities, with the least possible frequency and duration of interruptions.

The Energy Market Regulatory Authority (EPDK) obliges energy distribution companies to record short, temporary, and long electrical outages occurring within the energy distribution network for supervision purposes. This requirement aims to maintain transparency and ensure that this information is always presented in an open manner. Detailed data about long-term outages that need to be preserved are explained as:

- The voltage level and location of the origin of the outage,
- Date and start time of the outage,
- Source of the outage,
- Depending on the infrastructure status, the number of distribution and main users affected by the outage,
- Depending on the infrastructure status, outage duration for distribution and main users,
- Depending on the infrastructure status, separate outage durations and corresponding customer numbers for distribution and main users supplied with energy gradually,
- Time when the outage ended for all affected users.

Extended-only outages fall into two categories: outages with notice and outages without notice. Records of unnotified outages specified in the second paragraph are kept only at the distribution level for short and temporary outages.

The electrical distribution company evaluates energy supply continuity quality parameters for each year based on Low Voltage (LV) or Medium Voltage (MV) levels and zoning conditions. The assessments encompass:

- System-wide average interruption duration and frequency indices for both notified and non-notified long outages,
- System-wide average interruption frequency index for short and temporary outages,
- Equivalent interruption duration and frequency indices for both notified and non-notified long outages,
- At the LV level, on a user basis, calculations of equivalent interruption duration and frequency indices for both notified and non-notified long outages.

These evaluations are conducted to assess the quality of energy supply continuity for different categories of outages, considering LV or MV levels and zoning conditions.

SAIDI is calculated for each of the "n" total interruptions occurring throughout a calendar year, as well as for each of the "m" user groups that experience these interruptions and subsequently have their energy supply restored step by step. The mathematical expression for calculating SAIDI is shown in Equation 1.

$$\mathrm{SAIDI} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}(U_{i,j} * t_{i,j})}{U_{total}} \tag{1}$$

In Equation 1:

- $U_{i,j}$: Represents the number of users in group j who are affected simultaneously by the *ith* interruption.
- $t_{i,j}$: Represents the duration of the interruption for user group j.
- U_{total}: Represents the total number of users served by the distribution company at the beginning of each calendar year.

SAIFI is calculated considering the total "n" interruptions that occur within a calendar year and is based on the Equation 2:

$$\mathrm{SAIFI} = \frac{\sum_{i=1}^{n} U_{\mathrm{i}}}{U_{total}} \tag{2}$$

In Equation 2:

- U_{i}, Represents the number of users affected by the ith interruption.

The CAIDI is calculated for each feeder by summing up the durations of all "n" interruptions occurring within a calendar year (Equation 3):

$$\mathrm{CAIFI} = \sum_{i=1}^{n} t_i \tag{3}$$

In Equation 3, $t_i$represents the duration of the *ith* interruption for each feeder.

CAIFI term refers to the evaluation of the total "n" interruptions that occur within a calendar year. It is calculated separately for each feeder, indicating the number of interruptions.

If the CAIDI and CAIFI calculated for each feeder exceed the acceptable threshold values proposed, the distribution company is obligated to compensate users based on the principles determined below. The authority to review and adjust these values remains with the regulatory authority.

For CAIDI and CAIFI calculations, the proposed threshold values are as follows:

For CAIDI:

- Within Zoning Area: 72 hours
- Outside Zoning Area: 96 hours

For CAIFI,

- Within Zoning Area: 56 times
- Outside Zoning Area: 72 times

The compensation amount to be paid to the user for CAIDI is calculated using the Equation 4:

$$PUFO_f = [\text{CAIFI}f - \text{TVCAIFI}f] * ENS * AD_f \quad (4)$$

In Equation 4:

- $PUFO_f$: Represents the compensation amount to be paid to the user for unmet targets due to "f" feeder.
- CAIFIf: Represents the equivalent interruption duration index calculated for "f" feeder in the previous calendar year.
- TVCAIFIf: Represents the acceptable threshold value for equivalent interruption duration index.
- ENS: Represents the cost of the unit of energy not supplied (approved by the Authority upon the distribution company's proposal within the framework of procedures and principles determined by the Authority).
- AD_f: Represents the average demand in kW for "f" feeder in the previous calendar year.

Compensation amounts at the feeder level are allocated based on the connection capacities of consumers connected to the relevant feeder and are offset in a lump sum or in equal installments from the distribution service fees of the following year. Compensation payments are made without the need for individual applications. According to the Regulation on the Continuity of Electricity Supply, Commercial and Technical Quality of Electricity Delivered in the Distribution System of the Electricity Market, compensation to consumers does not eliminate the right to claim damages for damage to their own equipment, provided that the consumer is not at fault.

3. Energy supply continuity in ring grids

As a method for ensuring energy supply continuity, an example of an electrical distribution network's ring line will be discussed. The Ring Network; To minimize the impact of power outages in the supply areas of F-13 and F-14, which originate from the District Transformer Station (TM), a ring network has been established at the TR113 main building shown as Figure 1.

F-14, with a characteristic of 477 MCM, is supplied by a total of 4142 subscribers, including 4142 Low Voltage (LV) subscribers and 8 Medium Voltage (MV) subscribers, and is fed by a total of 43 transformers. On the other hand, F-13, with a characteristic of 3/0 Pigeon, is supplied by 110 LV subscribers, 8 MV subscribers, and a total of 10 transformers. In the event of an MV fault on the feeders, since there is no alternative supply point, a significant number of subscribers remain without power for an extended period. During the time it takes to rectify the fault and restore power to the line, subscribers are left without electricity. Furthermore, this situation results in the distribution company having to pay compensation fines due to the inability to ensure supply continuity.

The Geographic Information System (GIS) used by the Distribution Company, shown in Figure 1, integrates the distribution network onto the zoning layout. The yellow-marked area represents the region where the F-14 feeder is energized, while the blue area represents the region where the F-13 feeder is energized. It can be observed from the image that both feeders, indicated by the two colors, merge in the same root building. In the case of a fault or outage, the region left without power can be supplied from the other feeder. Thus, faults can be rectified without leaving subscribers without power, ensuring supply continuity. Additionally, the coupling cell within the ring network, depicted in the image, is a cell with inputs from two separate sources and possesses an automatic switching feature. This prevents any delays during switching operations, ensuring efficient maneuvering.

The Distribution Company obtained data from the Inavitas system, where analyzers installed on feeders in the District TM measure and report quality parameters such as power, current, voltage, etc. The Inavitas system serves as a program for analyzing feeders and is commonly used by Distribution Companies. The graph depicting the apparent power (S) values during fault conditions for the F-13 and F-14 feeders, which are utilized as the ring network, is presented based on data from the Inavitas system. In Figure 2, the F-13 feeder is indicated by the blue color, and the F-14 feeder is represented by the black color. Upon observing the graph, it becomes evident that the load of F-14, indicated in black, is transferred to F-13, depicted in blue, at the point where F-14 is disconnected.

In Figure 3, it is observed that there is a fault in the square area corresponding to F-14, resulting in the feeder losing power. By activating F-13, which serves as an alternative power source for F-14, the creation of a powerless area is prevented. Both feeders receive power from the F-13 F-14 ring network, as indicated by their supply areas.

Based on the data obtained from Inavitas for a 10-minute interval, an outage occurred in the F-14 feeder on July 25, 2023, at 23:00, and power was restored around 10:50 on July 29, 2023. A total of 4142 subscribers fed from the F-14 feeder were affected by the outage. The process of transferring the load from F-14 to F-13 took 50 minutes, and the restoration of F-14 to its normal state took an additional 30 minutes. There are reasons behind the extended time taken for the activation and deactivation of the ring network. One possible reason is the failure to report the outage as an alert. If outage information is not provided to the 186 electrical fault alert line, the teams unaware of the outage cannot take action. Another reason for the extended process of activating and deactivating the ring network is the mandatory implementation of occupational health and safety conditions by the electricity distribution companies. During the electrical operation in the

Distribution Company, a "Visual Confirmation" is conducted. Operators monitor and guide the stages of the maneuver using tablets called "press-talk," ensuring that occupational safety measures are taken at maneuver points, the correct safety equipment is used, proper grounding is established, correct isolation is achieved, and energy control is verified. Therefore, maneuvers that are expected to be shorter in duration can take longer due to these occupational health and safety considerations. However, the automatic activation and deactivation of alternative power sources can be achieved by incorporating the ring network's root building or distribution centers into the SCADA system.

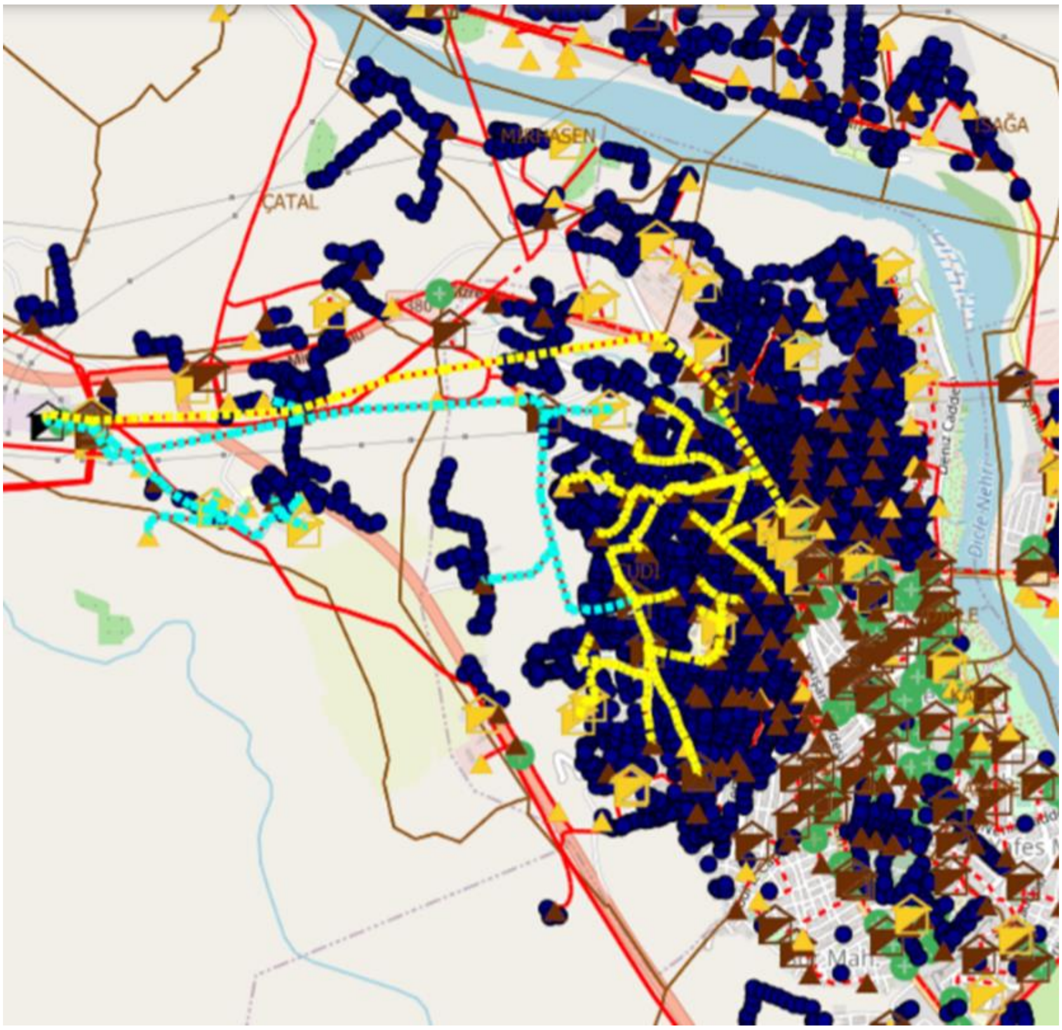

Figure 1. Model of F13-F14 Ring Network.

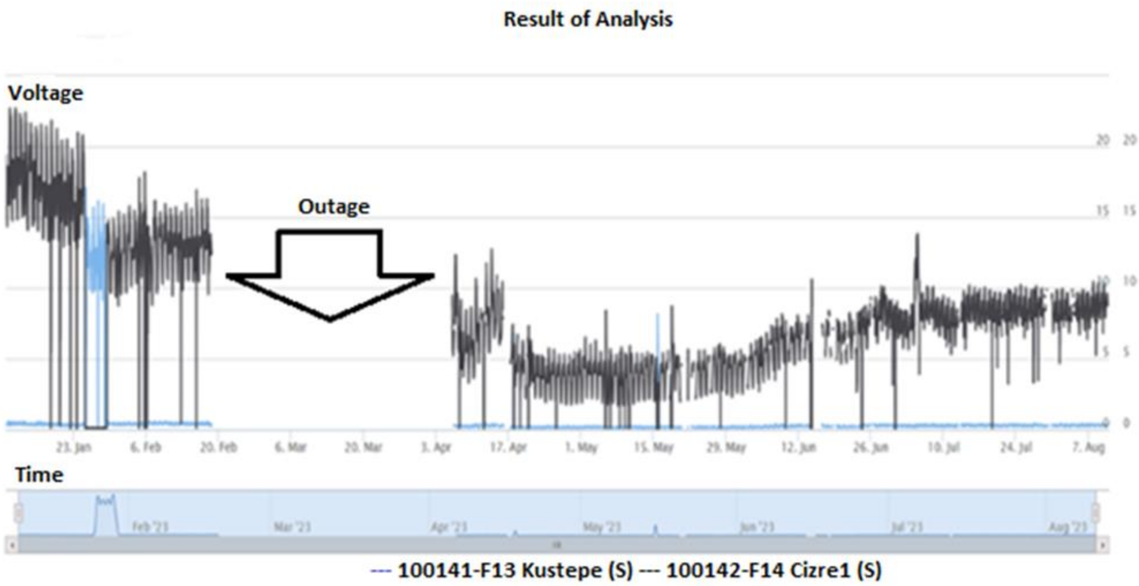

Figure 2. Outage of F-13 F14 ring grid model.

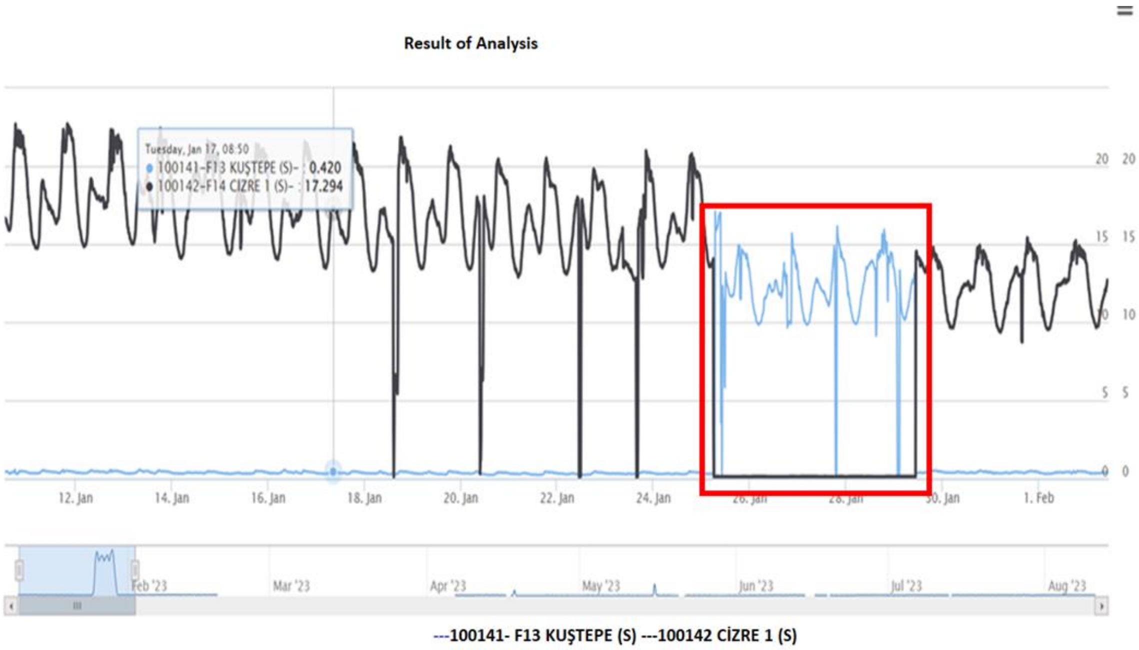

Figure 3. Support of F-13 ring grid model.

F13 and F14 information showing the number of customers, load points, amount of energy, number of faults and the duration of these faults are shown in Table 1.

In Table 2, the calculation of compensation penalties that distribution companies are responsible for in the event of long-duration outages is provided. If the alternative power supply is not activated, distribution companies incur significant penalties for each long-duration outage. However, when there are alternative power sources for the feeders in case of a fault, the occurrence of long-duration outages is prevented, and no penalties are imposed.

Table 1. F13 and F14 Feeders data.

Period of 2023	F13	F14
Number of Subscribers	118	4150
OG Number of Failures	18	168
Failure Time (Hours)	31	297,3
P (Kw)	0,4	15,5
Conductor Characteristics	3/0 PIGEON	477 HAWK

Table 2. F-14/F-13 Ring Status Interruption.

F-14/F-13 Ring Status Interruption	No	Yes
Starting Interruption	25.07.2023 23:00	25.07.2023 23:00
End Interruption	29.07.2023 10:50	29.07.2023 10:50
End Interruption (Min)	83,833	1,33
Number of Affected Subscribers (Urban AG)	4.142	4.142
Number of Affected Subscribers (Urban OG)	8	8
Total Number of Affected Subscribers District	4.150	4.150
If the Leakage Rate was below 40%, how much compensation would be paid (TL)	457.414	-

Considering the situation where the ring network is not activated on July 25, 2023, at 23:00, an outage occurred in the F-14/F-13 feeder, and power was restored around 10:50 on July 29, 2023, affecting 4142 subscribers fed from the F-14 feeder. The F-14 feeder remained without power for approximately 84 hours. According to the "Electricity Market Regulation": "Under this Regulation, the compensation amounts to be paid to users by the distribution company have been determined for the year 2021. Compensation amounts are updated using the revaluation rate published every year, and the updated compensation amounts are used for payments starting from the following year." In this context, the compensation amounts to be paid to users for the year 2022 are as follows: For long-duration outage compensation, residential subscribers with a contract capacity of 160 kVA or less will receive 108.96 TL, while other subscribers will receive 217.92 TL. Users with a contract capacity between 160 kVA and 630 kVA (inclusive) will receive 653.76 TL, and users with a contract capacity above 630 kVA will receive 1307.52 TL. For annual outage compensation calculations, CAIFI is set at 54.48 TL, and CAIDI is set at 27.24 TL. Users with a contract capacity between 160 kVA and 630 kVA (inclusive) will receive 480 TL, while users with a contract capacity above 630 kVA will receive 960 TL." Based on this information, the total compensation amount to be paid to subscribers affected by long outages is calculated. All AG subscribers are considered to have a contract capacity of less than 160 kVA, while OG subscribers are considered to have a contract capacity between 160 kVA and 630 kVA.

The Long Duration Outage Compensation has been calculated as 457,414 TL. In the event of a long-duration outage, the distribution company is responsible for paying the compensation penalty. If the alternative power source is not activated, distribution companies incur significant penalties for each long outage. When there are alternative feeders available for the feeders in case of a fault, long-duration outages are prevented, and no penalties are incurred.

In Figure 4, Inavitas data for June 2021 is presented where the F-13/F-14 ring network was not established. Upon examining this data, it can be observed that during the month, in cases of outages in F-14, where there is no alternative power source, feeder users experienced prolonged periods without electricity. The highlighted red square indicates instances where the load in F-14 has dropped to zero, while the load in F-13 remains unchanged.

In the absence of the F-13/F-14 ring investment, let's analyze the situation for a fault that occurred. According to the 10-minute data obtained from Inavitas as shown in Figure 5, a fault occurred in F-14 at around 15:20, and power was restored at around 20:20. Since there is no alternative power source, all subscribers within the supply area of the F-14 feeder experienced a total of 5 hours without electricity.

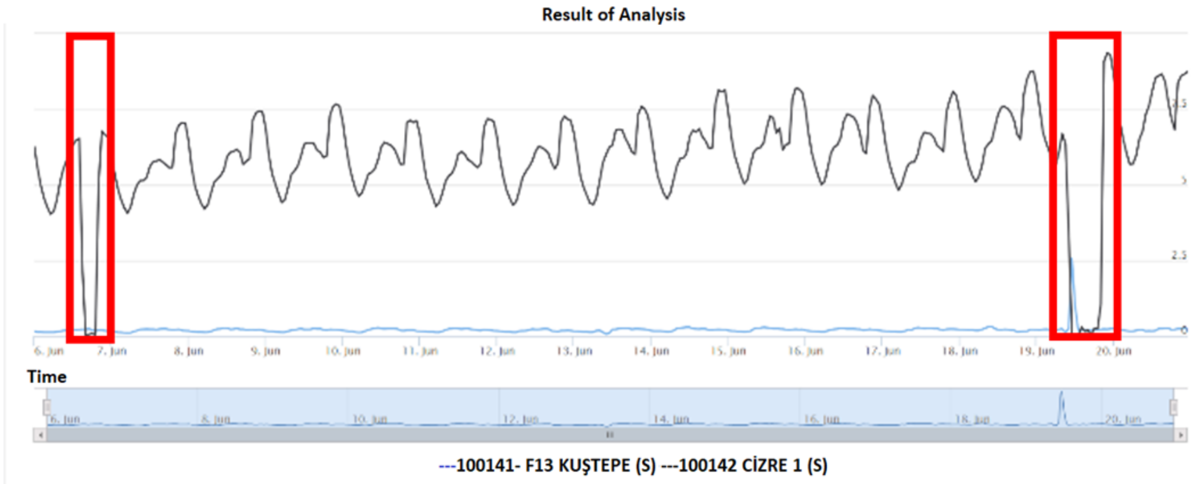

Figure 4. Without electricity for a long time June 2021.

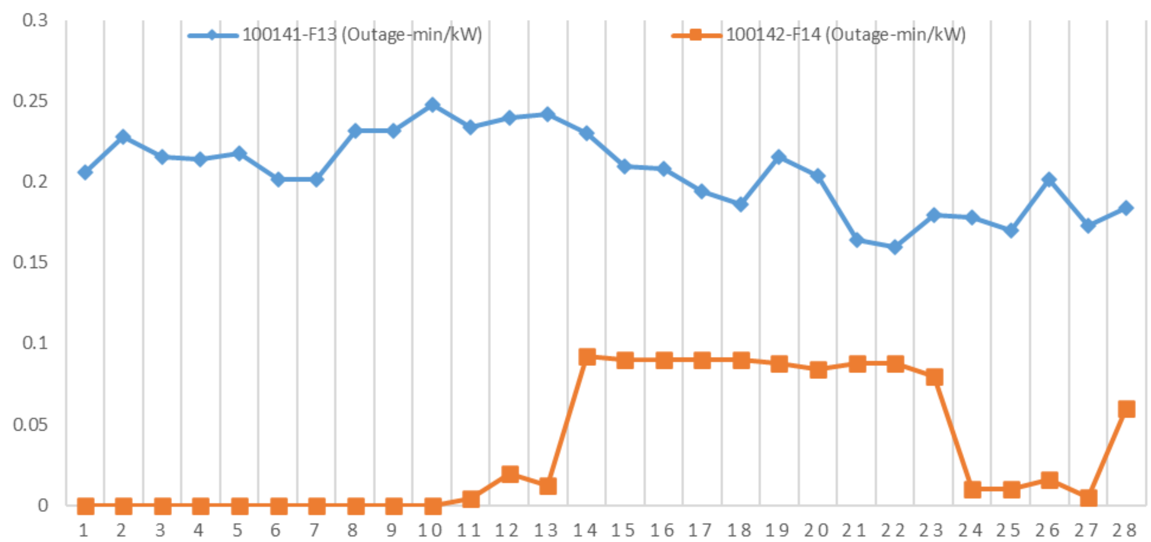

Figure 5. Numerical data for F13 and F14 for the year 2021.

Considering the energy consumption in 2021, assuming the current situation is half as much, the number of subscribers is assumed to be 2500. In order to perform feeder-based compensation calculation.

Assuming that there were 20 occurrences of the existing fault, and all subscribers are in the same tariff and have the same characteristics (Equation 5-6):

$$\mathrm{CAIFI} = \sum_{i=1}^{n} t_i \quad (\mathrm{CAIDI}) = 100 \tag{5}$$

$$PUFO_f = [\mathrm{CAIFI}f - \mathrm{TVCAIFI}f] * ENS * AD_f = [100 - 72] * 6 * 60 * 100 * 0.8 = 806{,}400.00 \text{ TL} \quad (6)$$

The 2021 residential unit price is 0.8 TL, and the average power of the feeder is chosen as 6 kW.

In the case of a long-duration outage that occurred on June 19, 2021, in F-14, lasting for approximately 11 hours, when the compensation calculation is made, it was determined that for long-duration outages in 2021, compensation of 80 TL per subscriber with a power capacity of less than 160 kVA should be paid. With a hypothetical example of 2021 subscriber numbers, it is evident that solutions need to be implemented due to the impact of prolonged outages on users' quality of life, as well as the responsibility of distribution companies for not providing continuous and quality electrical energy, which can result in penalty conditions. Network investments should aim to provide alternative power sources and ensure high-quality and continuous electrical energy.

Figure 6 displays a GIS view of the cell layout of the F-13/F-14 ring installation. According to the network, there is an input cell (F-14), two output cells supplying separate transformers, one backup cell, and one transformer protection cell within the root building due to the presence of an internal transformer. Additionally, there is an F-13 ring cell along with a coupling cell to enable ring operation with F-13. The coupling cell is where two separate energy sources enter. In the event of a fault, it automatically switches to the energy source that is operational. The cost of the installed facility is calculated, and the investment amount to be incurred is determined.

The installation cost of medium voltage metal-clad modular cells and a monoblock concrete transformer building for the recommended ring system has been investigated. This cost, based on the 2023 TEDAŞ unit price, results in an estimated cost of 534,095.06 TL for the installed F-13/F14 ring investment network.

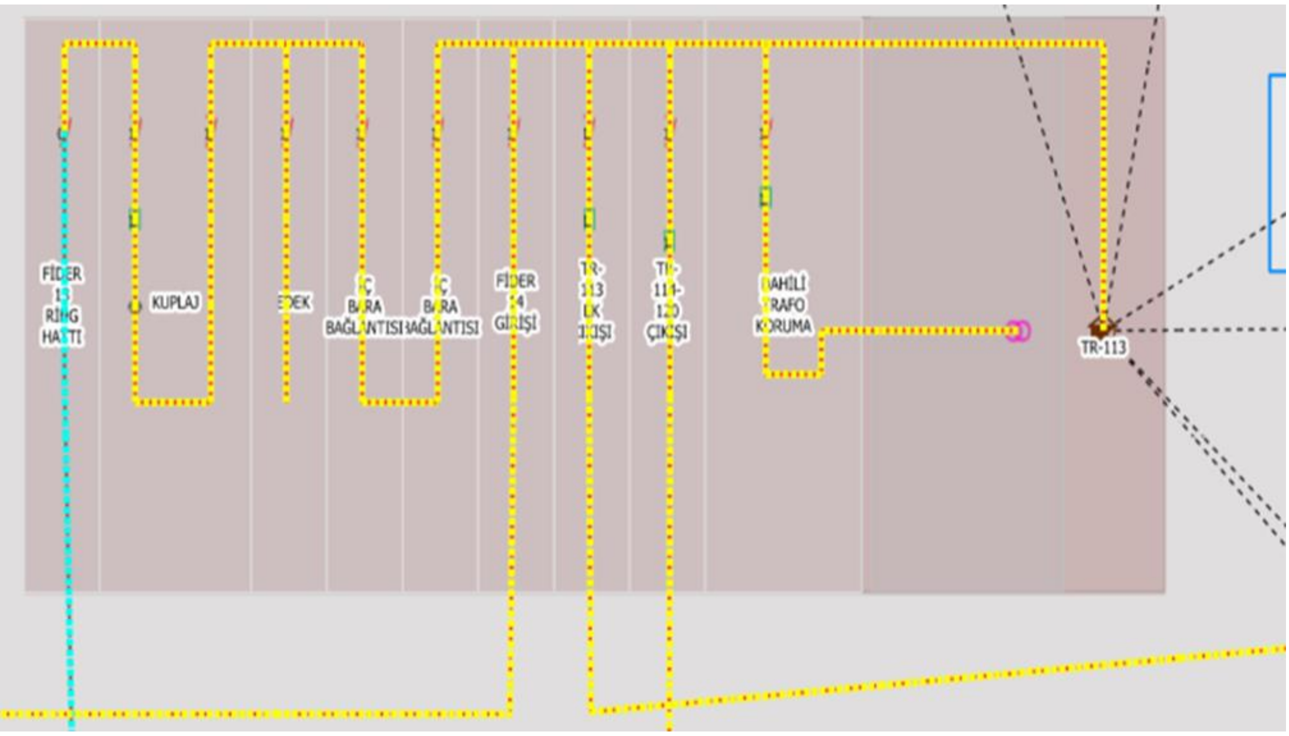

Figure 6. System of Model TR113 Cell Layout.

4. Conclusion

The proposed methodology focuses on evaluating the effectiveness of a specific method to increase the continuity of energy supply in ring networks. The F13/F14 Ring Grid model was used as a framework to analyze the impact of this method, thus adopting the cost-benefit approach to begin the analysis. This involves evaluating the costs associated with implementing the method, such as the costs associated with upgrading or replacing existing grid infrastructure to accommodate the ring grid configuration. On the other hand, the benefits of the method are evaluated by taking into account the improvements in energy supply continuity with the implementation of the ring network. One of the main issues examined in the methodology is the calculation of compensation penalties. These penalties are determined according to predetermined criteria and aim to encourage distribution companies to maintain service quality at a certain level. By quantifying the penalties that will be imposed on distribution companies for prolonged or frequent outages that exceed a certain threshold, the analysis provides a means to measure the potential financial impact of the method on these companies. Additionally, the methodology includes a comparison between costs and benefits associated with the method. While the costs include those incurred in installing the ring grid, the benefits include improvements in energy supply continuity and a corresponding reduction in outage-related costs.

The study aims to determine whether the advantages gained from applying the method outweigh the associated costs by conducting a comprehensive cost-benefit analysis. It is worth noting that the methodology takes into account a variety of factors beyond just reliability considerations. For example, they include investment costs, regulatory requirements and customer preferences regarding acceptable levels of energy supply continuity. By considering these factors collectively, a more holistic assessment of the feasibility and effectiveness of the method can be obtained. Overall, the coupling methodology used in this study offers a structured approach to evaluate the potential benefits, costs and feasibility of implementing a method aimed at increasing the continuity of energy supply in ring networks. This method uses the F13/F14 Ring Grid model, where one line is fed from the other in case of fault on a feeder. Conducting a comprehensive cost-benefit analysis, the study aims to provide insight into the economic and operational consequences of adopting this method. As a result, ensuring the continuity of electricity supply is vital for the needs and functioning of modern society. Strategies such as the use of alternative energy sources, installation of backup energy lines, infrastructure investments and technological innovations play an important role in minimizing the negative effects of power outages and meeting the energy needs of society. These steps not only increase the continuity of energy supply, but also contribute to the establishment of a sustainable and reliable energy infrastructure. In this study, the most important process to ensure the continuity of energy supply in network enterprises is the provision of an alternative power source. The alternative power source, which prevents users from being without electricity due to any potential interruption in the grid, is advantageous for both users and distribution companies.

Looking at the cost calculation, although it might seem like an initial expensive investment, comparing the potential costs of compensation fines for single long outages or total possible outages on the feeder, as shown in Figure 6.5, reveals that the investment cost of the ring network would be much more beneficial. Furthermore, like any investment, long-term returns of alternative energy investments should be taken into account. In the model, two output cells feed separate transformers for the F-14 feeder, and there is one spare cell. Additionally, a transformer protection cell exists within the main building. For achieving a ring connection with F-13, there is a coupling cell along with an F-13 ring cell. The investment made in the coupling cell is used as a cell where two different energy sources can enter. In the case of an unexpected fault, it provides uninterrupted energy supply by automatically switching to the source with energy. The investment cost for the established coupling cell is calculated as 535,095.06 TL. On the other hand, the compensation costs attributed to distribution company due to outages, for example, in the year 2021, an outage of 5 hours resulted in a fine of 806,400.00 TL. The designed ring investment would be lower than this amount, which is 271,304.94 TL, thus preventing such an outage. Similarly, in 2021, a penalty of 200,000.00 TL was issued due to an outage lasting 11 hours. Another analyzed outage occurred in 2023, lasting for 11.5 hours, which resulted in a calculated fine of 457,414.00 TL.

The method employed in the study compared the outcomes and penalty processes between the presence and absence of the F-13/F-14 ring network. It was determined that the investment cost, which is approximately equal to the estimated compensation amount for a long outage in F-14, is more profitable in the long run. To ensure that electricity distribution companies prioritize the continuity of energy supply, a comparison between such penalty situations and investments that would improve the grid needs to be made. These investments will not only enhance the grid in the long term but also ensure user satisfaction while avoiding the occurrence of penalty situations.

Author contributions

Rojin Temiz: Conceptualization, Methodology, Software, Writing-Original draft preparation. **Mehmet Rida Tur:** Data curation, Software, Validation, Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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Comparative analysis of machine learning techniques for credit card fraud detection: Dealing with imbalanced datasets

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Abstract

The main objective of this research is to evaluate the performance of machine learning algorithms in the field of credit card fraud detection and then compare them according to various performance metrics. Seven different supervised classification algorithms including Logistic Regression, Decision Trees, Random Forest, XGBoost, Naive Bayes, K-Nearest Neighbors and Support Vector Machine were used. The performance of these algorithms was measured through a comprehensive evaluation of metrics including Accuracy, Precision, Recall, F-Score, AUC and AUPRC values. Furthermore, ROC curves and confusion matrices were used to evaluate these algorithms. The data preparation phase is critical in this study. The data imbalance problem arises as an unequal distribution between fraudulent and non-fraudulent transactions. Addressing this imbalance is imperative for successful model training and subsequent reliable results. Various techniques, such as Scaling and Distribution, Random Under-Sampling, Dimensionality Reduction, and Clustering, are employed to ensure an accurate evaluation of model performance and its ability to generalize effectively. As a result, the "Random Forest" and "K-Nearest Neighbors" algorithms exhibit the highest performance levels in this research with 97% accuracy rates. This study contributes significantly to the ongoing fight against financial fraud and provides valuable guidance for future research efforts.

1. Introduction

Credit card fraud is a type of crime in which credit card information is obtained without permission and misused. The history of credit card fraud begins with the emergence of credit cards. Credit cards first began to be used in the USA in the 1950s [1]. At that time, the security measures of credit cards, which consisted of paper or metal plates instead of plastic cards, were very weak. For this reason, credit card fraud and theft became common problems from the outset. Credit card fraud causes both financial and ethical harm to credit card holders and financial institutions, constituting a significant problem worldwide. In 2019, the USA experienced a loss of $28.65 billion due to credit card fraud [2]. In Türkiye, 1.2 billion TL was lost due to credit card fraud in 2020 [3]. Therefore, combating credit card fraud has become an important field of work.

Both legal and technological measures are taken to combat credit card fraud. From a technological perspective, magnetic strips were added to credit cards in the 1960s, signature panels in the 1970s, holograms in the 1980s, and chips in the 1990s [4]. Today, methods such as biometric authentication, virtual credit cards, one-time passwords, tokenization, and blockchain have been developed. Legally, laws and regulations have been established and implemented at national and international levels to address credit card fraud [5]. These measures enhance the security of credit cards and make it more challenging for fraudsters to carry out their activities. However, fraudsters have also developed new methods and identified vulnerabilities in these security measures. In this context, fraudulent techniques such as copying magnetic stripe cards, using signature panel cards with forged signatures, imitating hologram cards, and compromising chip cards have emerged [6]. These fraudulent methods can be described in broader terms as follows:

- Card theft or loss: If a credit card is physically stolen or lost, the individual who discovers or steals it can use the card. This approach is the most straightforward and ancient.
- Card copying (skimming): Thieves engage in card copying by utilizing a specialized device to read and

copy the data from the magnetic strip of a credit card. This technique is commonly utilized at ATMs, gas stations, or restaurants.

- Phishing: Phishing involves duping individuals into divulging their credit card number, expiration date, and security code through deceitful emails, phone calls, or websites, usually perpetrated through emails or calls masquerading as the bank or institution.

The rise of online shopping, fueled by the extensive utilization of the internet, has emerged as a pivotal juncture in credit card fraud, presenting both convenience and peril to credit card holders. Fraudsters have ingeniously employed a multitude of tactics, such as counterfeit websites, phishing emails, malevolent software, and the exploitation of security vulnerabilities in wireless networks, to acquire credit card information. Moreover, as there is no requirement to physically present the credit card when making online purchases, stolen or lost credit cards can be readily utilized [7].

2. Credit card fraud detection

With the increasing number of cases of credit card fraud, the detection of this type of fraud has become of great importance. Credit card fraud detection is the process of classifying credit card transactions as normal or abnormal. This process is important to prevent or reduce losses for both credit card holders and banks. Various quantitative and statistical methods have been used in credit card fraud detection from past to present. Some of these methods are as follows:

- Behavioral analysis: This method aims to identify transactions that deviate from the norm by monitoring the shopping habits, spending amounts, frequency, and locations of credit card holders [8].
- Rule-based analysis: This method attempts to detect suspicious transactions by evaluating credit card transactions according to certain rules [9]. These rules can be criteria such as the transaction amount exceeding a certain threshold, the location of the transaction being far from the place of residence of the credit card holder, the frequency of the transaction exceeding a certain limit.
- Scoring analysis: In this method, certain points are assigned to credit card transactions, and it is aimed to measure the risk levels of transactions. Scores can be calculated based on variables such as transaction amount, transaction location, transaction time and transaction type. When the score of the transaction exceeds a certain threshold, the transaction is considered suspicious.

These methods have advantages as well as disadvantages. Advantages include simplicity, understandability, and applicability. The disadvantages include high false alarm rate, low accuracy, lack of flexibility and inability to adapt to new fraud methods [10]. With the developments in information technologies, the disadvantages of traditional detection methods are tried to be eliminated or reduced with current technologies such as machine learning and data mining. The applications of these technologies in credit card fraud detection are outlined as follows:

- Machine learning methods: Machine learning methods are automatically classifying credit card transactions based on patterns or features in the data. These methods include algorithms that can cope with the complexity and volume of data and discover hidden relationships in the data. Machine learning methods include various algorithms such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Decision Trees (DT) [11].
- Data mining methods: Data mining is the classification of credit card transactions according to statistical or logical rules in the data. These methods enable data to be transformed into meaningful and useful information. Among data mining methods, algorithms like K-Nearest Neighbor (KNN), Logistic Regression (LR), and Bayes' theorem are commonly employed [12].

There are significant challenges when using both machine learning techniques and traditional methods for detecting credit card fraud. One of these challenges is the imbalance and scarcity of data. While the vast majority of credit card transactions are considered normal, a small percentage can be classified as abnormal or fraudulent. While this makes it relatively straightforward for machine learning models to learn normal transactions, it becomes challenging to distinguish abnormal transactions. Additionally, credit card fraud data is often not shared due to privacy concerns, or there are limited datasets available, which hinders the provision of sufficient data for training and testing machine learning models. Various methods have suggested to tackle the issue of data instability and scarcity; these include:

- Data resampling methods: These involve the adjustment of normal or abnormal operation numbers to attain data balance. Utilizing techniques such as the Synthetic Minority Oversampling Technique (SMOTE) allows for an increase in minority class instances, specifically abnormal transactions [13]. Similarly, methods like random subsampling or near neighbor-based subsampling when employed significantly reduce majority class quantities; these represent normal operations [14].
- Transfer learning methods: This technique enable data acquired from different sources to be transferred to the target dataset. For instance, credit card transaction data from different banks or regions can be processed for the target bank or region. In this way, the amount of data can be increased, and model performance can be improved [15].
- Deep learning methods: With deep learning methods, complex and high-dimensional data can be processed and hidden patterns and relationships in the data can be discovered. Techniques such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) can learn the temporal and spatial characteristics of credit card transaction data and detect fraudulent transactions [16].

Another challenge of using machine learning methods to detect credit card fraud is related to the way these methods work. While machine learning models classify credit card transactions as normal or abnormal, they may not be able to explain how and why they make these decisions. This can undermine the trust of both credit card holders and banks. Moreover, machine learning models may produce false positive or false negative results. This may increase the financial and moral losses of both credit card holders and banks. Various methods have been proposed to solve the problem of explainability and transparency of the decision process. Some of them are as follows:

- Decision tree-based methods: With these methods, credit card transactions are classified as normal or abnormal and the decisions taken are shown in simple and understandable rules. For instance, techniques like Random Forests (RF) yield results through the consensus of multiple DT, and the rules of these DT can be examined to understand the outcome [17].
- Sensitivity analysis-based methods: Sensitivity analysis-based methods show the importance of the input variables that are effective in these decisions when making classification. For example, approaches like LR calculate coefficients for input variables, indicating the impact of these variables on the outcome. To see this effect, the values of the input variables can be changed to see how the result changes [16].
- Comparative analysis-based methods: They are methods that show similar or different operations that play a role in these decisions during classification. For example, algorithms such as KNN consider the k closest transactions when deciding whether a transaction is normal or abnormal. To see how these transactions are selected, distance measures between transactions are examined [17].

Machine learning techniques for credit card fraud detection have become a popular research area in recent years due to their benefits. Studies in this area are evaluated with different datasets, techniques, performance measures and application scenarios. Some of these studies demonstrate the effectiveness and advantages of machine learning techniques in credit card fraud detection [11,16-17]. Another part of the work presents the challenges faced by machine learning techniques in credit card fraud detection and proposed solutions to overcome them [13-15].

In this research, models were created using various machine learning algorithms and a prediction was performed for the detection of credit card fraud and suspicious transactions. The aim of the research is to identify the machine learning algorithms that give the best results in credit card fraud and suspicious transaction detection. In addition, another aim of the research is to reveal which data preprocessing processes can be used when working on imbalanced datasets with machine learning algorithms.

3. Material and Method

In this section, explanations of the machine learning algorithms used in the research, performance metrics employed for comparing the algorithms, characteristics of the dataset, and information about the data preparation process are included.

3.1. Algorithms utilized

Machine learning is a sub-branch of artificial intelligence and is the ability of computers to make intelligent decisions by learning from data. Machine learning uses various methods according to the nature of the data and objective variables. When these methods are analyzed, three categories emerge as (1) supervised learning, (2) unsupervised learning and (3) reinforcement learning [18]. Supervised learning is an approach to learning in which a machine learning model tries to learn the relationship between a given input and a target output [19]. Supervised learning is typically divided into two fundamental categories: classification and regression. Classification basically aims to predict whether an input belongs to a certain category or not. Regression, on the other hand, focuses on predicting a continuous numerical output associated with input data. It is used to predict a specific value or a continuous function of an output variable [20]. In this research, supervised classification algorithms are used because credit card fraud detection requires real-time intervention and requires identification between two main classes: fraudulent and non-fraudulent transactions. The real-time nature of credit card transactions requires fast and accurate decision making. Supervised classification algorithms, which learn from historical data, are capable of instantly categorizing each transaction as it occurs, thus playing a crucial role in timely detection and prevention of fraudulent acts. Therefore, the choice of supervised classification algorithms is in line with the rigorous requirements of credit card fraud detection and provides an efficient and agile system for the protection of monetary transactions.

3.2. Supervised classification algorithms

In this research, a total of seven supervised classification algorithms were employed to detect credit card fraud and suspicious transactions, which included Logistic Regression, Decision Trees, Random Forest, XGBoost, Naive Bayes, K-Nearest Neighbor, and Support Vector Machine.

3.2.1. Logistic regression

LR is a classification algorithm whose main purpose is to estimate the probability that an object or event belongs to a certain class [21]. This estimation is based on the relationship between the independent variables or features and the weights. Each feature has a separate weight, and these weights are learned during the training phase of the model. Predictions are made using a sigmoid function, which converts real numbers into a probability value between 0 and 1. The higher the probability, the more likely it is that the object belongs to a certain class. The accuracy of the model is determined by the error rate on the training data and this model can be used to classify new data and estimate probabilities [22].

The formula of logistic regression is given in Equation 1. When the formula is interpreted in terms of credit card fraud detection, $P(Y=1)$ represents the probability that an event or transaction belongs to a certain class (for example, fraud); $X_1, X_2, \dots X_k$ denotes the independent variables related to the credit card transaction (such as transaction amount, transaction location, etc.); and $b_0, b_1, b_2, \dots b_k$ represent the weights learned during the model's training, signifying the impact level for each feature.

$$P(Y = 1) = \frac{1}{1 + e^{-(b_0 + b_1X_1 + b_2X_2 + \ldots + b_kX_k)}} \quad (1)$$

3.2.2. Decision trees

DT are a machine learning method employed for addressing classification and regression problems. These trees analyze a dataset, creating a hierarchical structure where decisions are made in a step-by-step manner. This hierarchical tree begins with the root node and branches into different paths, with each node representing the value of a specific feature or variable [18]. The dataset undergoes processing within this tree structure, with data being divided into subgroups, and decisions being made at each node. These decisions are utilized to classify data points or predict target variables. DT employ various criteria to select attributes that best encapsulate the information within the data. Some of these criteria include concepts like entropy, gain rate, and the Gini index [23]. DT can perform effectively, particularly when dealing with nonlinear data or complex relationships.

3.2.3. Random forest

RF is considered a collective machine learning technique, effectively used in data mining and classification problems. RF primarily comprises decision trees. The operational principle of RF involves partitioning the dataset into random subsets and creating a distinct decision tree for each subset. These decision trees are trained independently and are utilized for classifying data points or predicting target variables. The final forecast is made by averaging the votes or forecasts of these decision trees [24].

One of the key advantages of RF is that it can handle the complexity of the dataset and model non-linear relationships. This allows RF to work particularly well with complex and high-dimensional datasets. Moreover, RF can reduce the noise in the data and avoid the problem of overfitting. Therefore, RF is a widely preferred algorithm for classification and regression problems [25].

3.2.4. Gradient boosting decision tree

The Gradient Boosting Decision Tree (XGBoost) is a collective learning method that successfully solves both classification and regression problems. This algorithm is built by combining multiple decision trees, but these trees are not randomly generated; rather, each tree focuses on correcting the errors of the previous trees [26]. This method involves an iteration process in which trees are built sequentially. Each new tree is trained to reduce the errors of the predictions of the previous trees. XGBoost is especially preferred for problems that require high performance and work with large datasets. This method provides high accuracy in processing complex data and provides an effective regularization mechanism to prevent overfitting [27].

3.2.5. Naïve bayes

Naive Bayes (NB) is a machine learning algorithm based on Bayes theorem and used to solve classification problems. This algorithm is basically a probabilistic classifier, meaning that it uses probability rules to calculate the probability that an object or data belongs to a certain class. Naive Bayes is called "naive" (pure or simple) because it is an algorithm whose assumptions are quite simple and independent.

One of the advantages of the algorithm is that once trained, it can accurately classify data even on small datasets. This is especially important in applications with limited data. The fundamental principle underlying NB assumes that each data feature independently influences the class label, and the product of these influences provides the class prediction [28].

3.2.6. K-Nearest neighbor

KNN algorithm is a supervised learning algorithm for classifying an observation or predicting a value. The basic idea is that the class to which an observation belongs is determined based on the classes of its nearest neighbors. This closeness is typically calculated by Euclidean distance, shown in Equation 2, or other similar distance metrics.

The logic of the algorithm is quite simple. First, for a given observation, K nearest neighbors need to be found. These neighbors are determined by the distance metric around the observation. KNN looks at the class labels of these neighbors and assigns the class label of the majority as the predicted class.

KNN is the algorithm of choice for small datasets or entry-level classification problems due to its simple working principle and easy comprehensibility. However, it should be applied with caution when used on large datasets due to its computational complexity [29].

$$d(x, y) = \sqrt{\sum_{i=1}^{n} \sqrt{(y_i - x_i)^2}} \quad (2)$$

3.2.7. Support vector machine

SVM is an efficient classification and regression algorithm for high-dimensional datasets. Its basic principle is based on separating and classifying data by creating a hyperplane (bounding) in an n-dimensional space. This hyperplane has the same dimension as the number of independent variables (n) and acts as a classification discriminator by dividing data points into two classes [30].

A good SVM model tries to follow this hyperplane, which has the greatest distance to the nearest training data points. This distance affects the generalization ability of the model. The greater the distance, the more likely the model is to perform better on new data. Therefore, SVM aims to optimally separate data points.

Furthermore, SVM offers the ability to transform data into another space using kernel functions. This is useful for handling situations where data cannot be separated linearly or where a space is needed that will provide a better separation.

3.3. Data validation method

In this research, training and test data validation method is used to detect credit card fraud and suspicious transactions. This method aims to evaluate the performance of the model by dividing the dataset into two main parts. The first part, the "Training Dataset", is used in the learning phase of the model. The model is trained on this dataset and learns the patterns and relationships between the data. The second part, the "Test Dataset", is used to evaluate the performance of the model. It shows how the model reacts to data outside this dataset.

Figure 1 shows the flowchart of the model created in accordance with the training and test validation method. The aim is to identify issues with the model and assess its performance on real-world data, thereby contributing to the acquisition of more reliable results through the maintenance of a balanced approach between the training and testing phases [31].

3.4. Performance metrics

Conventional techniques for evaluating machine learning classifiers employ measurements that establish a connection between the level of confusion and the disparities between the ground truth data and the model's predictions, with TP, TN, FP, and FN representing true positives, true negatives, false positives, and false negatives, in that order.

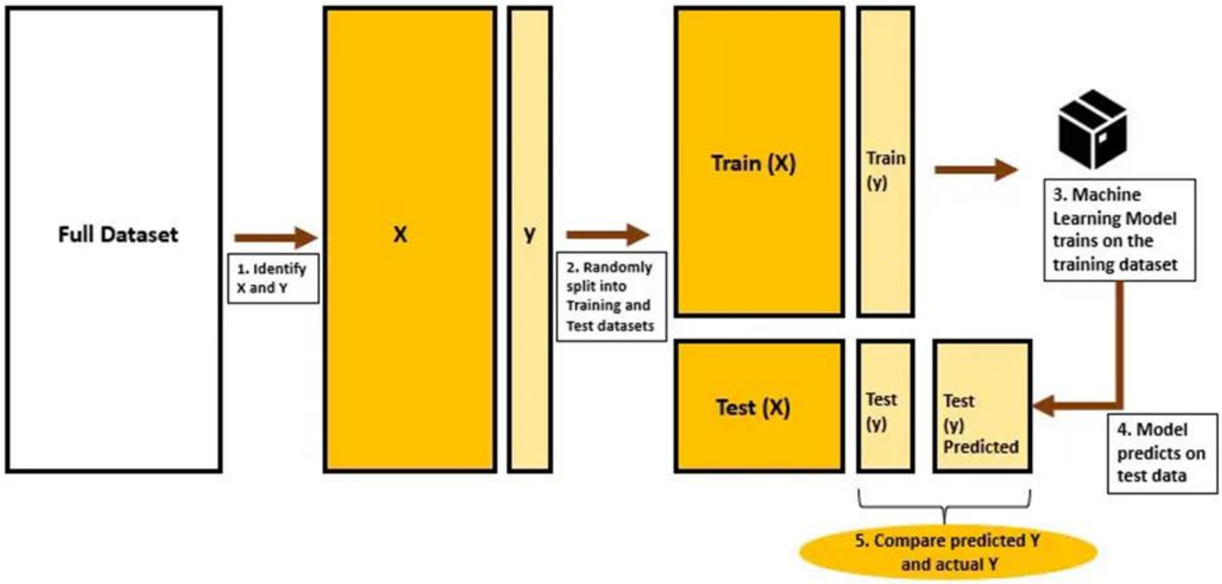

Figure 1. Training and testing validating method.

3.4.1. Accuracy

Accuracy is employed to assess the effectiveness in the retrieval and processing of data in the evidence domain. The Equation 3 can be used to express the proportion of correctly classified outcomes as follows:

$$Accuracy = \frac{TP + TN}{TP + FP + TN + FN} \quad (3)$$

3.4.2. Precision

Precision is a performance metric that quantifies the proportion of accurately identified positive cases among the total number of identified positive cases. This can be illustrated as shown in Equation 4.

$$Precision = \frac{TP}{TP + FP} \quad (4)$$

3.4.3. Recall

Recall, often referred to as sensitivity, represents the ratio of relevant instances successfully retrieved out of the total number of retrieved instances. This can be described as shown in Equation 5.

$$Recall = \frac{TP}{TP + FN} \quad (5)$$

3.4.4. F-Measure/F1-Score

The f-measure considers both precision and recall. It can be thought of as the weighted average of all values, as shown in Equation 6.

$$F1 = 2 * \frac{(precision * recall)}{(precision + recall)} \quad (6)$$

3.4.5. Receiver operating characteristic curve

The Receiver Operating Characteristic Curve (ROC) is a graphical representation of the performance of a classification model at all classification thresholds. The ROC curve has two parameters: True Positive Rate (TPR) and False Positive Rate (FPR). Lowering the classification threshold results in more items being classified as positive [32].

TPR is calculated using the formula expressed in Equation 7.

$$TPR = \frac{TP}{TP + FN} \quad (7)$$

FPR, the False Positive Rate, is defined as shown in Equation 8.

$$FPR = \frac{FP}{FP + TN} \tag{8}$$

3.4.6. The area under the curve

The Area Under the Curve (AUC) of the ROC Curve is expressed as the area beneath the ROC Curve. The AUC value varies between 0 and 1. A model with a 100% prediction error rate has an AUC of 0. A model with 100% correct predictions has an AUC of 1 [33].

3.4.7. Area under the precision-recall curve

Area Under the Precision-Recall Curve (AUPRC) is an important metric used to evaluate the performance of a classification model, especially in scenarios with imbalanced classes. It quantifies the trade-off between precision (the ratio of true positives to all positive predictions) and recall (the ratio of true positives to all actual positives) as the classification threshold changes. AUPRC represents the area under the precision-recall curve, which ranges from 0 to 1. A higher AUPRC value indicates better model performance, with better classification of both positive and negative samples. This metric helps fine-tune models to achieve a balance between precision and recall, ultimately improving overall classification performance.

3.5. Dataset

The dataset consists of credit card transactions made by European cardholders in September 2013. It spans two days and covers a total of 284,807 transactions, of which 492 were fraudulent [34]. Notably, this dataset exhibits a significant class imbalance, with fraudulent transactions representing only 0.172% of the total. Machine learning is faced with obstacles when dealing with imbalances in datasets, as there is a notable disparity in the distribution of classes. This discrepancy can create bias towards the dominant class when training models using these datasets, resulting in inadequate identification of patterns related to the minority class. This can hinder the ability to apply learned patterns to new data, particularly for the less represented class, and standard accuracy measurements may provide deceptive results.

The dataset consists solely of numerical input variables obtained through Principal Component Analysis (PCA), with features V1 to V28 representing PCA-derived principal components. "Time" and "Amount" are the only features that have not been transformed using PCA. "Time" represents the elapsed time in seconds since the first transaction, while "Amount" denotes the value of the transaction. The "Class" feature serves as the response variable, taking a value of 1 for fraud cases and 0 for non-fraud cases. Given the class imbalance, accuracy is best assessed using the AUPRC. To comprehend the data and understand the significance of each feature in relation to the model's predictions, a bar chart is used. This bar chart, depicted in Figure 2, provides insight into the features that have a more significant impact on the outcomes of the model, helping to understand the relationships between the features and the performance of the model.

The correlation table, illustrating the relationships between each feature in the dataset, is presented in Figure 3.

Table 1 provides a list of features and their descriptions, which are crucial in the detection of transactions classified as fraudulent, as evident from the information presented in Figure 2 and Figure 3.

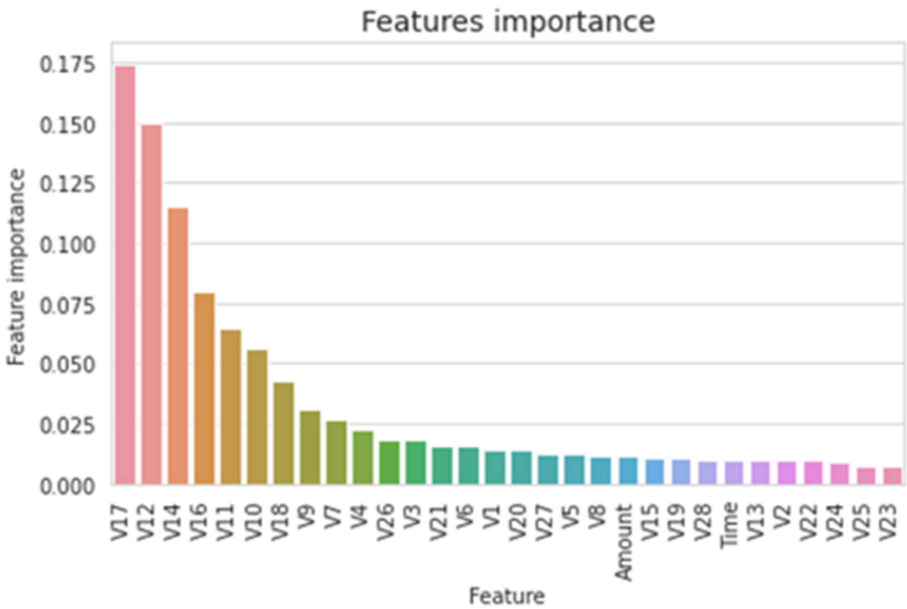

Figure 2. Features importance.

3.6. Data preparation

If the dataset is imbalanced, meaning one class has significantly more examples than the other, model training can become biased and yield misleading results. Therefore, data balancing is necessary. In the dataset used for this research, the overwhelming majority of transactions are non-fraudulent. Consequently, some initial data preprocessing was performed.

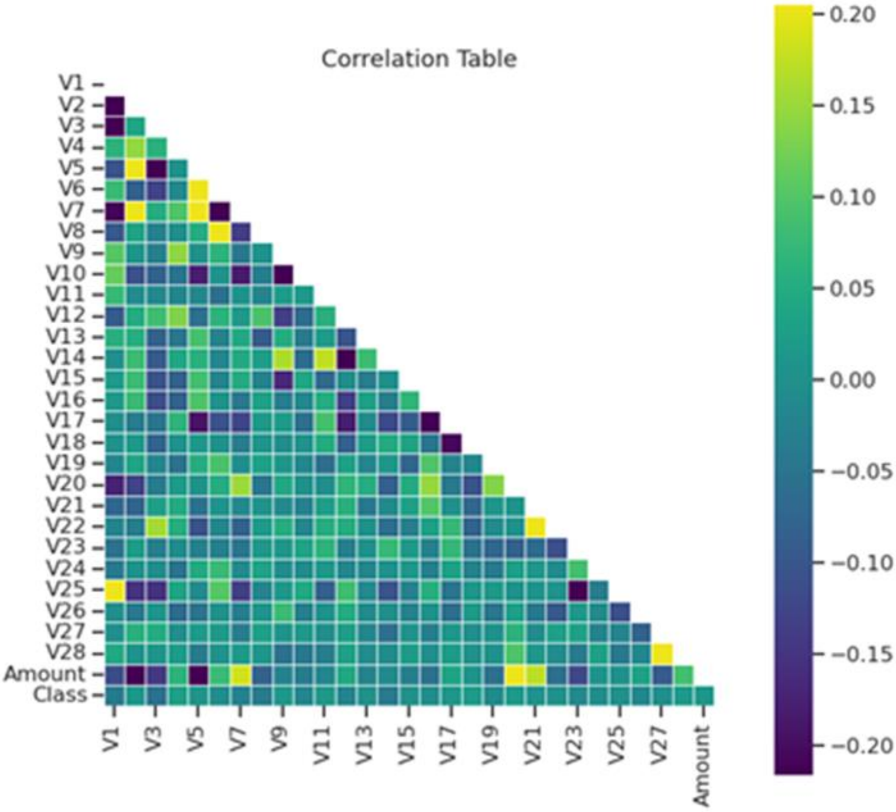

Figure 3. Correlation table.

Table 1. Features and descriptions.

Features	Description
ID	A distinct identifier for each row
Time	The duration in seconds between the current transaction and the first transaction in the dataset
V1-V28	Characteristics resulting from dimensionality reduction, applied to safeguard user identities and sensitive features
Amount	The transaction value
Class	Target category (1 for fraudulent transactions, 0 for legitimate transactions)

3.6.1. Scaling and distribution

In the specified phase of our study, the 'Time' and 'Amount' columns were standardized to the same scale as the other columns, employing Z-score standardization. Z-score standardization, also referred to as Z-score normalization or zero-mean normalization, is an essential statistical technique utilized to convert a numerical variable into a standard normal distribution with a mean of 0 and a standard deviation of 1. This method proves highly valuable in the realm of data preprocessing for machine learning and statistical analysis. The process of Z-score standardization can be described in the following steps, which guarantee the features are on a unified scale, enabling direct comparison and avoiding the dominance of any individual variable in the modeling process.Data collection: Starting with the raw data, which includes the “Time” and “Amount” columns, as well as other relevant features.

1. Compute the mean and standard deviation: Calculate the mean (μ) and standard deviation (σ) for both the “Time” and “Amount” columns. The mean denotes the average value, while the standard deviation quantifies the spread and variability of the data.
2. Z-score transformation: The Z-score (z) for each data point (x) in the "Time" and "Amount" columns is calculated using the Z-score (Equation 9):

$$Z - score(z) = \frac{\pi - \mu}{\sigma} \quad (9)$$

Equation 9 utilizes z as the standardized representation, x as the initial data point, and μ (mu) and σ (sigma) as symbols for the column's mean and standard deviation respectively. By applying this computation to every data point, novel figures are generated for the columns of “Time” and “Amount”, guaranteeing their means approximate 0 and their deviations approximate 1. The collective influence of feature scaling ultimately leads to heightened model efficacy and increased precision in identifying fraudulent activity.

3.6.2. Random under-sampling

At this stage, the 'Random Subsampling' technique is used to address the problem of class imbalance in the dataset. The primary goal is to prevent overfitting in machine learning models and ensure their effective performance. Below is a step-by-step description of the process:

1. The degree of class imbalance in the dataset was first assessed by determining the number of samples for each class label, for both fraudulent transactions (Fraud = "1") and non-fraudulent transactions.
2. Once the number of samples for fraudulent transactions was determined, the dataset was balanced by setting the number of non-fraudulent transactions equal to the number of fraudulent transactions to achieve a 50/50 balanced ratio. The aim is to ensure that if there are 492 cases of fraud, there are an equal number of 492 cases of non-fraudulent transactions.
3. To apply this technique, a sub-sample of the dataset was created to ensure a balanced 50/50 ratio between the two classes. This sub-sample consists of only 492 fraud instances and 492 non-fraudulent transaction instances.
4. Performing data shuffling is crucial to guarantee the reliability of the model's performance. Shuffling helps to eliminate possible biases or patterns in the dataset that could affect the training and evaluation of the model.

By following these steps, not only is the problem of class imbalance addressed, but the data is organized in such a way that machine learning models can generalize effectively and make accurate predictions.

3.6.3. Dimensionality reduction and clustering

The process of dimensionality reduction and clustering is performed to increase the understanding of the underlying structure of the dataset, to streamline the data and to distinguish patterns or clusters within it. At this stage, the t-distributed stochastic neighbor embedding (t-SNE) method is used, which serves as a technique for data visualization and dimensionality reduction. This method takes high-dimensional data points and transforms them into a lower-dimensional space to improve our understanding of the structure of the data. t-SNE is particularly used for visualizing data by preserving similarities and dissimilarities between data points. The primary objective is to simplify the dataset and, in doing so, improve the applicability of various machine learning techniques for fraud detection. Specifically, t-SNE excels in clustering both fraudulent and non-fraudulent cases, as evidenced by the results depicted in Figure 4. This observation remains consistent across various scenarios, even after randomizing the dataset. Essentially, this implies that applying additional predictive models is likely to be successful in effectively differentiating between fraud and non-fraud cases.

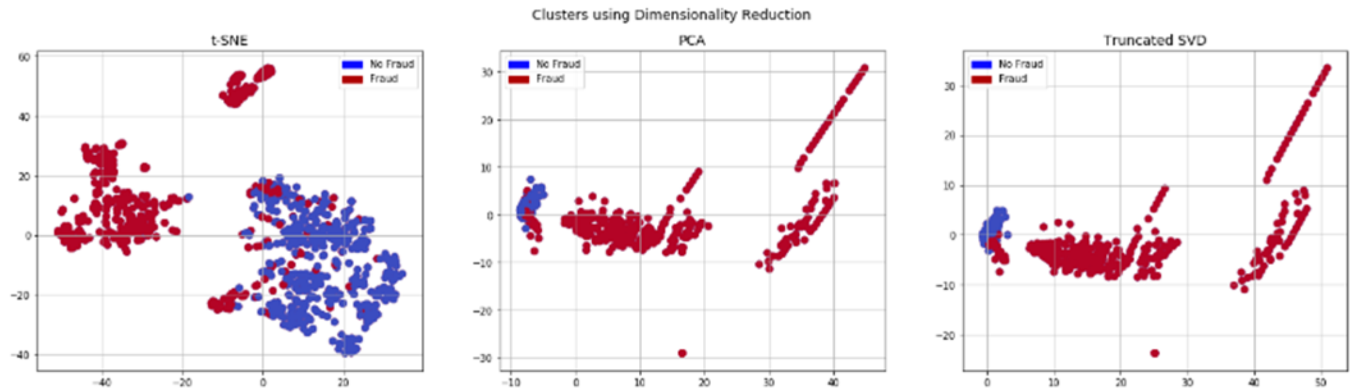

Figure 4. Clusters using dimensionality reduction.

4. Experimental study and results

In this study, supervised classification algorithms such as LR, DT, RF, XGBoost, NB, KNN, and SVM algorithms were employed to detect fraudulent transactions in credit card transactions. When creating the model, the dataset was divided into two parts: 80% for training and 20% for testing. In all the algorithms used, the random state was set to 42. The number of trees in the RF was defined as 12. In KNN, the number of neighbors was set to 5. In the XGBoost algorithm, the learning rate was determined as 0.01, the number of predictors was set to 10, and the number of seeds was 25. In the SVM, the kernel used was the Radial Basis Function (RBF), and the C parameter was set to 2. In SVM optimization, the C parameter indicates the degree to which misclassification of each training sample will be avoided. Figure 5 and Figure 6 presents the confusion matrices for the utilized algorithms.

When examining Figure 5 and Figure 6, confusion matrices were employed as a crucial tool to analyze the performance of each algorithm in a detailed manner. Notably, the RF algorithm excelled in correctly identifying non-fraudulent transactions, demonstrating the highest True Negative value. On the KNN algorithm exhibited remarkable performance in correctly classifying transactions carrying signs of fraud, boasting the highest True Positive value. On the other hand, the NB algorithm displayed a tendency to have higher False Negative values, which could potentially increase the risk of failing to identify fraudulent transactions. Other algorithms exhibited similar performance characteristics.

When examining Figure 7, the graph presents the AUC-ROC (Area Under the Receiver Operating Characteristic) and AUPRC scores of different machine learning algorithms. These scores serve as critical metrics for evaluating the performance of classification models. AUC-ROC measures the trade-off between the false positive rate and the true positive rate. It reflects a model's ability to accurately classify non-fraudulent transactions while minimizing false positives. A higher

AUC-ROC score indicates a better overall classification performance. On the other hand, AUPRC assesses the balance between recall and precision and is particularly useful for imbalanced classification tasks. High AUPRC scores indicate a model's ability to effectively detect fraudulent transactions and minimize false positives.

The graph shows that the RF algorithm exhibits the highest AUC-ROC and AUPRC scores, demonstrating its outstanding performance in accurately identifying legitimate transactions and effectively detecting fraudulent ones. Similarly, the KNN algorithm shows remarkable proficiency in correctly classifying fraudulent transactions, as evidenced by its superior AUC-ROC and AUPRC scores. In contrast, the NB algorithm shows relatively lower AUC-ROC and AUPRC scores, indicating potential limitations in accurately detecting fraudulent transactions.

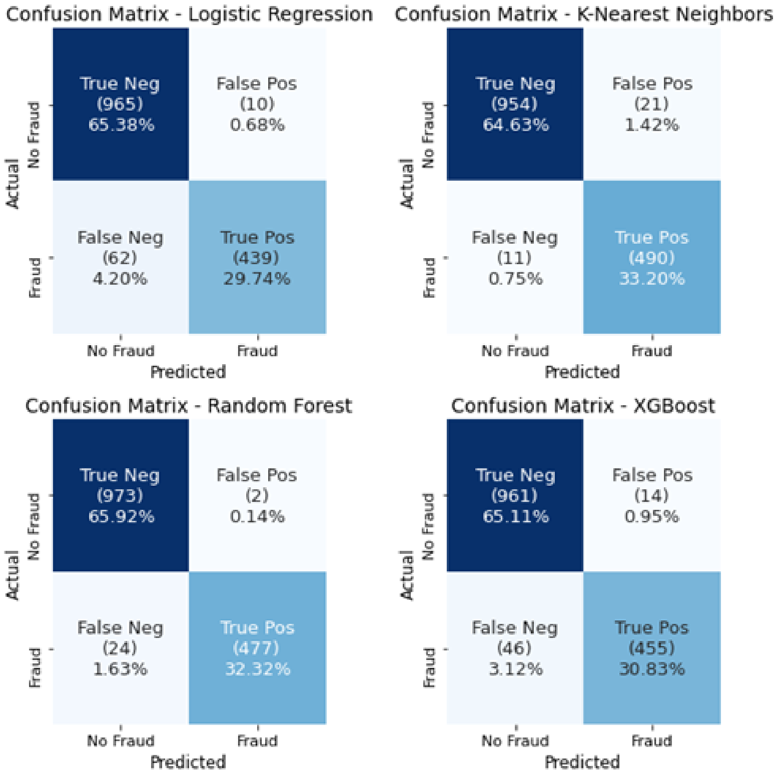

Figure 5. Confusion matrices.

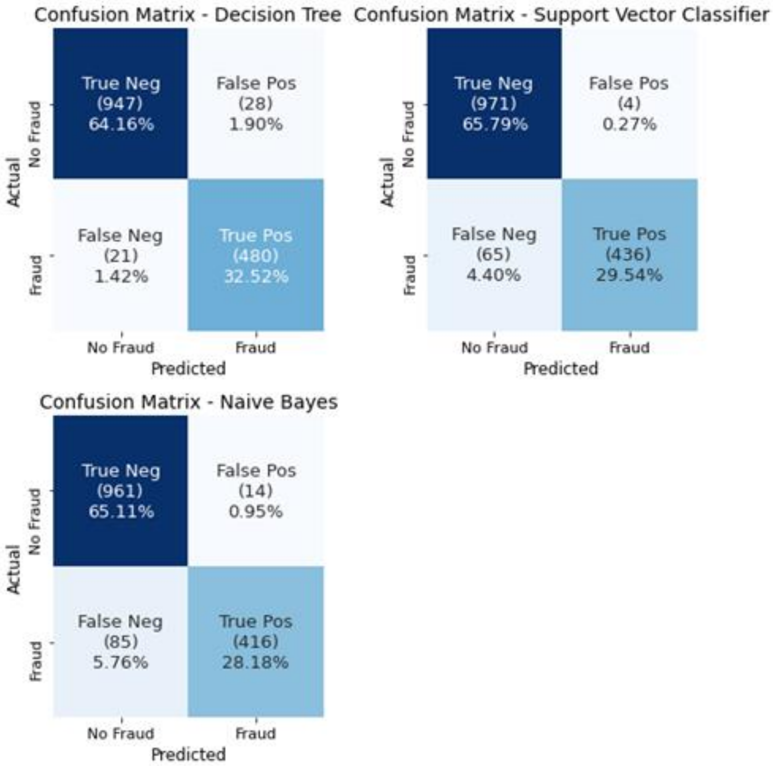

Figure 6. Confusion matrices.

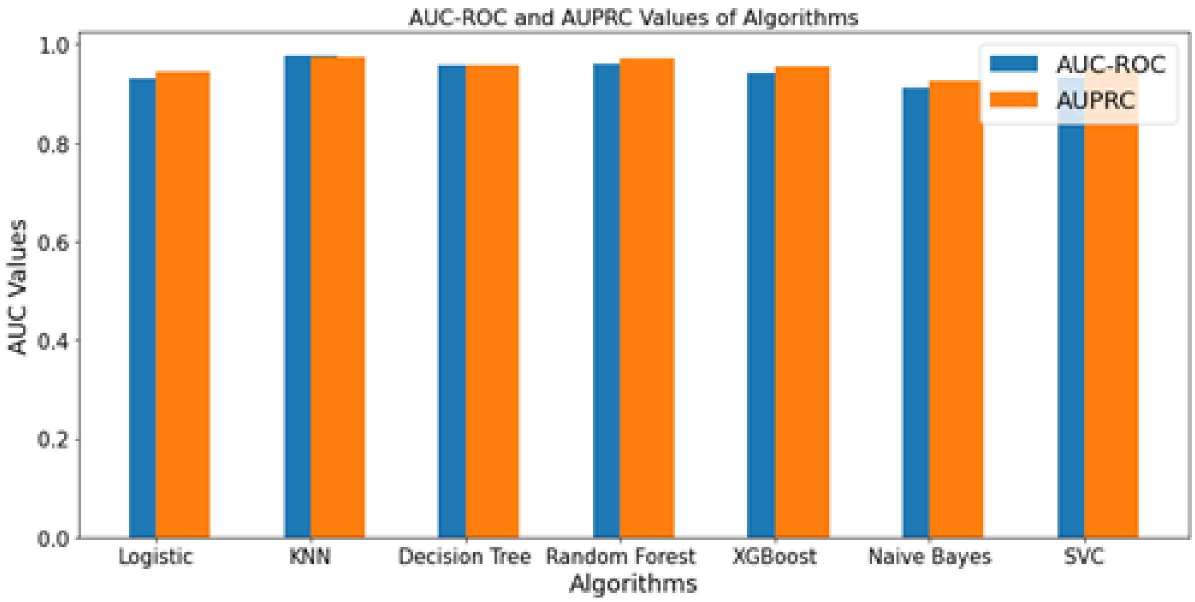

Figure 7. AUC-ROC and AUPRC values of algorithms.

Table 2 shows that two algorithms, RF and KNN, show strong potential in this area. However, some other algorithms also show performance metrics close to RF and KNN, indicating that there is no single solution for credit card fraud detection and that the choice of algorithm may depend on specific operational requirements and priorities.

Table 2. Performance metrics.

Classifier	Accuracy	Precision	Recall	F1-Score	AUC-ROC	AUPRC
LR	0.95	0.97	0.87	0.92	0.93	0.94
KNN	0.97	0.96	0.96	0.96	0.97	0.97
DT	0.96	0.94	0.95	0.95	0.96	0.95
RF	0.97	0.99	0.94	0.96	0.97	0.98
XGBoost	0.96	0.98	0.91	0.94	0.94	0.95
NB	0.94	0.96	0.86	0.90	0.91	0.92
SVC	0.95	0.98	0.88	0.93	0.93	0.95

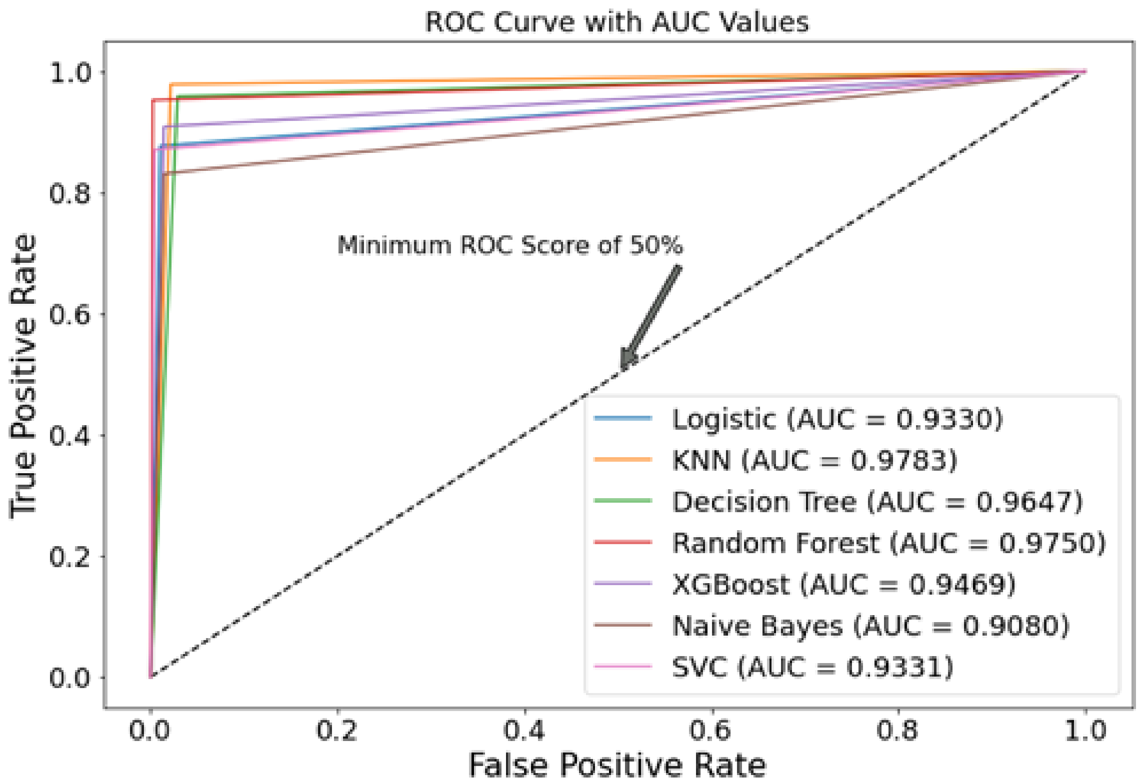

Figure 8. ROC curve with AUC values.

RF exhibits an accuracy rate of %97, indicating its flexible classification capability. This corresponds to an AUC-ROC score of 0.97 and an AUPRC score of 0.98, highlighting its expertise in distinguishing between fraudulent and non-fraudulent transactions (F1-Score = 0.96). These AUC values underline the likely utility of the model in detecting credit card fraud. Moreover, the concordant performance indicators suggest that RF can deliver reliable predictions even in situations involving imbalanced datasets, which is a common obstacle in fraud detection.

KNN excels in correctly distinguishing fraudulent transactions with a 97% accuracy rate and AUC-ROC score of 0.97 and AUPRC score of 0.97 (F1-Score = 0.96). The high accuracy rate and high AUC values emphasize that KNN is a powerful algorithm for credit card fraud detection.

It is worth noting that the NB algorithm shows relatively lower performance metrics compared to the other algorithms, with 94% accuracy. The precision (0.96) and recall (0.86) values, while not significantly lower, are relatively less competitive when considered in the context of the task (F1-Score = 0.90). This highlights the limitations of this algorithm in achieving accuracy levels comparable to other algorithms, especially in situations where higher precision and recall rates are crucial.

When the ROC curve plot in Figure 8 is analyzed, it is seen that the classifiers exhibit a high performance. The ROC curve provides a visual representation of how a model's sensitivity (true positive rate) and specificity (true negative rate) change at various thresholds.

The two prominent algorithms in this context are KNN and RF. Both algorithms achieved very high AUC scores, emphasizing their proficiency in data classification. KNN shows an AUC score of 0.97, emphasizing its effectiveness in correctly identifying cases while maintaining the balance between precision and recall. RF, on the other hand, exhibits an equal AUC score of 0.97, emphasizing its superior performance in classification.

4. Discussion

Researchers in the fraud detection field are constantly exploring and debating the effectiveness of different methodologies. Within the framework of this discourse, this section explores the comparison of the current study findings with previous studies. Employing preprocessing techniques such as scaling, random under-sampling, dimensionality reduction, and clustering can enhance fraud detection rates when comparing study findings with research on the same dataset using classification algorithms [35] and [36]. Additionally, classifying algorithms were proven to be as successful as deep learning algorithms, consistent with papers [37] and [38]. However, papers [39] and [40] advocate for deep learning algorithms as optimal, but the decision should be situation dependent. Deep networks outperform with larger datasets and exhibit versatility across various domains, thereby conferring them with distinct advantages. Nevertheless, in contexts where the emphasis lies on interpretability and cost-effectiveness rather than the intricacy of deep learning models, classification algorithms arise as a more pragmatic option. The straightforwardness and efficient utilization of resources by classification algorithms render them highly suitable for scenarios with constrained computational resources or where a transparent comprehension of the decision-making process is imperative [41]. These insights actively contribute to ongoing discussions regarding the selection of appropriate methodologies in the field of fraud detection, providing valuable considerations for real-world applications.

5. Conclusion

This study meticulously examined seven supervised classification algorithms, namely LR, DT, RF, XGBoost, NB, KNN, and SVM, to identify the most effective machine learning algorithms in the field of credit card fraud detection. After a thorough review, the evaluation of these algorithms to detect instances of credit card fraud and suspicious transactions yielded remarkable results and successfully achieved the goal of the study.

The data preparation phase in this study played a crucial role in guaranteeing the reliability and precision of the subsequent analysis. To address the issue of class imbalance, it becomes imperative to perform a preliminary data balancing process to overcome the uneven distribution between non-fraudulent and fraudulent transactions. Improving model performance and accuracy in fraud detection requires significant adjustments in scale and distribution, as well as the creation of a balanced sub-sample. A technique called "random subsampling" was used to ensure fair representation of both types of transactions and to minimize class imbalance and overfitting. Furthermore, the application of clustering and dimensionality reduction techniques increased our understanding of the structure of the dataset and facilitated the implementation of various machine learning algorithms. Among these algorithms, the t-SNE algorithm exhibited exceptional precision in categorizing fraudulent and non-fraudulent samples.

The RF algorithm proved to be the most efficient algorithm based on performance measurements. It exhibits exceptional accuracy, as evidenced by its remarkable AUC-ROC and AUPRC scores. It demonstrates a remarkable ability to correctly identify legitimate transactions while minimizing false positives, an important consideration in fraud detection. Alongside RF, KNN demonstrates exceptional proficiency in accurately classifying transactions that show signs of fraud, as evidenced by the highest true positive values. Its precise identification of fraudulent transactions positions it as an important algorithm for credit card fraud detection. Furthermore, the NB algorithm is relatively less competitive when considered in the context of the task.

In a broader context, these findings play an important role in ongoing efforts to combat financial fraud and guarantee the protection of customer and corporate assets. The selection of an algorithm holds immense significance, driven by data characteristics, the delicate equilibrium between sensitivity and accuracy, and the comparative expenses of false positives and false negatives. Depending on specific needs and priorities, the optimal approach for a company and its customers varies. If the main goal is to reduce false positives and effectively detect legitimate transactions, it is advantageous to use the RF algorithm. Alternatively, if precise identification of fraudulent transactions is crucial, particularly in cases where fraud indicators are present, the KNN algorithm may be better suited for this purpose. As the financial sector progresses, such research will provide invaluable perspectives and direction for the establishment of resilient fraud detection systems. It is evident that advancements are being made towards more secure financial transactions, and these outcomes denote a substantial progression in that trajectory. This has the potential to unlock opportunities for further exploration and pragmatic applications in the industry.

Conflicts of interest

The authors declare no conflicts of interest.

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Analyzing global competitiveness of Turkish air conditioning industry

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Abstract

The global economy significantly relies on the air conditioning sector, which has been gaining increased importance worldwide and in Türkiye due to the impact of global warming, climate change, and the diminishing energy resources. As a multifaceted industry encompassing air conditioning, heating, installation, insulation, refrigeration and ventilation sector has been adapting to the growing demand for environmentally friendly and energy-efficient solutions. This study analyzes air conditioning industry of Türkiye and its sub-product groups in terms of its ability to compete internationally, spanning from 2001 to 2021. To assess competitiveness, we employed various analytical tools, including Balassa's Revealed Comparative Advantages Index (RCA), Vollrath Indices (RXA, RMP, RTA, RC), Revealed Symmetric Comparative Advantages Index (RSCA), Trade Balance Index (TBI), and Product Mapping method. Notably, there is no research that scrutinize the competitiveness of the Turkish air conditioning industry utilizing the Product Mapping. The study findings emphasize that air conditioning industry of Türkiye has competitiveness. Within the sub-product group, the analysis reveals that Türkiye has competitiveness for 11 products, a near-limit competitiveness for 3 products, and a lack of competitiveness for 10 products.

1. Introduction

Recently, due to globalization, information and technological developments, the nature of competition has altered radically. The most significant actor in the growth and development of the country's economy is international trade. Export plays a crucial role in reducing the dependence of enterprises on the domestic market and increasing their competitiveness. In short, the existence of competitiveness in a country and the existence of stability on a macroeconomic scale depend on qualified workforce, an effectively functioning market order and the existence of a developed commercial infrastructure. Stigler [1] clarified the concept of competition as "*the competitive activity of two or more people*". While Classical Economists put forward the concept of competition as a dynamic structure, Neo-Classical Economists analyzed the concept of competition with static equilibrium under perfect competition conditions. Jevon mentioned the significance of the concept of competition as follows: "*If there is no competition between economic agents and workers, there is little, or even nothing, that economics can do.*" [2]. Some academics have enlightened the determinants of competitiveness. Adam Smith [3], as absolute cost advantage, Ricardo [4], as comparative cost advantage, Eli Heckscher and Bertil Ohlin [5]as factor endowment, Kenen [6] and Keesing [7], as skilled labor force, Posner [8], as technology innovation, Vernon [9], Krugman [10], Grossman and Helpman [11] and Lai [12], technological innovations, development of new products, as activities of multinational companies, Porter [13], at high level and as a constantly increasing productivity, Moon et al., [14], as the interaction between local diamonds and global diamonds, Cho [15], as the ability of human factors to use physical factors effectively, Aiginger [16], as the ability to create wealth, Cho, Moo and Young [17] explained it as the interaction of local and international factors and the opening of human factors to inter-country circulation .

The world has entered a transition process with the transition from the 20th century to the 21st century. The main effects of this process on the world have been realized as global warming and environmental effects. In this process of alteration, the need for the air conditioning sector to provide comfortable living conditions is gradually booming. In addition, factors such as the growth of the construction industry, climate change and increasing consumer tendency towards comfort have also increased the demand for the air conditioning sector. Sub-product groups such as heating, cooling, ventilation and air conditioning systems and equipment are in high demand by consumers owing to increasing temperatures every year, cold winters, and unpredictable climatic conditions. During the Covid-19 pandemic, the demand for ventilation systems in the sector has increased and its significance has been recognized. These factors reveal that the air conditioning industry will be an indispensable part of the future and will be an industry that increases its importance day by day. Therefore, these enhanced the focus of the study.

The air conditioning sector is one of the most significant export items of the machinery-manufacturing sector. Türkiye has become an important player in the air conditioning sector, meeting the rapidly developing domestic demand, both in an intensely competitive environment and with increasing exports in international markets. This air conditioning sector rises its added value with engineering and design services.

This study analyzes air conditioning industry of Türkiye and its sub-product groups in terms of its ability to compete internationally, spanning from 2001 to 2021. In this regard, Balassa's Revealed Comparative Advantage Index (RCA), Vollrath Indices (RXA, RMP, RTA, RC), Revealed Symmetric Comparative Advantage Index (RSCA), Trade Balance Index (TBI) and Product Mapping were used in this study. There was no study, which was conducted to analyze air conditioning industry of Türkiye in terms of global competitiveness.

Studies in the literature within the scope of the air conditioning industry are generally related to the field of engineering. Since the number of studies in the literature is very limited in terms of evaluating the place of the air conditioning industry in international competitiveness, both nationally and internationally, it is supposed that this study will contribute to the literature and be important as a reference source for future research.

This study is essentially divided into four sections. After the introduction section, the foreign trade situation of the air conditioning sector is mentioned. Subsequently, studies using both the Air Conditioning sector and product mapping method were included in the literature review section. In the methodology section, the indices used are explained in detail. In the results, global competitiveness of the air conditioning industry and sub-products are analyzed. Assessment of the index results and recommendations for the sector are involved in the conclusion section.

2. Foreign trade of the air conditioning sector

The demand for the air conditioning sector is rising with increasing global disposable incomes and the growth of the construction industry. The air conditioning sector is a sector that is increasingly gaining importance in the global economy. Table 1 lists the exporting countries of the global air conditioning industry for the 2020-2022 periods. It was recorded as 477 billion dollars in 2020. In 2021, total air conditioning exports increased compared to 2020 and reached 567 billion dollars. In 2022, total air conditioning exports were 559 billion dollars. China ranks first in the world in air conditioning exports. Then, countries such as Germany, USA, Italy, Japan, Mexico, France, Netherlands, Korea, United Kingdom and Thailand come next. China's air conditioning exports 95 billion dollars of air conditioning exports in 2020, 120 billion dollars of air conditioning exports in 2021 and 123 billion dollars of air conditioning exports in 2022.

According to Table 1, Germany's total air conditioning exports in 2020, which ranks second in world air conditioning exports, were 63 billion dollars, 73 billion dollars in 2021 and 65 billion dollars in 2022. The USA, which ranks third in the world in terms of air conditioning, realized air conditioning exports of 46 billion dollars in 2020, air conditioning exports of 51 billion dollars in 2021 and air conditioning exports of 54 billion dollars in 2022. Ranking fourth in global air conditioning exports, Italy's total air conditioning exports in 2020 were recorded as 29 billion dollars, total air conditioning exports in 2021 were recorded as 36 billion dollars and in 2022 were recorded as 34 billion dollars. Ranking fifth in global air conditioning exports, Japan's total air conditioning exports in 2020 were 19 billion dollars, its total air conditioning exports in 2021 were 23 billion dollars and its total air conditioning exports in 2022 were 21 billion dollars.

According to the data in the Table 1, Türkiye ranks 19th in global air conditioning exports and its global air conditioning export share is 3%. Türkiye's air conditioning exports have increased gradually in the 2017-2021 periods.

When the export data of the sub-product groups of the world air conditioning industry is examined, the total exports of the heating sub-product group in 2021 are 41 billion dollars, the total exports of the refrigeration sub-product group in 2021 are 65 billion dollars, the total exports of the air conditioning sub-product group in 2021 are 86 billion dollars, The total exports installation of the year 2021 were 253 billion dollars, the total exports of the ventilation sub-product group in 2021 were 110 billion dollars, and the total exports of the insulation sub-product group in 2021 were 10 billion dollars [18].

Global air conditioning sector imports are increasing. Table 2 demonstrates the data of the air conditioning importing countries spanning from 2020 to 2022. Therefore, in 2020, global air conditioning imports were documented as 487 billion dollars, 575 billion dollars in 2021, and 574 billion dollars in 2022. The USA ranks first in global air conditioning imports. Subsequently, there are respectively. countries such as Germany, China, France, Mexico, Canada, the United Kingdom, Japan, Italy, the Netherlands and Russia.

According to Table 2, total air conditioning imports of the USA in 2020 were 69 billion dollars, total air conditioning imports were 85 billion dollars in 2021 and total air conditioning imports were 93 billion dollars in 2022. Germany, which ranks second in global air conditioning imports, reached total air conditioning imports of 36 billion dollars in 2020, total air conditioning imports of 44 billion dollars in 2021 and total air conditioning imports of 41 billion dollars in 2022. China, which ranks third in global air conditioning imports, imported 33 billion dollars of air conditioning in 2020, 39 billion dollars of air conditioning in 2021 and 35 billion dollars of air conditioning in 2022. The total air conditioning imports of France, which ranks fourth in global air conditioning imports, in 2020 was 18 billion dollars, the total air conditioning imports in 2021 were 22 billion dollars and in 2022 was 21 billion dollars. Mexico, which ranks fifth in global air conditioning imports, imported 15 billion dollars of air conditioning in 2020, 19 billion dollars of air conditioning in 2021 and 22 billion dollars of air conditioning.

According to the data in the Table 2, Türkiye ranks 20th in global air conditioning imports and its global air conditioning import share is 2%.

Table 1. World air conditioning industry export (Compiled by authors via ITC Trademap data).

Exporters	2020	2021	2022
World	477.642.745	567.735.063	559.596.561
China	95.290.278	120.494.105	123.805.987
Germany	63.575.524	73.374.642	65.771.003
USA	46.624.978	51.346.563	54.834.214
Italy	29.873.559	36.035.958	34.595.083
Japan	19.610.597	23.208.215	21.668.148
Mexico	18.051.974	20.688.738	23.881.755
France	14.946.513	16.911.924	16.112.124
Netherlands	12.906.944	14.898.799	12.959.485
Korea,	13.561.678	14.714.788	15.206.907
United Kingdom	12.728.606	14.404.137	14.322.954
Thailand	9.989.726	12.341.700	12.810.852
Belgium	9.347.350	11.387.127	11.024.615
Czech Republic	9.061.103	10.666.216	9.883.389
Poland	7.826.820	10.059.651	12.30.036
Austria	6.208.927	7.864.945	8.011.061
Switzerland	6.678.192	7.776.167	8.235.981
Canada	6.797.228	7.596.966	8.531.084
Spain	6.235.812	7.553.296	7.591.763
Türkiye	5.203.415	6.888.041	6.680.529

Table 2. World's air conditioning industry import (Compiled by authors by means of ITC Trademap data).

Importers	2020	2021	2022
World	487.090.330	575.967.053	574.725.445
USA	69.115.048	85.178.949	93.232.958
Germany	36.636.764	44.809.202	41.443.862
China	33.294.351	39.694.804	35.114.283
France	18.318.730	22.724.032	21.772.437
Mexico	15.593.475	19.009.295	22.221.526
Canada	15.657.401	18.512.257	20.880.250
United Kingdom	14.102.445	17.140.853	18.342.043
Japan	13.996.775	16.204.937	15.541.302
Italy	12.037.165	15.662.571	16.673.763
Netherlands	11.864.569	14.490.527	13.807.740
Russia	11.529.097	14.115.285	8.830.917
Korea	11.592.483	12.669.891	13.061.176
Poland	9.046.610	11.561.800	11.748.406
Spain	9.204.822	11.074.372	10.844.016
Belgium	8.678.978	10.977.947	10.315.411
India	7.638.821	9.804.226	9.574.173
Czech Republic	6.994.500	8.600.555	7.977.232
Thailand	6.499.229	8.074.522	8.101.439
Australia	6.756.441	7.965.329	8.487.309
Türkiye	6.555.121	7.836.864	7.199. 606

When the import data of the sub-product groups of the world air conditioning industry is examined, the total imports of the heating sub-product group in 2021 are 41 billion dollars, the total imports of the refrigeration sub-product group in 2021 are 67 billion dollars, the total imports of the air conditioning sub-product group in 2021 are 86 billion dollars, the total imports of installation the year 2021 were 258 billion dollars, the total imports of the ventilation sub-product group in 2021 were 111 billion dollars, and the total imports of the insulation sub-product group in 2021 were 10 billion dollars [18].

Türkiye's air conditioning exports are gradually increasing in the periods between 2017-2022. Türkiye's air conditioning export and import data for the 2012-2022 periods are demonstrated in Figure 1. Türkiye's total air conditioning exports in 2012 were 3 billion dollars, total air conditioning exports were 4 billion dollars in 2013, total air conditioning exports were 4 billion dollars in 2014, total air conditioning exports were 3 billion dollars in 2015, total air conditioning exports were 3 billion dollars in 2016, air conditioning exports are 4 billion dollars in 2017, total air conditioning exports are 4 billion dollars in 2018, total air conditioning exports are 5 billion dollars in 2019, total air conditioning exports are 5 billion dollars in 2020, total air conditioning exports are 6 billion dollars in 2021 and total air conditioning exports are 6 billion dollars in 2022. The countries to which Türkiye exports air conditioning are respectively Germany, the United Kingdom, Italy, France, Iraq, Russia, Spain and Romania [18].

Türkiye's total air conditioning imports in 2012 were 5 billion dollars, total air conditioning imports were 7 billion dollars in 2013, total air conditioning imports were 6 billion dollars in 2014, total air conditioning imports were 6 billion dollars in 2015, total air conditioning imports were 6 billion dollars in 2016, total air conditioning imports were 6 billion dollars in 2017, total air conditioning imports are 6 billion dollars in 2018, total air conditioning imports are 5 billion dollars in 2019, total air conditioning imports are 6 billion dollars in 2020, total air conditioning imports are 7 billion dollars in 2021 and total air conditioning imports are 7 billion dollars in 2022. The countries from which Türkiye imports air conditioning are respectively China, Germany, Italy, USA, France, Czech Republic, Korea, Poland, Thailand, United Kingdom, and Japan [18].

Figure 1. Türkiye’s air conditioning export and import (Compiled by authors via ITC Trademap).

3. Literature review

There are many studies in the literature on national competitiveness analysis for sectors and sub-sectors both in the world and in our country. Generally, in Türkiye's air conditioning sector reports, a section is separated for competitive analysis and competitive analysis is made by means of Porter's diamond model. In the literature review, it was determined that there is no study analyzing the exports and imports of the Turkish Air Conditioning sector and examining the international competitiveness of the sector within the temporal cycle (2001-2021). It is considered that this study will contribute to the literature in filling this gap. This study contributes to the literature in terms of enabling detailed global competitiveness analysis of Türkiye’s air conditioning industry and sub-products by means of various indices and addressing the product mapping for the first time.

There are studies in the literature within the scope of the air conditioning sector. These; Lehtonen and Sipilä [19], in the study, both sector analysis and competition analysis were conducted by making phone calls to Air Conditioning (HVAC) companies. It was emphasized that the air conditioning sector will change and grow significantly in recent years. Srikandi et al., [20], conducted a comparative analysis of HVACR company (Daikin and Carrier) and used strategic management approach in the analysis. Isaac & Vuuren [21], analyzed the potential development and changes in future energy use for air conditioning and residential heating in the context of climate change. In the study, it is highlighted that energy demand for air conditioning will increase rapidly in the 21st century. Visintin & Rapaccini [22] examined the relationship between higher levels of service provision and better financial performance of companies operating in the HVAC sector in Italy (250 companies). The study offers findings that service provision has an impact on company profitability. Acül [23], in this study, the general situation of the Turkish air conditioning and installation sector and the developments in foreign trade were reflected, and the R&D infrastructure of the sector was examined. Emphasis is placed on the efficient and versatile structuring of SME R&D departments in the air conditioning and installation sector, and a management model has been proposed on how to use resources effectively. Ors and Yumus [24] determined the determinants of the competitiveness of the air conditioning sector in the study and the interview method was used in the study. According to the findings of this study, demand conditions, general production infrastructure of the sector, access to raw materials and semi-finished products, legal regulation related to the sector, volatility in financial markets including exchange rates, determinants such as foreign political relations, and engineering quality have been revealed. Erturan [25], in this study, the development and performance of the financial structure of the air conditioning sector was examined through financial analysis techniques.

Generally, studies in the literature on measuring international competitiveness use Balassa's index and Vollrath indexes. Turkish literature using the product mapping method is extremely limited [26-32]. Topçu and Sarıgül [26] analyzed the competitiveness of the five sectors with the highest share in Türkiye's exports (textile, clothing, iron and steel, electrical machinery, motor vehicles) for the period 2000-2014. Bashimov and Aydın [27] examined the competitiveness of the aquaculture sector of the Baltic countries (Estonia, Lithuania, Latvia) for the periods 2001-2015 and determined the place of the relevant sector in foreign trade by means of the product mapping. Bakkalcı [28] investigated the competitiveness of the Turkish automotive industry for the period 1995-2016 and determined its place in foreign trade as using the product mapping. Bakkalcı [29] analyzed the competitiveness of Türkiye's textile industry within the framework of the period 2001-2016 and applied the product mapping method. Keskingöz [30] examined the competitiveness of 24-chapters belonging to Türkiye's agricultural sector for the period 2001-2017 and revealed which chapters had comparative advantage. Yeldan et al., [31] evaluated the competitiveness of the Turkish iron and steel sector for the periods 2001-2017 and used the product mapping to determine the sector's place in foreign trade. Başkol and Bektaş [32] analyzed the competitiveness of the Turkish iron-steel industry in the periods covering the years 2000-2019 and examined specifically in nine with three-digit sub-sectors.

Studies in the international literature on product mapping method are [33-39]. Ischukova and Smutka [33] investigated the structure of Russian foreign trade in agricultural products for the period of 1998-2010 in terms of specialization and competitive performance. Astaneh et al., [34] examined the competitiveness of Iran's stone fruit exports spanning from 1997 to 2010 and determined the target market for Iran's stone fruit exports. Ischukova and Smutka [35] scanned the competitive performance of Russia's agricultural and food exports and compared with special regions (Asia, Africa, America, Commonwealth of Independent States, European Union countries). Pawlak [36] determined the level and changes in the comparative advantages of Poland's agricultural-food sector in the US markets for the period of 2001-2017. Saeyang and Nissapa [37] analyzed the competitiveness of Indonesia, Malaysia and Thailand in the four-palm oil world market trade for the period of 2001-2017. Tandra et al., [38] examined the international competitiveness of palm oil exporters of countries in the world for the period of 1996-2019. Saxena et al., [39] mapped comparative advantage and trade balance of India's horticultural products (HS-6 Digit 40 products). In addition, seasonality advantage and export potential were revealed.

4. Data sources and methodology

4.1. Data Sources

Export and import data used in this study were taken from the TradeMap. In the study, HS Code of the air conditioning industry and sub-products (air conditioning, heating, installation, insulation, refrigeration and ventilation) were determined within the scope of the Customs Tariff Statistics Position. HS Code for the air conditioning sector, whose international competitiveness was analyzed within the scope of the study, are demonstrated in Table 3. Export and import data regarding Türkiye's air conditioning sector were analyzed and competitiveness was evaluated within the framework of the 2001-2021 periods.

4.2. Methodology

International competitiveness indices available in the literature were used as methodology in the study. In this context, the indices used in the study and applied to measure international competitiveness are as follows:

Bela Balassa developed the Revealed Comparative Advantage (RCA) index in 1965. It is a frequently used measure to compare relative advantages in export performance by country and sectors [40]. This index is calculated by calculating the ratio of the country's exports in that sector to its total exports and then dividing the world's exports of the same sector to its total exports. The formula used to calculate the Revealed Comparative Advantage (RCA) index is shown in Equation 1:

$$RCA = \frac{X_{kt}^{j} \ / \ X_{t}^{j}}{X_{kt}^{w} \ / \ X_{t}^{w}} \tag{1}$$

In Equation 1, 'j' represents the country, 't' represents the period, 'k' represents the product or sector, and 'w' represents the world country groups. If the RCA value is less than 1, the country is at a disadvantage in terms of comparative advantages revealed in the relevant goods or sector group, and when the value is greater than 1, the country has comparative advantage in the relevant goods and sector group [41].

Vollrath [42], who criticized the Balassa Index for only taking exports into account, identified the deficiencies in Balassa's RCA and developed several new indices as an alternative to this index. Unlike the Balassa Index, Vollrath prevented double counting of the country's data by subtracting the export data of the examined sector from the total exports [43]. Vollrath [42] developed the Relative Export Advantage index (RXA), Relative Import Index (RMP), Relative Trade Advantage Index (RTA) and Revealed Competitiveness Index (RC).

Relative Export Advantage Index (RXA) is calculated by means of export data, as in the Revealed Comparative Advantage Index. This index, unlike the Balassa index, prevents double counting of the country and sector. The index is defined as the ratio of a country's export share of a certain sector or product in the world market to the same country's share in world exports of all other sectors or products [44]. The formula used to calculate the Relative Export Advantage Index (RXA) is shown in Equation 2:

$$RXA= (X_{ij}/ \textstyle\sum_{l,l\neq j} X_{il})/ \sum_{k,k\neq j} X_{kj}/ \sum_{k,k\neq i} \sum_{l,l\neq j} X_{kl}) \tag{2}$$

Table 3. HS Codes of sub-product groups of the air conditioning sector "HVAC-R Exporters Association (ISIB).

Sub-product groups of the air conditioning sector	Hs Code	Production Description
Heating	732181	Stoves, heaters, grates, fires, wash boilers, braziers and similar appliances, of iron or steel, for gas fuel or for both gas and other fuels (excl. cooking appliances, whether or not with oven, separate ovens, plate warmers, central heating boilers, geysers and hot water cylinders and large cooking appliances)
	732211	Radiators for central heating, non-electrically heated, and parts thereof, of iron or steel (excl. parts, elsewhere specified or included, and central-heating boilers)
	840220	Superheated water boilers
	840310	Central heating boilers, non-electric (excl. vapor generating boilers and superheated water boilers of heading 8402)
	840410	Auxiliary plant for use with boilers of heading 8402 or 8403, e.g. economizers, superheaters, soot removers and gas recoverees;
	841610	Furnace burners for liquid fuel
	841939	Dryers (excl. lyophilization apparatus, freeze drying units, spray dryers, dryers for agricultural products, for wood, paper pulp, paper or paperboard, for yarns, fabrics and other textile products, dryers for bottles or other containers, hairdryers, hand dryers and domestic appliances)
	851610	Electric instantaneous or storage water heaters and immersion heaters
Refrigeration	841891	Furniture designed to receive refrigerating or freezing equipment
	841490	Parts of: air or vacuum pumps, air or other gas compressors, fans and ventilating or recycling hoods incorporating a fan, and gas-tight biological safety cabinets, n.e.s.
	841850	Furniture "chests, cabinets, display counters, show-cases and the like" for storage and display, incorporating refrigerating or freezing equipment (excl. combined refrigerator-freezers with separate external doors, household refrigerators and freezers of the chest type of a capacity <= 800 l or of the upright type of a capacity <= 900 l)
	841989	Machinery, plant or laboratory equipment, whether or not electrically heated, for the treatment of materials by a process involving a change of temperature such as heating, cooking, roasting, sterilizing, pasteurizing, steaming, evaporating, vaporizing, condensing or cooling, n.e.s. (excl. machinery used for domestic purposes and furnaces, ovens and other equipment of heading 8514)
Air Conditioning	841430	Compressors for refrigerating equipment
	841520	Air conditioning machines of a kind used for persons, in motor vehicles
Ventilation	830710	Flexible tubing of iron or steel, with or without fittings
	841460	Hoods incorporating a fan, whether or not fitted with filters, having a maximum horizontal side <= 120 cm
Istallation	391731	Flexible tubes, pipes and hoses, of plastics, burst pressure >= 27,6 MPa
	392111	Plates, sheets, film, foil and strip, of cellular polymers of styrene, unworked or merely surface-worked or merely cut into squares or rectangles (excl. self-adhesive products, floor, wall and ceiling coverings of heading 3918 and sterile surgical or dental adhesion barriers of subheading 3006.10.30
	741220	Copper alloy tube or pipe fittings "e.g., couplings, elbows, sleeves"
	902511	Thermometers, liquid-filled, for direct reading, not combined with other instruments
	902610	Instruments and apparatus for measuring or checking the flow or level of liquids (excl. meters and regulators)
Insulation	400819	Rods and profile shapes, of cellular rubber
	680610	Slag-wool, rock-wool and similar mineral wools, incl. intermixtures thereof, in bulk, sheets or rolls
	701939	Webs, mattresses, boards and similar nonwoven products, of glass fibres (excluding mats and thin sheets "voiles")

In Equation 2, X is export and I and k indices are product categories; j and l represent countries. If the value of RXA is greater than 1, it has a competitive advantage in products and sectors; if it is less than 1, it has a competitive disadvantage in products and sectors [45].

The Relative Import Penetration Index (RMP), unlike the Relative Export Advantage Index, is calculated by means of import data. The difference between RMP and RXA indices is that the formula is grounded on import data as opposed to export data [44]. Imports (M) are involved in the equation instead of exports. The formula used to calculate the Relative Import Penetration Index (RMP) is shown in Equation 3:

$$\mathrm{RMP} = (\mathrm{M_{ij}} / \sum_{l,l\neq j} \mathrm{M_{il}}) \Big/ (\sum_{k,k\neq i} \mathrm{M_{kj}} / \sum_{k,k\neq i} \sum_{l,l\neq j} \mathrm{M_{kl}}) \tag{3}$$

If the RMP index value is greater than 1, it points out a competitive disadvantage in the product or sector, and if it is less than 1, it points out a competitive advantage in the product or sector [46].

Relative Trade Advantage Index (RTA) is consisted of by considering the differences between the Relative Export Advantage Index and the Relative Import Penetration Index. This index takes both export and import aspects into account, therefore it will offer more accurate results in calculating competitiveness. If the RTA index is positive, it indicates that it has competitive power in the sector and product group, and if the RTA index is negative, it indicates that it does not have competitive power or does not have an advantage in the sector and product group [44]. The formula used to calculate the Relative Trade Advantage Index is shown in Equation 4:

$$RTA = RXA_{ij} - RMP_{ij} \tag{4}$$

Vollrath [42] developed the Revealed Competitive Advantage Index (RC). This index is calculated by considering the logarithm of the difference between the Relative Export Advantage Index (RXA) and the Relative Import Penetration Index (RMP). It is revealed that if the RC index value is positive, it has a comparative competitive advantage in the sector or product group, and if the RC index has negative values, it does not have a comparative advantage in the relevant sector and product group [46]. The formula used to calculate the Revealed Competitive Advantage Index (RC) is shown in Equation 5:

$$RC_{ij} = ln(RXA_{ij}) - ln(RMP_{ij}) \tag{5}$$

In this formula, RC_{ij} is the Relative Competitive Advantage Index of country j in product or sector i; RXAij demonstrates The Relative Export Advantage Index of country j in product i or sector, RMP_{ij} demonstrates The Relative Import Penetration Index of country j in product i or sector. According to Vollrath [42], the Revealed Competitive advantage index (RC) is a more preferable measurement than RXA and RTA since it displays better the supply and demand index [45].

The Revealed Symmetric Comparative Advantage Index (RSCA), Laursen [47], if the export value of any product or sector is 0, the asymmetry problem arises and this problem affects the evaluation of the analysis. Hence, the RCA index requirements to be adjusted symmetrically within its neutral value. Dalum, Laursen and Villumsen [48] recommended the Revealed Symmetric Comparative Advantage Index for corrections. Laursen suggested the Equation 6 to make the RCA index symmetrical [47]:

$$RSCA = \frac{RCA - 1}{RCA + 1} \tag{6}$$

The values of the Revealed Symmetric Comparative Advantage Index (RSCA) diverge between ''-1 or +1''. If RSCA>0, it indicates that the relevant country has a comparative advantage in the product or sector. Otherwise, if RSCA<0, it indicates that the relevant country has a comparative disadvantage in the product or sector [50].

Trade Balance Index (TBI) was developed by Lafay [49] and is recognized as the Lafay index in the literature. This index shows whether the relevant country is a net exporter or net importer of the sector or product. The formula used to calculate the Trade Balance Index is shown in Equation 7:

$$TBI_{TRairconditioning}: \frac{(E_{TRairconditioning} - M_{TRairconditioning})}{(E_{TRairconditioning} + M_{TRairconditioning})} \tag{7}$$

In Equation 7, " $E_{TRairconditioning}$" represents Türkiye's air conditioning sector exports. ''$M_{TRAirconditioning}$'' represents Türkiye's air conditioning industry imports. If the Trade Balance Index value is negative, it is called "net importer" in the relevant product or sector, and if it is positive, it is called "net exporter" in the relevant product or sector [50].

Widodo [50] developed Product Mapping method. The product map was generated by means of the Revealed Symmetric Comparative Advantage Index (RSCA) and the Trade Balance Index (TBI). In the sector examined, both the foreign trade balance and competitiveness of the country are evaluated together. Product mapping comprise of four different groups (A, B, C, D). Group A consists of products that have both comparative advantage and export specialization. Group B is one of the products that have a comparative advantage yet do not display specialization in exports; Group C contains of products that have specialization in exports however do not have a comparative advantage; Group D consists of products that do not have comparative advantage or specialization in exports (Table 4).

Table 4. Product mapping [50].

RSCA>0	Group B: Comparative Advantage Net-importer (RSCA>0 and TBI<0)	Group A: Comparative Advantage Net-exporter (RSCA>0 and TBI>0)
RSCA<0	Group D: Comparative Disadvantage Net-importer (RSCA<0 and TBI<0) TBI<0	Group C: Comparative Disadvantage Net-exporter (RSCA<0 and TBI>0) TBI>0

5. Results

Table 5 displays the global competitiveness analysis results of the air conditioning industry. The results differ depending on Türkiye's air conditioning exports and imports. RCA index results have fluctuated over certain periods and the average value of this index is calculated as 1.01. These index values are above 1 in the periods covering 2007-2014 and 2018-2021. In other periods, calculated values are less than 1. The average value of the RXA index calculated in the 2001-2021 periods was recorded as 1.04. RCA index results are parallel to RXA index results. When the results of these two indices are evaluated in general, results indicate that the air conditioning sector has competitiveness and shows specialization in exports. In order to the RMP index to have competitiveness in the relevant sector or product group, the calculated value need be below 1. RMP index results were found to be greater than 1 throughout the periods covered in the study, which reveals the excess imports of the relevant products. Since RTA and RC indices consider both export and import aspects into account, the calculated results will be objective. The values calculated for both indices in the 2008, 2010, 2011, 2012, 2014, 2019, 2020 and 2021 periods are positive. Therefore, it has been determined that it has a competitive advantage in the air conditioning sector in these periods. RSCA index, the average value calculated in the 2001-2021 periods is greater than zero, which demonstrates the comparative advantage of the relevant sector. However, the average value of the TBI index calculated in the 2001-2021 periods is less than zero, which indicates that these products are net-importers. In the 2001-2006 and 2015-2017 periods, the product mapping reveals that the air conditioning sector has a net- importer (Group D) with comparative disadvantage. In other periods, it has a comparative advantage of the relevant products but is net- importer (Group B). According to the product mapping method for the 2001-2021 periods, the average results were RSCA>0, TBI<0, therefore it was determined that Turkish Air Conditioning sector has a comparative advantage in trade however is a net-importer (Group B).

Table 5. International competitiveness analysis of the air conditioning industry (Compiled by authors).

Year	RCA	RXA	RMP	RTA	RC	RSCA	TBI	Product Mapping
2001	0,69	0,70	1,37	-0,67	-0,29	-0,18	-0,44	Group D-RSCA<0, TBI<0
2002	0,75	0,76	1,43	-0,66	-0,27	-0,14	-0,45	Group D-RSCA<0, TBI<0
2003	0,81	0,83	1,16	-0,33	-0,14	-0,10	-0,34	Group D-RSCA<0, TBI<0
2004	0,82	0,85	1,11	-0,26	-0,11	-0,09	-0,33	Group D-RSCA<0, TBI<0
2005	0,90	0,92	1,07	-0,14	-0,06	-0,05	-0,29	Group D-RSCA<0, TBI<0
2006	0,97	1,00	1,15	-0,15	-0,06	-0,01	-0,29	Group D-RSCA<0, TBI<0
2007	1,01	1,05	1,13	-0,08	-0,03	0,00	-0,25	Group B-RSCA>0, TBI<0
2008	1,06	1,09	1,09	0,00	0,00	0,02	-0,20	Group B-RSCA>0, TBI<0
2009	1,04	1,08	1,15	-0,06	-0,02	0,02	-0,18	Group B-RSCA>0, TBI<0
2010	1,16	1,20	1,05	0,14	0,05	0,07	-0,18	Group B-RSCA>0, TBI<0
2011	1,23	1,28	1,11	0,17	0,06	0,10	-0,21	Group B-RSCA>0, TBI<0
2012	1,11	1,15	1,11	0,03	0,01	0,05	-0,20	Group B-RSCA>0, TBI<0
2013	1,14	1,18	1,25	-0,06	-0,02	0,06	-0,26	Group B-RSCA>0, TBI<0
2014	1,12	1,17	1,04	0,12	0,04	0,06	-0,15	Group B-RSCA>0, TBI<0
2015	0,99	1,03	1,14	-0,11	-0,04	-0,00	-0,21	Group D-RSCA<0, TBI<0
2016	0,93	0,97	1,32	-0,35	-0,13	-0,03	-0,29	Group D-RSCA<0, TBI<0
2017	0,97	1,00	1,12	-0,12	-0,04	-0,01	-0,23	Group D-RSCA<0, TBI<0
2018	1,06	1,10	1,12	-0,02	-0,00	0,03	-0,12	Group B-RSCA>0, TBI<0
2019	1,09	1,13	1,09	0,04	0,01	0,04	-0,06	Group B-RSCA>0, TBI<0
2020	1,14	1,18	1,13	0,05	0,02	0,06	-0,11	Group B-RSCA>0, TBI<0
2021	1,19	1,25	1,17	0,07	0,02	0,09	-0,06	Group B-RSCA>0, TBI<0
Average	1,01	1,04	1,16	-0,11	-0,04	0,01	-0,23	Group B-RSCA>0, TBI<0

Table 6-8 demonstrate the international competitiveness analysis results for the Heating sub-product. When the RCA Index results calculated for the products (HS Code 732181, HS Code 732211 and HS Code 840310) were assessed in general, the values were found to be 1 and above. The average values of the index results were respectively calculated as 2.77, 26.34 and 6.93. The results of the RXA index are parallel to the results of the RCA index. Therefore, according to the index results, it has been determined that Türkiye has competitiveness in these three products and indicates specialization in exports. However, when the RCA index results calculated for the other three products (HS Code 840220, HS Code 841610 and HS Code 851610) are evaluated in general, it is realized that the values are 1 and below. The average values of the index results were respectively calculated as 0.13, 0.69 and 0.31. The results are similar to the RXA index. Therefore, according to the results of these two indexes, it has been revealed that Türkiye does not have competitiveness in these products and does not specialize in exports. When the results calculated for the products (HS Code 840410 and HS Code 841939) are examined, it has been determined that the competitiveness of these products is at the limit and it is comprehended from the latest index results that the competitiveness of these products will increase in the future. In order for the RMP Index to gain competitive advantage in the relevant sector or product group, the calculated values need to below one. The calculated RMP index results of the products (HS Code 732181, HS Code

732211) are below one, therefore the comparative advantage of these products emerges. The RMP index results calculated for the products (HS Code 840220, HS Code 840310, HS Code 840410, and HS Code 841939) are above one, thus revealing the import surplus of these products. In two non-competitive products (HS Code 841610 and HS Code 851610), the calculated RMP index values are below one, which indicates that the import of these products is low. Since RTA and RC indices consider both export and import aspects into account, the calculated results will be objective. When these index results are assessed in general, the values calculated for the products (HS Code 732181, HS Code 732211 and HS Code 840310) are positive. Therefore, it has been determined that these products have a competitive advantage. Although there are fluctuations in some periods, the calculated values for other products (HS Code 840220, HS Code 840310, HS Code 840410, HS Code 841939, HS Code 841610 and HS Code 851610) are negative. When assessed generally, it reveals the comparative advantage of the products (HS Code 732181, HS Code 732211 and HS Code 840310) due to RSCA >0. RSCA index results calculated for the products (HS Code 840220, HS Code 841610 and HS Code 851610) determined that the values are less than zero; therefore, Türkiye does not have a comparative advantage in these products. The TBI index values calculated for the products (HS Code 732181, HS Code 732211 and HS Code 840310) are greater than zero. Consequently, it reveals the net-exporter of these products. Though there are fluctuations, the TBI index value calculated for the products (HS Code 840220, HS Code 841610 and HS Code

Table 6. International competitiveness analysis for heating sub-product (2001-2006) (Compiled by authors).

Year	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
2001	732181	3,16	3,21	0,18	3,03	1,24	0,51	0,88	Group A- RSCA>0, TBI>0
	732211	21,84	24,59	0,47	24,12	1,71	0,91	0,94	Group A-RSCA>0, TBI>0
	840220	0,04	0,04	0,98	-0,94	-1,33	-0,91	-0,93	Group D-RSCA<0, TBI<0
	840310	0,49	0,49	0,39	0,11	0,11	-0,34	0,04	Group C-RSCA<0, TBI>0
	840410	0,99	0,99	25,86	-24,86	-1,41	0,00	-0,95	Group B-RSCA>0, TBI<0
	841610	0,24	0,24	1,86	-1,62	-0,90	-0,62	-0,82	Group D-RSCA<0, TBI<0
	841939	0,15	0,15	2,38	-2,22	-1,19	-0,73	-0,90	Group D-RSCA<0, TBI<0
	851610	0,25	0,25	0,93	-0,68	-0,57	-0,60	-0,65	Group D-RSCA<0, TBI<0
2002	732181	2,88	2,92	0,15	2,76	1,26	0,48	0,88	Group A- RSCA>0, TBI>0
	732211	27,17	32,02	0,17	31,85	2,27	0,92	0,97	Group A-RSCA>0, TBI>0
	840220	0,07	0,07	1,50	-1,43	-1,31	-0,86	-0,93	Group D-RSCA<0, TBI<0
	840310	1,76	1,78	3,92	-2,14	-0,34	0,28	-0,48	Group B-RSCA>0, TBI<0
	840410	0,28	0,28	20,20	-19,92	-1,86	-0,56	-0,98	Group D-RSCA<0, TBI<0
	841610	0,30	0,30	1,80	-1,50	-0,77	-0,53	-0,78	Group D-RSCA<0, TBI<0
	841939	0,21	0,21	2,35	-2,14	-1,05	-0,66	-0,87	Group D-RSCA<0, TBI<0
	851610	0,19	0,19	1,00	-0,81	-0,72	-0,68	-0,75	Group D-RSCA<0, TBI<0
2003	732181	4,07	4,18	0,09	4,08	1,64	0,60	0,95	Group A-RSCA>0, TBI>0
	732211	32,89	41,50	0,02	41,48	3,15	0,94	0,99	Group A-RSCA>0, TBI>0
	840220	0,10	0,10	1,39	-1,29	-1,14	-0,82	-0,90	Group D-RSCA<0, TBI<0
	840310	4,58	4,73	4,53	0,20	0,02	0,64	-0,10	Group B-RSCA>0, TBI<0
	840410	0,28	0,28	4,56	-4,29	-1,22	-0,57	-0,93	Group D-RSCA<0, TBI<0
	841610	0,43	0,43	0,87	-0,43	-0,30	-0,39	-0,48	Group D-RSCA<0, TBI<0
	841939	0,23	0,23	1,81	-1,59	-0,91	-0,63	-0,83	Group D-RSCA<0, TBI<0
	851610	0,32	0,32	0,87	-0,55	-0,43	-0,52	-0,55	Group D-RSCA<0, TBI<0
2004	732181	2,81	2,87	0,11	2,76	1,41	0,47	0,93	Group A- RSCA>0, TBI>0
	732211	30,67	38,97	0,05	38,92	2,85	0,93	0,99	Group A-RSCA>0, TBI>0
	840220	0,08	0,09	1,40	-1,31	-1,20	-0,84	-0,92	Group D-RSCA<0, TBI<0
	840310	4,49	4,64	5,05	-0,40	-0,04	0,64	-0,18	Group B-RSCA>0, TBI<0
	840410	0,43	0,43	3,68	-3,25	-0,93	-0,40	-0,86	Group D-RSCA<0, TBI<0
	841610	0,30	0,30	0,87	-0,56	-0,46	-0,53	-0,62	Group D-RSCA<0, TBI<0
	841939	0,51	0,52	1,93	-1,41	-0,57	-0,32	-0,67	Group D-RSCA<0, TBI<0
	851610	0,46	0,46	1,25	-0,79	-0,43	-0,37	-0,54	Group D-RSCA<0, TBI<0
2005	732181	2,81	2,87	0,11	2,75	1,40	0,47	0,92	Group A-RSCA>0, TBI>0
	732211	31,06	39,85	0,04	39,81	2,97	0,93	0,99	Group A-RSCA>0, TBI>0
	840220	0,07	0,08	1,36	-1,29	-1,25	-0,86	-0,93	Group D-RSCA<0, TBI<0
	840310	4,64	4,81	5,48	-0,67	-0,06	0,65	-0,22	Group B-RSCA>0, TBI<0
	840410	1,55	1,57	5,06	-3,49	-0,51	0,22	-0,73	Group B-RSCA>0, TBI<0
	841610	0,71	0,71	0,68	0,03	0,02	-0,17	-0,19	Group D-RSCA<0, TBI<0
	841939	0,47	0,47	1,50	-1,03	-0,50	-0,36	-0,67	Group D-RSCA<0, TBI<0
	851610	0,68	0,68	1,88	-1,20	-0,44	-0,19	-0,63	Group D-RSCA<0, TBI<0
2006	732181	2,26	2,30	0,14	2,16	1,20	0,38	0,89	Group A-RSCA>0, TBI>0
	732211	26,22	32,27	0,53	31,74	1,78	0,92	0,93	Group A-RSCA>0, TBI>0
	840220	0,08	0,09	1,35	-1,26	-1,18	-0,84	-0,92	Group D-RSCA<0, TBI<0
	840310	4,18	4,32	5,91	-1,59	-0,14	0,61	-0,32	Group B-RSCA>0, TBI<0
	840410	0,81	0,81	4,03	-3,21	-0,69	-0,11	-0,79	Group D-RSCA<0, TBI<0
	841610	0,80	0,80	0,62	0,19	0,12	-0,11	-0,09	Group D-RSCA<0, TBI<0
	841939	0,52	0,52	1,68	-1,15	-0,51	-0,32	-0,64	Group D-RSCA<0, TBI<0
	851610	0,93	0,94	1,77	-0,83	-0,28	-0,03	-0,51	Group D-RSCA<0, TBI<0

Table 7. International competitiveness analysis for heating sub-product (2007-2014) (Compiled by authors).

Year	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
2007	732181	2,33	2,37	0,15	2,21	1,17	0,40	0,88	Group A-RSCA>0, TBI>0
	732211	24,60	30,43	0,24	30,19	2,10	0,92	0,97	Group A-RSCA>0, TBI>0
	840220	0,09	0,09	1,39	-1,30	-1,18	-0,83	-0,92	Group D-RSCA<0, TBI<0
	840310	4,46	4,62	4,67	-0,05	0,00	0,63	-0,16	Group B-RSCA>0, TBI<0
	840410	1,10	1,11	3,23	-2,13	-0,47	0,05	-0,67	Group B-RSCA>0, TBI<0
	841610	0,82	0,83	0,45	0,37	0,26	-0,10	0,08	Group C-RSCA<0, TBI>0
	841939	1,06	1,07	2,02	-0,95	-0,28	0,03	-0,51	Group B-RSCA>0, TBI<0
	851610	0,61	0,61	1,17	-0,56	-0,28	-0,24	-0,49	Group D-RSCA<0, TBI<0
2008	732181	2,13	2,17	0,14	2,02	1,16	0,36	0,89	Group A-RSCA>0, TBI>0
	732211	21,83	26,64	0,07	26,57	2,55	0,91	0,99	Group A-RSCA>0, TBI>0
	840220	0,05	0,06	1,26	-1,20	-1,34	-0,89	-0,94	Group D-RSCA<0, TBI<0
	840310	4,57	4,76	4,22	0,54	0,05	0,64	-0,08	Group B-RSCA>0, TBI<0
	840410	1,07	1,08	1,26	-0,18	-0,07	0,03	-0,33	Group B-RSCA>0, TBI<0
	841610	0,44	0,44	0,72	-0,27	-0,21	-0,39	-0,41	Group D-RSCA<0, TBI<0
	841939	0,58	0,58	1,90	-1,31	-0,51	-0,26	-0,64	Group D-RSCA<0, TBI<0
	851610	0,71	0,71	1,11	-0,39	-0,19	-0,17	-0,41	Group D-RSCA<0, TBI<0
2009	732181	5,02	5,24	0,26	4,97	1,29	0,66	0,88	Group A-RSCA>0, TBI>0
	732211	23,23	28,75	0,63	28,12	1,65	0,91	0,93	Group A-RSCA>0, TBI>0
	840220	0,09	0,10	1,43	-1,33	-1,17	-0,82	-0,90	Group D-RSCA<0, TBI<0
	840310	5,77	6,07	3,16	2,91	0,28	0,70	0,22	Group A-RSCA>0, TBI>0
	840410	0,97	0,98	0,84	0,14	0,07	-0,01	-0,13	Group D-RSCA<0, TBI<0
	841610	0,55	0,56	0,68	-0,12	-0,09	-0,29	-0,18	Group D-RSCA<0, TBI<0
	841939	0,73	0,73	2,15	-1,42	-0,47	-0,16	-0,62	Group D-RSCA<0, TBI<0
	851610	0,54	0,54	0,86	-0,32	-0,20	-0,30	-0,39	Group D-RSCA<0, TBI<0
2010	732181	9,71	10,48	0,22	10,25	1,67	0,81	0,91	Group A-RSCA>0, TBI>0
	732211	25,44	31,49	0,32	31,16	1,97	0,92	0,96	Group A-RSCA>0, TBI>0
	840220	0,11	0,12	1,70	-1,58	-1,16	-0,79	-0,91	Group D-RSCA<0, TBI<0
	840310	7,07	7,49	3,24	4,25	0,36	0,75	0,23	Group A-RSCA>0, TBI>0
	840410	0,39	0,39	0,81	-0,42	-0,32	-0,44	-0,41	Group D-RSCA<0, TBI<0
	841610	0,83	0,83	0,68	0,15	0,09	-0,09	-0,14	Group D-RSCA<0, TBI<0
	841939	1,02	1,03	1,09	-0,06	-0,03	0,01	-0,30	Group B-RSCA>0, TBI<0
	851610	0,51	0,52	0,84	-0,33	-0,21	-0,32	-0,49	Group D-RSCA<0, TBI<0
2011	732181	2,52	2,57	0,18	2,39	1,14	0,43	0,73	Group A-RSCA>0, TBI>0
	732211	23,18	28,02	0,27	27,75	2,00	0,91	0,96	Group A-RSCA>0, TBI>0
	840220	0,14	0,14	1,57	-1,43	-1,04	-0,75	-0,89	Group D-RSCA<0, TBI<0
	840310	8,81	9,45	3,71	5,74	0,41	0,80	0,23	Group A-RSCA>0, TBI>0
	840410	0,55	0,55	1,00	-0,45	-0,26	-0,29	-0,32	Group D-RSCA<0, TBI<0
	841610	0,92	0,93	0,57	0,36	0,21	-0,04	0,02	Group C-RSCA<0, TBI>0
	841939	1,00	1,01	3,57	-2,56	-0,55	0,00	-0,71	Group B-RSCA>0, TBI<0
	851610	0,60	0,60	0,83	-0,23	-0,14	-0,25	-0,46	Group D-RSCA<0, TBI<0
2012	732181	3,69	3,81	0,22	3,58	1,22	0,57	0,81	Group A-RSCA>0, TBI>0
	732211	23,47	29,15	0,17	28,98	2,22	0,91	0,97	Group A-RSCA>0, TBI>0
	840220	0,10	0,10	1,78	-1,68	-1,23	-0,81	-0,92	Group D-RSCA<0, TBI<0
	840310	8,05	8,65	3,50	5,15	0,39	0,78	0,27	Group A-RSCA>0, TBI>0
	840410	0,99	1,00	1,41	-0,41	-0,15	0,00	-0,30	Group B-RSCA>0, TBI<0
	841610	0,72	0,73	0,54	0,19	0,13	-0,16	0,01	Group C-RSCA<0, TBI>0
	841939	1,41	1,43	1,70	-0,27	-0,08	0,17	-0,32	Group D-RSCA<0, TBI<0
	851610	0,75	0,75	0,54	0,21	0,14	-0,15	-0,11	Group D-RSCA<0, TBI<0
2013	732181	2,75	2,81	0,29	2,52	0,97	0,46	0,69	Group A-RSCA>0, TBI>0
	732211	20,35	24,65	0,16	24,48	2,16	0,90	0,97	Group A-RSCA>0, TBI>0
	840220	0,09	0,09	1,80	-1,71	-1,29	-0,83	-0,93	Group D-RSCA<0, TBI<0
	840310	8,18	8,81	2,73	6,08	0,51	0,78	0,37	Group A-RSCA>0, TBI>0
	840410	0,78	0,79	5,42	-4,63	-0,84	-0,12	-0,79	Group D-RSCA<0, TBI<0
	841610	0,70	0,71	0,53	0,18	0,13	-0,17	-0,02	Group D-RSCA<0, TBI<0
	841939	0,98	0,99	1,95	-0,96	-0,29	-0,01	-0,53	Group D-RSCA<0, TBI<0
	851610	0,62	0,62	0,39	0,23	0,20	-0,23	-0,07	Group D-RSCA<0, TBI<0
2014	732181	3,06	3,14	0,66	2,48	0,67	0,50	0,53	Group A-RSCA>0, TBI>0
	732211	15,99	18,63	0,38	18,24	1,68	0,88	0,92	Group A-RSCA>0, TBI>0
	840220	0,17	0,17	1,93	-1,75	-1,03	-0,70	-0,87	Group D-RSCA<0, TBI<0
	840310	9,00	9,80	2,22	7,58	0,65	0,80	0,49	Group A-RSCA>0, TBI>0
	840410	0,41	0,41	1,31	-0,90	-0,50	-0,42	-0,59	Group D-RSCA<0, TBI<0
	841610	0,82	0,82	0,52	0,30	0,20	-0,10	0,06	Group C-RSCA<0, TBI>0
	841939	0,93	0,93	1,66	-0,72	-0,25	-0,04	-0,48	Group D-RSCA<0, TBI<0
	851610	0,48	0,48	0,19	0,29	0,40	-0,35	0,21	Group C-RSCA<0, TBI>0

Table 8. International competitiveness analysis for heating sub-product (2015-2021) (Compiled by authors).

Year	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
2015	732181	2,11	2,15	0,47	1,68	0,65	0,35	0,59	Group A-RSCA>0, TBI>0
	732211	17,79	21,27	0,14	21,13	2,17	0,89	0,97	Group A-RSCA>0, TBI>0
	840220	0,15	0,15	1,86	-1,71	-1,09	-0,74	-0,88	Group D-RSCA<0, TBI<0
	840310	9,45	10,38	2,51	7,87	0,62	0,81	0,49	Group A-RSCA>0, TBI>0
	840410	0,54	0,54	1,75	-1,21	-0,51	-0,30	-0,58	Group D-RSCA<0, TBI<0
	841610	0,71	0,71	0,51	0,20	0,15	-0,17	0,01	Group C-RSCA<0, TBI>0
	841939	1,02	1,03	2,45	-1,42	-0,37	0,01	-0,55	Group B-RSCA>0, TBI<0
	851610	0,38	0,38	0,65	-0,27	-0,23	-0,45	-0,46	Group D-RSCA<0, TBI<0
2016	732181	1,13	1,14	0,43	0,71	0,42	0,06	0,34	Group A-RSCA>0, TBI>0
	732211	15,17	17,69	0,08	17,60	2,32	0,87	0,98	Group A-RSCA>0, TBI>0
	840220	0,15	0,15	1,76	-1,61	-1,06	-0,74	-0,87	Group D-RSCA<0, TBI<0
	840310	9,49	10,44	2,39	8,04	0,64	0,81	0,53	Group A-RSCA>0, TBI>0
	840410	0,45	0,45	1,63	-1,18	-0,56	-0,38	-0,60	Group D-RSCA<0, TBI<0
	841610	0,44	0,44	0,40	0,04	0,04	-0,39	-0,07	Group D-RSCA<0, TBI<0
	841939	1,24	1,25	1,85	-0,60	-0,17	0,11	-0,38	Group B-RSCA>0, TBI<0
	851610	0,38	0,39	0,45	-0,07	-0,07	-0,44	-0,30	Group D-RSCA<0, TBI<0
2017	732181	1,41	1,43	0,33	1,10	0,63	0,17	0,57	Group A-RSCA>0, TBI>0
	732211	15,21	17,73	0,06	17,67	2,45	0,87	0,98	Group A-RSCA>0, TBI>0
	840220	0,15	0,15	1,76	-1,60	-1,06	-0,74	-0,87	Group D-RSCA<0, TBI<0
	840310	10,07	11,15	2,34	8,81	0,68	0,82	0,54	Group A-RSCA>0, TBI>0
	840410	1,61	1,64	0,58	1,06	0,45	0,24	0,43	Group A-RSCA>0, TBI>0
	841610	0,70	0,70	0,86	-0,16	-0,09	-0,18	-0,22	Group D-RSCA<0, TBI<0
	841939	1,12	1,13	1,18	-0,05	-0,02	0,06	-0,21	Group B-RSCA>0, TBI<0
	851610	0,43	0,43	0,41	0,01	0,01	-0,40	-0,24	Group D-RSCA<0, TBI<0
2018	732181	1,15	1,16	0,17	0,99	0,82	0,07	0,72	Group A-RSCA>0, TBI>0
	732211	15,72	18,36	0,11	18,25	2,19	0,88	0,97	Group A-RSCA>0, TBI>0
	840220	0,11	0,11	1,68	-1,57	-1,16	-0,79	-0,89	Group D-RSCA<0, TBI<0
	840310	10,89	12,13	2,78	9,35	0,64	0,83	0,56	Group A-RSCA>0, TBI>0
	840410	0,81	0,82	0,57	0,24	0,15	-0,11	0,04	Group C-RSCA<0, TBI>0
	841610	1,31	1,33	1,45	-0,13	-0,04	0,13	-0,16	Group B-RSCA>0, TBI<0
	841939	1,11	1,12	1,95	-0,82	-0,24	0,05	-0,37	Group B-RSCA>0, TBI<0
	851610	0,47	0,48	0,36	0,12	0,13	-0,36	-0,04	Grup D-RSCA<0, TBI<0
2019	732181	0,97	0,98	0,17	0,81	0,75	-0,01	0,70	Group C-RSCA<0, TBI>0
	732211	15,76	18,59	0,64	17,95	1,46	0,88	0,89	Group A-RSCA>0, TBI>0
	840220	0,32	0,33	2,16	-1,83	-0,82	-0,50	-0,76	Group D-RSCA<0, TBI<0
	840310	10,14	11,27	1,98	9,29	0,75	0,82	0,66	Group A-RSCA>0, TBI>0
	840410	1,32	1,34	0,38	0,96	0,55	0,14	0,59	Group A-RSCA>0, TBI>0
	841610	0,88	0,89	0,38	0,51	0,37	-0,06	0,25	Group C-RSCA<0, TBI>0
	841939	1,11	1,12	1,01	0,11	0,05	0,05	-0,03	Group B-RSCA>0, TBI<0
	851610	0,45	0,45	0,31	0,14	0,16	-0,38	0,04	Group C-RSCA<0, TBI>0
2020	732181	1,13	1,14	0,11	1,02	1,00	0,06	0,81	Group A- RSCA>0, TBI>0
	732211	13,88	16,04	0,40	15,64	1,59	0,86	0,92	Group A-RSCA>0, TBI>0
	840220	0,26	0,26	2,09	-1,83	-0,90	-0,59	-0,82	Group D-RSCA<0, TBI<0
	840310	10,21	11,36	2,04	9,32	0,75	0,82	0,63	Group A-RSCA>0, TBI>0
	840410	0,68	0,69	0,67	0,01	0,01	-0,19	-0,07	Group D-RSCA<0, TBI<0
	841610	0,85	0,85	0,45	0,41	0,28	-0,08	0,09	Group C-RSCA<0, TBI>0
	841939	1,51	1,53	1,41	0,12	0,04	0,20	-0,09	Group B-RSCA>0, TBI<0
	851610	0,47	0,47	0,42	0,05	0,05	-0,36	-0,15	Group D-RSCA<0, TBI<0
2021	732181	1,09	1,10	1,23	-0,13	-0,05	0,04	0,76	Group A -RSCA>0, TBI>0
	732211	14,09	16,45	0,09	16,36	2,23	0,86	0,97	Group A-RSCA>0, TBI>0
	840220	0,26	0,26	2,26	-1,99	-0,93	-0,58	-0,82	Group D-RSCA<0, TBI<0
	840310	9,21	10,19	1,31	8,88	0,89	0,80	0,74	Group A-RSCA>0, TBI>0
	840410	0,96	0,97	0,72	0,25	0,13	-0,02	0,14	Group C-RSCA<0, TBI>0
	841610	1,11	1,12	0,58	0,54	0,28	0,05	0,25	Group A-RSCA>0, TBI>0
	841939	1,74	1,77	1,48	0,29	0,08	0,27	0,03	Group A-RSCA>0, TBI>0
	851610	0,50	0,51	0,45	0,06	0,05	-0,33	-0,12	Group D-RSCA<0, TBI<0

851610) is less than zero, thus it reveals the net-importer of these products. According to the product mapping method, the products (HS Code 732181, HS Code 732211 and HS Code 840310) are included in Group A. The explanation for this is that it has been determined that net-exports (GROUP A) have a comparative advantage in the trade of these products. Although it differs from time to time, the products (HS Code 851610, HS Code 840410 and HS Code 841939) are involved in Group D.

Table 9-10 indicate the international competitiveness analysis results for the refrigeration sub-sector. When the RCA index results calculated for the products (HS Code 841891 and HS Code 841850) are evaluated in general, it is comprehended that the values are 1 and above. The average values of the index results are respectively calculated as 1.91 and 4.60. RXA index results are parallel to RCA index results. Therefore, according to the results of these two indexes, it has been revealed that Türkiye has competitiveness in these products and specializes in its exports. However, when the RCA index results for the other two products (HS Code 841990 and HS Code 841989) were examined in general, it was determined that the calculated values were 1 and below. The average value of the index results was respectively calculated as 0.70 and 0.35. These results are parallel to the RXA index. Hence, according to the results of these two indexes, it has been concluded that Türkiye does not have competitive power in these products and does not specialize in exports. In order for the RMP Index to gain competitive advantage in the relevant sector or product group, the calculated values require to below one. The RMP index results calculated for the products (HS Code 841891 and HS Code 841850) are below 1, thus it reveals that comparative advantage of these products. The RMP index values calculated for the non-competitive product (HS Code 841490) are below 1, thus it reveals that meagre import of this product. The calculated RMP index values of the product (HS Code 841989) are above 1, which in this context reveals the comparative disadvantage of this product. RTA and RC indices, which take both export and import aspects into consideration, will offer objective results. When the results of these two indexes are evaluated in general, the values calculated for the product (HS Code 841891 and HS Code 841850) are positive. Therefore, it has been determined that Türkiye has a competitive advantage in these products. The indices calculated for the product (HS Code 841490) are negative in the periods covering the years 2001-2004. Throughout all periods, the results of both indexes are negative for this product (HS Code 841989). Therefore, it has been revealed that Türkiye has a competitive disadvantage in these products. In general evaluation, due to RSCA>0, it reveals the comparative advantage of the products (HS Code 841891 and HS Code 841850). The RSCA index values analyzed for the products (HS Code 841990 and HS Code 841989) are less than zero, hence it has been determined that Türkiye does not have a comparative advantage in these products. When examined in general, the TBI index values analyzed for the products (HS Code 841891 and HS Code 841850) are greater than zero, thus it reveals that the net-exporter of these products. The fact that the TBI index values for the product (HS Code 841490) calculated in the 2001-2004, 2011, 2013 and 2020 periods are less than zero hence, it indicates that the net-importer of this product. TBI index values calculated for the product (HS Code 841989) are less than zero throughout totally periods; thus, Türkiye is in a net-importer for this product. Although there are alters from time to time according to the product mapping method, the products (HS Code 841891 and HS Code 841850) are included in Group A. In this context, it has been concluded that Türkiye is a net-exporter (GROUP A) with a comparative advantage in these products. The product (HS Code 841989) is involved in Group D and it has been determined that Türkiye is a net-importer with a comparative disadvantage in this product. The product (HS Code 841490) is involved in Group C for the periods 2005-2010, 2012, 2014-2019 and 2021, however, when it was generally evaluated results, this product is included in Group D.

Table 9. International competitiveness analysis for refrigeration sub-product (2001-2007) (Compiled by authors).

	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
2001	841891	0,31	0,31	1,74	-1,43	-0,74	-0,52	-0,78	Group D-RSCA<0, TBI<0
	841490	0,39	0,39	0,57	-0,17	-0,16	-0,44	-0,26	Group D-RSCA<0, TBI<0
	841850	0,87	0,87	0,88	-0,01	-0,01	-0,07	-0,07	Group D-RSCA<0, TBI<0
	841989	0,07	0,07	2,37	-2,29	-1,50	-0,86	-0,96	Group D-RSCA<0, TBI<0
2002	841891	0,25	0,26	0,67	-0,41	-0,42	-0,59	-0,69	Group D-RSCA<0, TBI<0
	841490	0,36	0,37	0,68	-0,31	-0,27	-0,47	-0,45	Group D-RSCA<0, TBI<0
	841850	2,03	2,05	0,38	1,67	0,73	0,34	0,62	Group A-RSCA>0, TBI>0
	841989	0,10	0,10	1,40	-1,29	-1,13	-0,81	-0,92	Group D-RSCA<0, TBI<0
2003	841891	0,42	0,42	0,37	0,05	0,05	-0,41	-0,20	Group D-RSCA<0, TBI<0
	841490	0,36	0,36	0,62	-0,26	-0,24	-0,47	-0,43	Group D-RSCA<0, TBI<0
	841850	3,40	3,48	0,39	3,08	0,94	0,55	0,75	Group A-RSCA>0, TBI>0
	841989	0,11	0,11	1,11	-1,00	-1,01	-0,80	-0,88	Group D-RSCA<0, TBI<0
2004	841891	0,61	0,61	0,49	0,12	0,10	-0,24	-0,30	Group D-RSCA<0, TBI<0
	841490	0,39	0,39	0,72	-0,33	-0,26	-0,44	-0,47	Group D-RSCA<0, TBI<0
	841850	3,33	3,41	0,55	2,86	0,79	0,54	0,65	Group A-RSCA>0, TBI>0
	841989	0,12	0,12	0,91	-0,79	-0,90	-0,79	-0,85	Group D-RSCA<0, TBI<0
2005	841891	1,28	1,30	0,27	1,03	0,68	0,12	0,34	Group A-RSCA>0, TBI>0
	841490	0,67	0,67	0,41	0,26	0,21	-0,20	0,01	Group C-RSCA<0, TBI>0
	841850	4,16	4,29	0,70	3,60	0,79	0,61	0,61	Group A-RSCA>0, TBI>0
	841989	0,18	0,18	1,10	-0,92	-0,78	-0,69	-0,83	Group D-RSCA<0, TBI<0
2006	841891	1,15	1,16	0,63	0,53	0,26	0,07	-0,26	Group B-RSCA>0, TBI<0
	841490	0,89	0,89	0,51	0,39	0,25	-0,06	0,02	Group C-RSCA<0, TBI>0
	841850	3,31	3,39	1,21	2,18	0,45	0,54	0,31	Group A-RSCA>0, TBI>0
	841989	0,19	0,19	1,04	-0,85	-0,74	-0,68	-0,82	Group D-RSCA<0, TBI<0
2007	841891	1,22	1,23	0,25	0,98	0,69	0,10	0,34	Group A-RSCA>0, TBI>0
	841490	0,98	0,99	0,46	0,53	0,33	-0,01	0,12	Group C-RSCA<0, TBI>0
	841850	3,58	3,69	0,90	2,78	0,61	0,56	0,47	Group A-RSCA>0, TBI>0
	841989	0,18	0,18	1,02	-0,85	-0,76	-0,70	-0,81	Group D-RSCA<0, TBI<0

Table 10. International competitiveness analysis for refrigeration sub-product (2008-2021) (Compiled by authors).

	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
2008	841891	0,33	0,33	0,15	0,18	0,34	-0,50	0,37	Group C-RSCA<0, TBI>0
	841490	0,87	0,88	0,44	0,44	0,31	-0,07	0,12	Group C-RSCA<0, TBI>0
	841850	3,85	3,99	0,68	3,31	0,77	0,59	0,61	Group A-RSCA>0, TBI>0
	841989	0,29	0,29	0,89	-0,59	-0,48	-0,55	-0,68	Group D-RSCA<0, TBI<0
2009	841891	1,55	1,57	0,26	1,31	0,78	0,22	0,56	Group A-RSCA>0, TBI>0
	841490	0,84	0,85	0,54	0,31	0,20	-0,08	0,09	Group C-RSCA<0, TBI>0
	841850	4,45	4,63	0,48	4,15	0,98	0,63	0,76	Group A-RSCA>0, TBI>0
	841989	0,23	0,24	0,92	-0,69	-0,59	-0,62	-0,70	Group D-RSCA<0, TBI<0
2010	841891	1,00	1,01	0,09	0,91	1,03	0,00	0,65	Group A-RSCA>0, TBI>0
	841490	0,88	0,89	0,44	0,44	0,30	-0,06	0,11	Group C-RSCA<0, TBI>0
	841850	5,85	6,13	0,58	5,55	1,02	0,71	0,73	Group A-RSCA>0, TBI>0
	841989	0,58	0,58	0,74	-0,16	-0,11	-0,27	-0,43	Group D-RSCA<0, TBI<0
2011	841891	0,96	0,96	0,17	0,79	0,75	-0,02	0,45	Group C-RSCA<0, TBI>0
	841490	0,84	0,85	0,53	0,31	0,20	-0,09	-0,06	Group D-RSCA<0, TBI<0
	841850	7,21	7,63	0,62	7,01	1,09	0,76	0,75	Group A-RSCA>0, TBI>0
	841989	0,41	0,41	0,86	-0,45	-0,32	-0,42	-0,56	Group D-RSCA<0, TBI<0
2012	841891	1,06	1,07	0,14	0,93	0,87	0,03	0,59	Group A-RSCA>0, TBI>0
	841490	0,69	0,69	0,43	0,27	0,21	-0,18	0,04	Group C-RSCA<0, TBI>0
	841850	5,86	6,17	0,50	5,67	1,09	0,71	0,77	Group A-RSCA>0, TBI>0
	841989	0,44	0,44	1,33	-0,89	-0,48	-0,39	-0,66	Group D-RSCA<0, TBI<0
2013	841891	1,74	1,77	0,04	1,73	1,66	0,27	0,90	Group A-RSCA>0, TBI>0
	841490	0,74	0,75	0,49	0,26	0,18	-0,15	-0,04	Group D-RSCA<0, TBI<0
	841850	6,08	6,43	0,58	5,84	1,04	0,72	0,74	Group A-RSCA>0, TBI>0
	841989	0,38	0,38	1,60	-1,22	-0,62	-0,45	-0,75	Group D-RSCA<0, TBI<0
2014	841891	2,39	2,44	0,09	2,36	1,46	0,41	0,86	Group A-RSCA>0, TBI>0
	841490	0,69	0,69	0,33	0,36	0,32	-0,18	0,17	Group C-RSCA<0, TBI>0
	841850	6,68	7,11	0,49	6,62	1,16	0,74	0,81	Group A-RSCA>0, TBI>0
	841989	0,43	0,43	1,10	-0,67	-0,41	-0,40	-0,63	Group D-RSCA<0, TBI<0
2015	841891	1,41	1,43	0,08	1,35	1,26	0,17	0,83	Group A-RSCA>0, TBI>0
	841490	0,62	0,63	0,36	0,27	0,25	-0,23	0,13	Group C-RSCA<0, TBI>0
	841850	4,97	5,22	0,41	4,81	1,10	0,67	0,80	Group A-RSCA>0, TBI>0
	841989	0,40	0,41	1,12	-0,72	-0,44	-0,42	-0,62	Group D-RSCA<0, TBI<0
2016	841891	4,48	4,67	0,08	4,59	1,75	0,63	0,94	Group A-RSCA>0, TBI>0
	841490	0,62	0,63	0,39	0,24	0,21	-0,23	0,09	Group C-RSCA<0, TBI>0
	841850	4,85	5,08	0,36	4,73	1,15	0,66	0,83	Group A-RSCA>0, TBI>0
	841989	0,39	0,39	2,71	-2,33	-0,85	-0,44	-0,82	Group D-RSCA<0, TBI<0
2017	841891	5,74	6,07	0,06	6,01	2,01	0,70	0,96	Group A-RSCA>0, TBI>0
	841490	0,71	0,72	0,43	0,29	0,23	-0,17	0,08	Group C-RSCA<0, TBI>0
	841850	4,78	5,02	0,26	4,76	1,29	0,65	0,87	Group A-RSCA>0, TBI>0
	841989	0,40	0,40	1,47	-1,07	-0,56	-0,43	-0,71	Group D-RSCA<0, TBI<0
2018	841891	3,64	3,77	0,03	3,73	2,04	0,57	0,97	Group A-RSCA>0, TBI>0
	841490	0,77	0,78	0,42	0,36	0,26	-0,13	0,19	Group C-RSCA<0, TBI>0
	841850	5,16	5,42	0,24	5,18	1,35	0,68	0,90	Group A-RSCA>0, TBI>0
	841989	0,52	0,53	1,02	-0,49	-0,29	-0,31	-0,42	Group D-RSCA<0, TBI<0
2019	841891	2,58	2,65	0,05	2,59	1,71	0,44	0,95	Group A-RSCA>0, TBI>0
	841490	0,77	0,78	0,55	0,23	0,15	-0,13	0,11	Group C-RSCA<0, TBI>0
	841850	5,31	5,61	0,20	5,41	1,44	0,68	0,92	Group A-RSCA>0, TBI>0
	841989	0,66	0,67	1,03	-0,36	-0,19	-0,20	-0,31	Group D-RSCA<0, TBI<0
2020	841891	3,66	3,79	0,11	3,68	1,53	0,57	0,91	Group A-RSCA>0, TBI>0
	841490	0,79	0,80	0,72	0,07	0,04	-0,12	-0,07	Group D-RSCA<0, TBI<0
	841850	5,45	5,76	0,20	5,56	1,46	0,69	0,91	Group A-RSCA>0, TBI>0
	841989	0,56	0,57	1,11	-0,55	-0,29	-0,28	-0,44	Group D-RSCA<0, TBI<0
2021	841891	4,32	4,52	0,61	3,91	0,87	0,62	0,68	Group A-RSCA>0, TBI>0
	841490	0,85	0,86	0,49	0,37	0,24	-0,08	0,19	Group C-RSCA<0, TBI>0
	841850	5,38	5,70	0,21	5,49	1,44	0,69	0,89	Group A-RSCA>0, TBI>0
	841989	0,64	0,65	1,54	-0,90	-0,38	-0,22	-0,48	Group D-RSCA<0, TBI<0

Table 11 displays the international competitiveness analysis results for the air conditioning sub-product. It was determined that the RCA index values calculated for the product (HS Code 841430) in the 2001-2021 periods were below 1. The results are parallel to the RXA index. The calculated value for the product of these two indices was recorded as 0.27. Therefore, according to these two indices, it has been revealed that Türkiye does not have competitive power in the product and does not specialize in exports. When the RCA index results calculated for the product (HS Code 841520) are examined, it is realized that the values in the 2008-2011 and 2016-2019 periods are 1 and above. The average value of the RCA index was calculated as 0.79, and the average value of the RXA index was calculated as 0.80. Hence, according to the results of these two indexes, it has been determined that Türkiye does not have competitiveness in this product and does not specialize in its exports. In order for the RMP Index to gain competitive advantage in the relevant sector or product group, the calculated values necessitate to below one. The calculated values for the product (HS Code 841430) are above 1, therefore it indicates that the comparative disadvantage of the product. The RMP index values analyzed for the product (HS Code 841520) are below 1, thus it reveals that the import of this product is meagre. RTA and RC indices, which take both export and import aspects into consideration, will provide objective results. The results of these two indexes indicate that the values calculated for the product (HS Code 841430) are negative throughout the whole period (2001-2021), thus it demonstrates that the comparative disadvantage of this product. The values analyzed for the product (HS Code 841520) in the 2001-2007, 2014-2015 and 2020-2021 periods are negative, therefore it was revealed that this product has a competitive disadvantage. RSCA index values calculated for the product (HS Code 841430) throughout totally periods are less than zero, thus it indicates that product has a comparative disadvantage. It has been determined that Türkiye does not have a comparative advantage in this product (HS Code 841520) due to RSCA<0 in the 2001-2007, 2012-2015 and 2020-2021 periods. The fact that the TBI index is less than zero throughout the periods considered reveals the net-importer of the product (HS Code 841430). TBI index reveals the net-importer of the product (HS Code 841520), because it is less than zero in other periods except the 2008-2011 and 2018-2019 periods. According to the product mapping method, the product (HS Code 841430) is included in Group D. The explanation for this is that it has been concluded that Türkiye is a net-importer (GROUP D) with a comparative disadvantage in trade in this product. The other product (HS Code 841520) is involved in Group D in the 2001-2007, 2012-2015 and 2020-2021 periods, while the product is included in Group A in the 2008-2011 and 2018-2019 periods. However, when evaluated in general, this product is involved in Group D.

Table 11. International competitiveness analysis for air conditioning sub-product (2001-2021) (Compiled by authors).

	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
2001	841430	0,23	0,23	1,40	-1,16	-0,77	-0,62	-0,78	Group D-RSCA<0, TBI<0
	841520	0,01	0,01	0,35	-0,34	-1,67	-0,99	-0,97	Group D-RSCA<0, TBI<0
2002	841430	0,19	0,19	1,61	-1,42	-0,93	-0,68	-0,85	Group D-RSCA<0, TBI<0
	841520	0,00	0,00	0,21	-0,20	-1,67	-0,99	-0,97	Group D-RSCA<0, TBI<0
2003	841430	0,36	0,36	1,81	-1,45	-0,70	-0,47	-0,76	Group D-RSCA<0, TBI<0
	841520	0,01	0,01	0,43	-0,42	-1,67	-0,98	-0,97	Group D-RSCA<0, TBI<0
2004	841430	0,39	0,39	2,33	-1,94	-0,77	-0,44	-0,79	Group D-RSCA<0, TBI<0
	841520	0,02	0,02	0,50	-0,48	-1,37	-0,96	-0,94	Group D-RSCA<0, TBI<0
2005	841430	0,33	0,33	2,68	-2,35	-0,91	-0,50	-0,85	Group D-RSCA<0, TBI<0
	841520	0,05	0,05	0,29	-0,23	-0,72	-0,90	-0,78	Group D-RSCA<0, TBI<0
2006	841430	0,37	0,37	2,99	-2,62	-0,91	-0,46	-0,85	Group D-RSCA<0, TBI<0
	841520	0,09	0,09	0,13	-0,04	-0,15	-0,83	-0,40	Group D-RSCA<0, TBI<0
2007	841430	0,43	0,43	3,26	-2,83	-0,88	-0,40	-0,83	Group D-RSCA<0, TBI<0
	841520	0,56	0,57	0,58	-0,02	-0,01	-0,28	-0,24	Group D-RSCA<0, TBI<0
2008	841430	0,46	0,47	3,30	-2,83	-0,85	-0,37	-0,81	Group D-RSCA<0, TBI<0
	841520	1,36	1,37	0,70	0,67	0,29	0,15	0,09	Group A-RSCA>0, TBI>0
2009	841430	0,55	0,55	3,92	-3,37	-0,85	-0,29	-0,79	Group D-RSCA<0, TBI<0
	841520	1,05	1,06	0,29	0,77	0,56	0,02	0,43	Group A-RSCA>0, TBI>0
2010	841430	0,39	0,39	3,31	-2,91	-0,92	-0,44	-0,84	Group D-RSCA<0, TBI<0
	841520	1,67	1,69	0,52	1,17	0,52	0,25	0,30	Group A-RSCA>0, TBI>0
2011	841430	0,29	0,29	3,17	-2,88	-1,04	-0,55	-0,89	Group D-RSCA<0, TBI<0
	841520	1,50	1,52	0,78	0,74	0,29	0,20	0,02	Group A-RSCA>0, TBI>0
2012	841430	0,17	0,17	2,99	-2,82	-1,25	-0,71	-0,93	Group D-RSCA<0, TBI<0
	841520	0,75	0,76	0,75	0,01	0,00	-0,14	-0,22	Group D-RSCA<0, TBI<0
2013	841430	0,14	0,14	2,87	-2,73	-1,30	-0,75	-0,94	Group D-RSCA<0, TBI<0
	841520	0,94	0,95	0,77	0,18	0,09	-0,03	-0,19	Group D-RSCA<0, TBI<0
2014	841430	0,21	0,21	2,55	-2,34	-1,08	-0,65	-0,89	Group D-RSCA<0, TBI<0
	841520	0,69	0,70	0,92	-0,22	-0,12	-0,18	-0,36	Group D-RSCA<0, TBI<0
2015	841430	0,13	0,13	2,59	-2,45	-1,28	-0,76	-0,92	Group D-RSCA<0, TBI<0
	841520	0,68	0,69	0,86	-0,18	-0,10	-0,19	-0,28	Group D-RSCA<0, TBI<0
2016	841430	0,14	0,14	2,73	-2,60	-1,30	-0,76	-0,92	Group D-RSCA<0, TBI<0
	841520	1,02	1,03	0,81	0,22	0,10	0,01	-0,06	Group B-RSCA>0, TBI<0
2017	841430	0,18	0,18	2,83	-2,65	-1,19	-0,69	-0,91	Group D-RSCA<0, TBI<0
	841520	1,03	1,04	0,88	0,16	0,07	0,02	-0,08	Group B-RSCA>0, TBI<0
2018	841430	0,20	0,20	3,29	-3,09	-1,22	-0,67	-0,90	Group D-RSCA<0, TBI<0
	841520	1,70	1,73	1,04	0,69	0,22	0,26	0,14	Group A-RSCA>0, TBI>0
2019	841430	0,15	0,15	3,33	-3,18	-1,35	-0,74	-0,92	Group D-RSCA<0, TBI<0
	841520	1,67	1,70	1,02	0,67	0,22	0,25	0,21	Group A-RSCA>0, TBI>0
2020	841430	0,19	0,19	3,64	-3,45	-1,29	-0,69	-0,92	Group D-RSCA<0, TBI<0
	841520	0,90	0,91	0,93	-0,02	-0,01	-0,05	-0,11	Group D-RSCA<0, TBI<0
2021	841430	0,17	0,17	3,74	-3,57	-1,35	-0,72	-0,92	Group D-RSCA<0, TBI<0
	841520	0,86	0,87	0,90	-0,03	-0,02	-0,08	-0,06	Group D-RSCA<0, TBI<0

Table 12 demonstrates the international competitiveness analysis results for the ventilation sub-product. The RCA index values calculated for the products (HS Code 830710 and HS Code 841460) are above 1. The average values of the index results were respectively calculated as 2.88 and 4.26. RCA index results and RXA index results are similar. In this context, it has been determined that Türkiye has competitiveness in these products and indicates specialization in exports. In order for the RMP Index to gain competitive advantage in the relevant sector or product group, the calculated values require to below one. In this context, when both products are evaluated in general, the calculated values are below 1. Therefore, it reveals the comparative advantage of these two products (HS Code 830710 and HS Code 841460). RTA and RC index values, which take into account both export and import aspects, are positive. Therefore, it has been revealed that Türkiye has a competitive advantage in these two products (HS Code 830710 and HS Code 841460). Due to RSCA>0 for the periods covering 2001-2021, it indicates that the product (HS Code 830710) has a comparative advantage. The other product (HS Code 841460) reveals the comparative advantage of the product, as the values calculated in other periods except 2001 are greater than zero. The fact that the TBI index is greater than zero throughout the periods reveals the net-exporter structure of the product (HS Code 830710). The other product (HS Code 841460) reveals the net-exporter structure of this product, since the calculated value is greater than zero in all periods except 2001. According to the product mapping method, the product (HS Code 830710) is in Group A, therefore it has been determined that Türkiye is a net-exporter (GROUP A) with a comparative advantage in the trade of this product. The product (841460) was included in Group D in 2001 and in Group A in other periods. In this context, it was revealed that it is a net-exporter (GROUP A) with a comparative advantage in the trade of this product.

Table 12. International competitiveness analysis for ventilation sub-product (2001-2021) (Compiled by authors).

	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
2001	830710	1,57	1,58	0,47	1,11	0,53	0,22	0,49	Group A-RSCA>0, TBI>0
	841460	0,58	0,58	0,67	-0,09	-0,06	-0,27	-0,24	Group D-RSCA<0, TBI<0
2002	830710	1,27	1,28	0,53	0,75	0,38	0,12	0,33	Group A-RSCA>0, TBI>0
	841460	1,23	1,24	0,69	0,55	0,26	0,10	0,17	Group A-RSCA>0, TBI>0
2003	830710	1,83	1,86	0,70	1,16	0,42	0,29	0,29	Group A-RSCA>0, TBI>0
	841460	1,62	1,64	0,73	0,91	0,35	0,24	0,27	Group A-RSCA>0, TBI>0
2004	830710	3,06	3,13	0,96	2,17	0,51	0,51	0,42	Group A-RSCA>0, TBI>0
	841460	2,19	2,22	0,82	1,41	0,43	0,37	0,33	Group A-RSCA>0, TBI>0
2005	830710	3,08	3,15	0,56	2,58	0,75	0,51	0,61	Group A-RSCA>0, TBI>0
	841460	2,66	2,71	0,93	1,78	0,46	0,45	0,33	Group A-RSCA>0, TBI>0
2006	830710	3,79	3,89	0,44	3,45	0,95	0,58	0,69	Group A-RSCA>0, TBI>0
	841460	3,55	3,64	1,06	2,58	0,54	0,56	0,39	Group A-RSCA>0, TBI>0
2007	830710	3,39	3,48	0,45	3,03	0,89	0,54	0,71	Group A-RSCA>0, TBI>0
	841460	3,79	3,91	0,99	2,92	0,60	0,58	0,45	Group A-RSCA>0, TBI>0
2008	830710	3,42	3,53	0,51	3,02	0,84	0,55	0,73	Group A-RSCA>0, TBI>0
	841460	4,34	4,50	0,90	3,60	0,70	0,63	0,53	Group A-RSCA>0, TBI>0
2009	830710	3,78	3,90	0,53	3,38	0,87	0,58	0,71	Group A-RSCA>0, TBI>0
	841460	5,27	5,51	0,79	4,72	0,84	0,68	0,67	Group A-RSCA>0, TBI>0
2010	830710	3,31	3,40	0,53	2,86	0,80	0,54	0,62	Group A-RSCA>0, TBI>0
	841460	6,24	6,56	0,80	5,76	0,92	0,72	0,67	Group A-RSCA>0, TBI>0
2011	830710	3,99	4,12	0,58	3,53	0,85	0,60	0,60	Group A-RSCA>0, TBI>0
	841460	6,87	7,25	0,92	6,33	0,90	0,75	0,63	Group A-RSCA>0, TBI>0
2012	830710	3,37	3,47	0,84	2,62	0,61	0,54	0,49	Group A-RSCA>0, TBI>0
	841460	6,15	6,48	0,91	5,57	0,85	0,72	0,64	Group A-RSCA>0, TBI>0
2013	830710	4,70	4,90	0,98	3,92	0,70	0,65	0,56	Group A-RSCA>0, TBI>0
	841460	5,49	5,76	1,21	4,55	0,68	0,69	0,49	Group A-RSCA>0, TBI>0
2014	830710	3,95	4,09	1,28	2,81	0,51	0,60	0,43	Group A-RSCA>0, TBI>0
	841460	4,95	5,18	1,22	3,95	0,63	0,66	0,47	Group A-RSCA>0, TBI>0
2015	830710	1,47	1,49	1,55	-0,06	-0,02	0,19	0,22	Group A-RSCA>0, TBI>0
	841460	4,39	4,57	1,56	3,01	0,47	0,63	0,36	Group A-RSCA>0, TBI>0
2016	830710	1,44	1,46	1,22	0,24	0,08	0,18	0,32	Group A-RSCA>0, TBI>0
	841460	4,11	4,28	0,85	3,42	0,70	0,61	0,57	Group A-RSCA>0, TBI>0
2017	830710	1,71	1,73	1,21	0,53	0,16	0,26	0,32	Group A-RSCA>0, TBI>0
	841460	4,61	4,82	0,70	4,12	0,84	0,64	0,66	Group A-RSCA>0, TBI>0
2018	830710	1,39	1,41	0,85	0,56	0,22	0,16	0,24	Group A-RSCA>0, TBI>0
	841460	5,40	5,68	0,48	5,21	1,08	0,69	0,81	Group A-RSCA>0, TBI>0
2019	830710	1,38	1,40	0,39	1,01	0,55	0,16	0,50	Group A-RSCA>0, TBI>0
	841460	5,70	6,04	0,28	5,76	1,34	0,70	0,90	Group A-RSCA>0, TBI>0
2020	830710	4,41	4,61	0,94	3,67	0,69	0,63	0,48	Group A-RSCA>0, TBI>0
	841460	5,27	5,56	0,32	5,23	1,24	0,68	0,86	Group A-RSCA>0, TBI>0
2021	830710	4,22	4,41	0,92	3,49	0,68	0,62	0,58	Group A-RSCA>0, TBI>0
	841460	5,08	5,36	0,30	5,06	1,25	0,67	0,87	Group A-RSCA>0, TBI>0

Table 13-15 display the international competitiveness analysis results for the installation sub-product. It is comprehended that the RCA index values calculated for the products (HS Code 391731, HS Code 392111 and HS Code 741220) are 1 and above. The average value of the RCA index results was respectively calculated as 5.82, 1.51 and 2.84. The results are similar to the RXA index. Therefore, according to the results of these two indices, it has been determined that Türkiye has competitiveness in these products and shows specialization in exports. However, in the general evaluation of the RCA index analyzed for the other two products (HS Code 902511 and HS Code 902610), it is comprehended that the values are below one. The average values of RCA index and RXA index results were calculated as 0.28 and 0.17, respectively. Therefore, it has been revealed that Türkiye does not have competitiveness in these products and does not specialize in exports. In order for the RMP Index to gain competitive advantage in the relevant sector or product group, the calculated values necessitate to below one. In this context, the values calculated in the 2010 and 2012-2021 periods are less than 1, thus indicating the comparative advantage of the relevant product (HS Code 391731). The RMP index values calculated for the product (HS Code 741220) are below 1, in this context revealing the comparative advantage of the product. The analyzed values in the 2002-2007 and 2009 periods are overhead 1, which demonstrates the comparative disadvantage of the relevant product (HS Code 902511). The RMP index results calculated for the product (HS Code 902610) are above 1, revealing the comparative disadvantage of the relevant product. RTA and RC indices, which take both export and import aspects into consideration, will offer objective results. The index values analyzed for the products (HS Code 391721, HS Code 392111 and HS 741220) are positive. Therefore, it has been determined that Türkiye has a competitive advantage in these products. For other products (HS Code 902511 and HS Code 902610), the calculated values are negative. In this context, it has been revealed that Türkiye has a competitive disadvantage in these products. When evaluated in general, the RSCA index results calculated for the products (HS Code 391731, HS Code 392111 and HS Code 741220) are greater than zero, thus it indicates that Türkiye has a comparative advantage in these products. As RSCA<0, in the 2001-2021 periods, it reveals that the relevant products (HS Code 902511 and HS Code 902610) do not have a comparative advantage. The TBI index values calculated for the products (HS Code 391731, HS Code 392111 and HS Code 741220) are greater than zero, thus it reveals that the net-exporter structure of these products. The TBI index value analyzed for other products (HS Code 902511 and HS Code 902510) is less than zero, in this context Türkiye is in a net-importer structure for these products. According to the product mapping method, the products (HS Code 391731, HS Code 392111 and HS Code 7412220) are located in Group A. The explanation for this is that Türkiye has been a net-exporter (GROUP A) with a comparative advantage in the trade of these products. Generally evaluated, the products (HS Code 902511 and HS Code 902610) are in Group D. Hence, it has been revealed that Türkiye is a net-importer (GROUP D) with a comparative disadvantage in these products.

Table 13. International competitiveness analysis for installation sub-product (2001-2006) (Compiled by authors).

	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
	391731	11,98	12,77	1,19	11,58	1,03	0,85	0,77	Group A-RSCA>0, TBI>0
	392111	1,25	1,26	0,23	1,03	0,73	0,11	0,63	Group A-RSCA>0, TBI>0
2001	741220	0,54	0,54	0,29	0,25	0,27	-0,30	0,13	Group C-RSCA<0, TBI>0
	902511	0,15	0,15	0,76	-0,61	-0,70	-0,74	-0,74	Group D-RSCA<0, TBI<0
	902610	0,09	0,09	1,02	-0,93	-1,06	-0,84	-0,89	Group D-RSCA<0, TBI<0
	391731	2,30	2,33	1,16	1,17	0,30	0,39	0,12	Group A-RSCA>0, TBI>0
	392111	1,39	1,40	0,10	1,30	1,14	0,16	0,82	Group A-RSCA>0, TBI>0
2002	741220	1,20	1,21	0,30	0,91	0,60	0,09	0,41	Group A-RSCA>0, TBI>0
	902511	0,27	0,27	1,16	-0,89	-0,63	-0,58	-0,74	Group D-RSCA<0, TBI<0
	902610	0,08	0,08	0,93	-0,85	-1,07	-0,85	-0,90	Group D-RSCA<0, TBI<0
	391731	2,46	2,50	1,32	1,18	0,28	0,42	0,13	Group A-RSCA>0, TBI>0
	392111	0,72	0,73	0,08	0,65	0,94	-0,16	0,72	Group C-RSCA<0, TBI>0
2003	741220	1,66	1,68	0,27	1,41	0,79	0,25	0,58	Group A-RSCA>0, TBI>0
	902511	0,24	0,24	1,14	-0,90	-0,68	-0,61	-0,77	Group D-RSCA<0, TBI<0
	902610	0,10	0,10	1,01	-0,91	-1,01	-0,82	-0,88	Group D-RSCA<0, TBI<0
	391731	3,99	4,11	1,53	2,58	0,43	0,60	0,25	Group A-RSCA>0, TBI>0
	392111	0,76	0,77	0,05	0,72	1,16	-0,13	0,81	Group C-RSCA<0, TBI>0
2004	741220	1,38	1,40	0,38	1,01	0,56	0,16	0,39	Group A-RSCA>0, TBI>0
	902511	0,21	0,21	1,15	-0,93	-0,73	-0,65	-0,82	Group D-RSCA<0, TBI<0
	902610	0,13	0,13	0,84	-0,71	-0,80	-0,77	-0,90	Group D-RSCA<0, TBI<0
	391731	8,49	9,03	1,45	7,59	0,80	0,79	0,53	Group A-RSCA>0, TBI>0
	392111	0,99	1,00	0,13	0,87	0,90	-0,01	0,68	Group C-RSCA<0, TBI>0
2005	741220	1,44	1,45	0,39	1,06	0,57	0,18	0,39	Group A-RSCA>0, TBI>0
	902511	0,46	0,46	1,75	-1,29	-0,58	-0,37	-0,75	Group D-RSCA<0, TBI<0
	902610	0,12	0,12	0,92	-0,80	-0,88	-0,78	-0,85	Group D-RSCA<0, TBI<0
	391731	9,13	9,77	1,16	8,61	0,93	0,80	0,62	Group A-RSCA>0, TBI>0
	392111	1,52	1,54	0,16	1,38	0,98	0,21	0,72	Group A-RSCA>0, TBI>0
2006	741220	1,99	2,02	0,59	1,43	0,53	0,33	0,36	Group A-RSCA>0, TBI>0
	902511	0,33	0,34	1,34	-1,00	-0,60	-0,50	-0,77	Group D-RSCA<0, TBI<0
	902610	0,11	0,11	1,07	-0,96	-0,97	-0,80	-0,88	Group D-RSCA<0, TBI<0

Table 14. International competitiveness analysis for installation sub-product (2007-2019) (Compiled by authors).

	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
2007	391731	7,28	7,71	1,26	6,46	0,79	0,76	0,55	Group A-RSCA>0, TBI>0
	392111	1,55	1,57	0,05	1,52	1,50	0,22	0,91	Group A-RSCA>0, TBI>0
	741220	2,19	2,23	0,68	1,55	0,51	0,37	0,32	Group A-RSCA>0, TBI>0
	902511	0,36	0,36	1,20	-0,84	-0,52	-0,47	-0,74	Group D-RSCA<0, TBI<0
	902610	0,13	0,13	1,15	-1,02	-0,93	-0,76	-0,86	Group D-RSCA<0, TBI<0
2008	391731	8,27	8,88	1,24	7,63	0,85	0,78	0,58	Group A-RSCA>0, TBI>0
	392111	1,10	1,11	0,08	1,03	1,13	0,05	0,80	Group A-RSCA>0, TBI>0
	741220	2,36	2,41	0,66	1,75	0,56	0,40	0,40	Group A-RSCA>0, TBI>0
	902511	0,21	0,21	0,93	-0,72	-0,65	-0,65	-0,79	Group D-RSCA<0, TBI<0
	902610	0,14	0,14	1,23	-1,09	-0,95	-0,76	-0,86	Group D-RSCA<0, TBI<0
2009	391731	6,87	7,28	1,04	6,24	0,84	0,75	0,66	Group A-RSCA>0, TBI>0
	392111	0,73	0,74	0,11	0,63	0,82	-0,15	0,67	Group C-RSCA<0, TBI>0
	741220	2,36	2,41	0,41	2,00	0,77	0,41	0,60	Group A-RSCA>0, TBI>0
	902511	0,24	0,25	1,33	-1,09	-0,74	-0,61	-0,80	Group D-RSCA<0, TBI<0
	902610	0,13	0,14	1,16	-1,02	-0,93	-0,76	-0,84	Group D-RSCA<0, TBI<0
2010	391731	8,15	8,69	0,78	7,91	1,05	0,78	0,76	Group A-RSCA>0, TBI>0
	392111	0,79	0,80	0,44	0,36	0,26	-0,12	0,11	Group C-RSCA<0, TBI>0
	741220	2,96	3,03	0,46	2,57	0,82	0,50	0,59	Group A-RSCA>0, TBI>0
	902511	0,16	0,16	0,65	-0,49	-0,62	-0,73	-0,77	Group D-RSCA<0, TBI<0
	902610	0,16	0,16	1,03	-0,88	-0,82	-0,73	-0,83	Group D-RSCA<0, TBI<0
2011	391731	7,63	8,09	1,37	6,72	0,77	0,77	0,56	Group A-RSCA>0, TBI>0
	392111	1,03	1,03	0,23	0,80	0,65	0,01	0,46	Group A-RSCA>0, TBI>0
	741220	3,19	3,27	0,51	2,75	0,80	0,52	0,53	Group A-RSCA>0, TBI>0
	902511	0,19	0,19	0,54	-0,36	-0,46	-0,69	-0,72	Group D-RSCA<0, TBI<0
	902610	0,18	0,18	1,06	-0,88	-0,77	-0,69	-0,83	Group D-RSCA<0, TBI<0
2012	391731	8,36	8,99	0,69	8,31	1,12	0,79	0,78	Group A-RSCA>0, TBI>0
	392111	1,22	1,23	0,11	1,12	1,04	0,10	0,77	Group A-RSCA>0, TBI>0
	741220	3,26	3,35	0,54	2,81	0,79	0,53	0,58	Group A-RSCA>0, TBI>0
	902511	0,29	0,29	0,60	-0,31	-0,32	-0,55	-0,64	Group D-RSCA<0, TBI<0
	902610	0,17	0,17	0,91	-0,74	-0,72	-0,71	-0,79	Group D-RSCA<0, TBI<0
2013	391731	7,02	7,47	0,57	6,91	1,12	0,75	0,78	Group A-RSCA>0, TBI>0
	392111	1,42	1,44	0,15	1,29	0,97	0,17	0,72	Group A-RSCA>0, TBI>0
	741220	3,85	3,99	0,54	3,45	0,87	0,59	0,62	Group A-RSCA>0, TBI>0
	902511	0,32	0,32	0,53	-0,21	-0,22	-0,52	-0,53	Group D-RSCA<0, TBI<0
	902610	0,17	0,17	0,80	-0,63	-0,68	-0,71	-0,78	Group D-RSCA<0, TBI<0
2014	391731	6,44	6,83	0,63	6,21	1,04	0,73	0,75	Group A-RSCA>0, TBI>0
	392111	2,10	2,14	0,10	2,04	1,32	0,36	0,87	Group A-RSCA>0, TBI>0
	741220	3,95	4,09	0,53	3,56	0,89	0,60	0,66	Group A-RSCA>0, TBI>0
	902511	0,16	0,16	0,60	-0,44	-0,58	-0,73	-0,73	Group D-RSCA<0, TBI<0
	902610	0,22	0,22	0,89	-0,66	-0,60	-0,64	-0,72	Group D-RSCA<0, TBI<0
2015	391731	4,98	5,22	0,64	4,58	0,91	0,67	0,71	Group A-RSCA>0, TBI>0
	392111	2,40	2,45	0,12	2,33	1,30	0,41	0,87	Group A-RSCA>0, TBI>0
	741220	3,67	3,81	0,59	3,22	0,81	0,57	0,64	Group A-RSCA>0, TBI>0
	902511	0,14	0,14	0,69	-0,55	-0,69	-0,75	-0,74	Group D-RSCA<0, TBI<0
	902610	0,17	0,17	1,16	-0,98	-0,82	-0,70	-0,81	Group D-RSCA<0, TBI<0
2016	391731	4,01	4,17	0,67	3,50	0,79	0,60	0,66	Group A-RSCA>0, TBI>0
	392111	1,95	1,99	0,17	1,82	1,07	0,32	0,80	Group A-RSCA>0, TBI>0
	741220	3,49	3,61	0,51	3,11	0,85	0,55	0,66	Group A-RSCA>0, TBI>0
	902511	0,20	0,20	0,68	-0,48	-0,54	-0,67	-0,64	Group D-RSCA<0, TBI<0
	902610	0,16	0,16	1,20	-1,04	-0,87	-0,72	-0,82	Group D-RSCA<0, TBI<0
2017	391731	1,78	1,81	0,76	1,05	0,38	0,28	0,54	Group A-RSCA>0, TBI>0
	392111	1,91	1,95	0,15	1,80	1,10	0,31	0,80	Group A-RSCA>0, TBI>0
	741220	3,79	3,93	0,44	3,49	0,95	0,58	0,70	Group A-RSCA>0, TBI>0
	902511	0,15	0,15	0,53	-0,38	-0,56	-0,75	-0,70	Group D-RSCA<0, TBI<0
	902610	0,19	0,19	1,17	-0,99	-0,80	-0,69	-0,80	Group D-RSCA<0, TBI<0
2018	391731	3,08	3,17	0,98	2,19	0,51	0,51	0,47	Group A-RSCA>0, TBI>0
	392111	2,07	2,12	0,12	1,99	1,23	0,35	0,86	Group A-RSCA>0, TBI>0
	741220	4,09	4,26	0,44	3,82	0,99	0,61	0,75	Group A-RSCA>0, TBI>0
	902511	0,22	0,22	0,35	-0,13	-0,21	-0,64	-0,43	Group D-RSCA<0, TBI<0
	902610	0,20	0,20	0,94	-0,74	-0,68	-0,67	-0,71	Group D-RSCA<0, TBI<0
2019	391731	3,14	3,24	0,99	2,24	0,51	0,52	0,52	Group A-RSCA>0, TBI>0
	392111	2,31	2,36	0,11	2,25	1,35	0,40	0,90	Group A-RSCA>0, TBI>0
	741220	3,96	4,12	0,54	3,57	0,88	0,60	0,71	Group A-RSCA>0, TBI>0
	902511	0,79	0,80	0,47	0,33	0,24	-0,11	0,20	Group C-RSCA<0, TBI>0
	902610	0,23	0,23	1,02	-0,79	-0,64	-0,62	-0,66	Group D-RSCA<0, TBI<0

Table 15. International competitiveness analysis for installation sub-product (2020-2021) (Compiled by authors).

	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
2020	391731	3,35	3,47	0,64	2,83	0,73	0,54	0,65	Group A-RSCA>0, TBI>0
	392111	2,31	2,36	0,06	2,30	1,60	0,39	0,94	Group A-RSCA>0, TBI>0
	741220	4,25	4,44	0,62	3,81	0,85	0,62	0,67	Group A-RSCA>0, TBI>0
	902511	0,34	0,34	0,31	0,03	0,04	-0,49	-0,32	Group D-RSCA<0, TBI<0
	902610	0,33	0,33	0,92	-0,59	-0,44	-0,50	-0,56	Group D-RSCA<0, TBI<0
2021	391731	3,43	3,55	0,58	2,97	0,79	0,55	0,71	Group A-RSCA>0, TBI>0
	392111	2,11	2,16	0,05	2,11	1,61	0,36	0,94	Group A-RSCA>0, TBI>0
	741220	4,01	4,19	0,58	3,61	0,86	0,60	0,69	Group A-RSCA>0, TBI>0
	902511	0,38	0,38	0,36	0,01	0,02	-0,45	-0,13	Group D-RSCA<0, TBI<0
	902610	0,28	0,28	1,01	-0,74	-0,56	-0,57	-0,63	Group D-RSCA<0, TBI<0

Table 16 demonstrates the international competitiveness analysis results for the insulation sub-product. The RCA index values calculated for the product (HS Code 400819) are overhead 1. These index values were at high levels in 2001 and 2002. The average value of the RCA index was calculated as 4.89 and the average value of the RXA index was calculated as 5.25. Therefore, it was determined that Türkiye has competitiveness in this product and shows specialization in exports. The RCA index values calculated for the product (HS Code 701939) are above 1 in the 2015-2021 periods and its competitiveness is at the limit. However, the RCA index calculated for the product (HS Code 680610) values are below 1 in all periods except the 2018 and 2021 periods. The average value of the RCA index was calculated as 0.80 Therefore, it has been revealed that Türkiye does not have competitiveness in this product and does not specialize in exports. In order for the RMP Index to gain competitive advantage in the relevant sector or product group, the calculated values require to below one. Although there are fluctuations from time to time, the RMP index values calculated for the products (HS Code 400819 and HS Code 680610) are recorded as 1 and above. Hence, it indicates the import surplus of these products. The RMP index values analyzed for the product with limit competitiveness (HS Code 701939) are below 1, in this context indicating that the import of the product is decrease. RTA and RC indices, which take both export and import aspects into consideration, will provide objective results. These index values calculated for products (HS Code 40819 and HS Code 701939) are positive. In this context, these products reveal that Türkiye's competitive advantage. The analyzed values for the other product (HS Code 680610) are negative. Therefore, it has been determined that Türkiye has a competitive disadvantage in this product. The RSCA index values calculated for the product (HS Code 400819) in the 2001-2021 periods are greater than zero, which point outs that the product has a comparative advantage. The RSCA index values analyzed for the product (HS Code 701939) in the 2015-2021 periods are bigger than zero, therefore it has been revealed that the product has a comparative advantage in these periods. As for the other product (HS Code 680610), the RSCA index values calculated in the 2001-2021 periods are less than zero, indicating that Türkiye does not have a comparative advantage in this product. The TBI index values calculated for the product (HS Code 400819) are greater than zero, thus revealing the net-exporter of the product. The TBI index values calculated for the product (HS Code 680610) in the 2001-2021 periods are less than zero, which highlights the net-importer of the product. The average value of the TBI index for the product (HS Code 701939) was recorded as 0.21, which reveals the net-exporter of the relevant product. According to the Product Mapping method, the product (HS Code 400819) is in Group A. Hence, Türkiye is a net-exporter (GROUP A) with a comparative advantage in the trade of this product. The product (HS Code 680610) is in Group D and this product reveals a net-importer with a comparative disadvantage. Only this product (HS Code 701939) is included in Group C. Therefore, it has been determined that this product has a comparative disadvantage but is in a net-exporter.

Grounded on the RSCA and TBI results and by the Cartesian coordinate system, the place of both the air conditioning sector and its sub-product group in the product map was determined and its place in foreign trade was revealed. In the product mapping created for both the air conditioning sector and sub-product groups, the years (2001, 2008, 2012, 2021 and on average) were selected randomly. In this context, the results of the air conditioning sector and sub-product group product map for 2001 are highlighted in Figure 2. In 2001, the air conditioning industry was included in Group D in product mapping. Thus, it has been determined that Türkiye has no comparative advantage in the air conditioning industry and is a net-importer. In 2001, products HS Code 732181, HS Code 392111, HS Code 830710, HS Code 732211, HS Code 400819 and HS Code 391731 were included in Group A. It is realized that our country had competitiveness in these products in 2001 and was a net-exporter. Products with HS Code 721220, HS Code 701939 and HS Code 840310 are in Group C. Therefore, it does not have a comparative advantage in these three products, but it reveals its net- exporter. HS Code 841850, HS Code 841460, HS Code 841490, HS Code 680610, HS Code 851610, HS Code 841610, HS Code 902511, HS Code 841891, HS Code 841430, HS Code 841939, HS Code 841989, HS Code 841520, HS Code 840220 and HS Code 902610 were classified as Group D in the product mapping in 2001. In this context, it is comprehended that Türkiye does not have a comparative advantage in the 14 products listed and is a net-importer. When evaluated in terms of the 2001 crisis, it is comprehended that the air conditioning industry and 14 products are in Group D. Türkiye has a trade deficit in air conditioning trade in this period.

Table 16. International competitiveness analysis for insulation sub-product (Compiled by authors).

	HS Code	RCA	RXA	RMP	RTA	RC	TBI	RSCA	Product mapping
2001	400819	25,63	29,50	0,97	28,53	1,48	0,92	0,93	GroupA-RSCA>0, TBI>0
	680610	0,63	0,63	0,96	-0,33	-0,18	-0,23	-0,40	Group D-RSCA<0, TBI<0
	701939	0,30	0,30	0,17	0,13	0,25	-0,54	0,18	Group C-RSCA<0, TBI>0
2002	400819	16,84	18,59	0,73	17,86	1,40	0,89	0,92	Group A-RSCA>0, TBI>0
	680610	0,82	0,83	2,09	-1,26	-0,40	-0,10	-0,59	Group D-RSCA<0, TBI<0
	701939	0,59	0,59	0,27	0,32	0,33	-0,26	0,24	Group C-RSCA<0, TBI>0
2003	400819	4,77	4,92	1,52	3,40	0,51	0,65	0,49	Group A-RSCA>0, TBI>0
	680610	0,90	0,90	0,96	-0,05	-0,03	-0,05	-0,21	Group D-RSCA<0, TBI<0
	701939	0,57	0,57	0,31	0,26	0,27	-0,28	0,18	Group C-RSCA<0, TBI>0
2004	400819	1,59	1,61	1,47	0,14	0,04	0,23	-0,05	Group B-RSCA>0, TBI<0
	680610	0,73	0,73	1,09	-0,36	-0,17	-0,16	-0,37	Group D-RSCA<0, TBI<0
	701939	0,68	0,69	0,40	0,29	0,23	-0,19	0,11	Group C-RSCA<0, TBI>0
2005	400819	1,51	1,52	1,12	0,40	0,13	0,20	0,02	Group A-RSCA>0, TBI>0
	680610	0,96	0,96	0,82	0,15	0,07	-0,02	-0,17	Group D-RSCA<0, TBI<0
	701939	0,58	0,58	0,37	0,21	0,19	-0,27	0,10	Group C-RSCA<0, TBI>0
2006	400819	2,54	2,59	0,88	1,71	0,47	0,43	0,37	Group A-RSCA>0, TBI>0
	680610	0,76	0,76	1,02	-0,25	-0,12	-0,14	-0,37	Group D-RSCA<0, TBI<0
	701939	0,38	0,38	0,26	0,11	0,16	-0,45	0,04	Group C-RSCA<0, TBI>0
2007	400819	2,92	2,98	1,22	1,77	0,39	0,49	0,34	Group A-RSCA>0, TBI>0
	680610	0,85	0,86	0,49	0,37	0,24	-0,08	-0,17	Group D-RSCA<0, TBI<0
	701939	0,31	0,31	0,35	-0,04	-0,05	-0,53	-0,14	Group D-RSCA<0, TBI<0
2008	400819	2,29	2,34	1,67	0,66	0,14	0,39	0,05	Group A-RSCA>0, TBI>0
	680610	0,60	0,60	0,87	-0,27	-0,16	-0,25	-0,39	Group D-RSCA<0, TBI<0
	701939	0,21	0,21	0,51	-0,30	-0,38	-0,66	-0,52	Group D-RSCA<0, TBI<0
2009	400819	1,98	2,01	1,36	0,65	0,17	0,33	0,16	Group A-RSCA>0, TBI>0
	680610	0,81	0,81	0,83	-0,01	-0,01	-0,11	-0,17	Group D-RSCA<0, TBI<0
	701939	0,70	0,70	0,45	0,26	0,20	-0,18	0,20	Group C-RSCA<0, TBI>0
2010	400819	3,12	3,19	0,98	2,21	0,51	0,51	0,45	Group A-RSCA>0, TBI>0
	680610	0,96	0,97	1,01	-0,04	-0,02	-0,02	-0,29	Group D-RSCA<0, TBI<0
	701939	0,81	0,81	0,51	0,31	0,21	-0,11	0,05	Group C-RSCA<0, TBI>0
2011	400819	4,20	4,33	0,90	3,43	0,68	0,62	0,53	Group A-RSCA>0, TBI>0
	680610	0,75	0,76	1,09	-0,33	-0,16	-0,14	-0,46	Group D-RSCA<0, TBI<0
	701939	0,74	0,74	0,44	0,30	0,22	-0,15	0,02	Group C-RSCA<0, TBI>0
2012	400819	4,13	4,28	0,81	3,47	0,72	0,61	0,55	Group A-RSCA>0, TBI>0
	680610	0,78	0,78	1,11	-0,33	-0,15	-0,13	-0,38	Group D-RSCA<0, TBI<0
	701939	0,92	0,93	0,42	0,51	0,35	-0,04	0,27	Group C-RSCA<0, TBI>0
2013	400819	5,82	6,13	1,26	4,87	0,69	0,71	0,45	Group A-RSCA>0, TBI>0
	680610	0,84	0,84	1,05	-0,21	-0,10	-0,09	-0,36	Group D-RSCA<0, TBI<0
	701939	0,91	0,91	0,50	0,42	0,26	-0,05	0,12	Group C-RSCA<0, TBI>0
2014	400819	4,40	4,58	0,89	3,69	0,71	0,63	0,53	Group A-RSCA>0, TBI>0
	680610	0,69	0,69	1,32	-0,63	-0,28	-0,18	-0,50	Group D-RSCA<0, TBI<0
	701939	0,98	0,99	0,64	0,35	0,19	-0,01	0,07	Group C-RSCA<0, TBI>0
2015	400819	4,03	4,19	0,48	3,71	0,94	0,60	0,70	Group A-RSCA>0, TBI>0
	680610	0,70	0,71	1,17	-0,46	-0,22	-0,18	-0,40	Group D-RSCA<0, TBI<0
	701939	1,55	1,57	0,42	1,15	0,57	0,22	0,49	Group A-RSCA>0, TBI>0
2016	400819	4,20	4,38	0,89	3,49	0,69	0,62	0,50	Group A-RSCA>0, TBI>0
	680610	0,66	0,66	1,01	-0,35	-0,19	-0,21	-0,36	Group D-RSCA<0, TBI<0
	701939	1,74	1,77	0,34	1,42	0,71	0,27	0,59	Group A-RSCA>0, TBI>0
2017	400819	2,75	2,82	0,92	1,89	0,48	0,47	0,24	Group A-RSCA>0, TBI>0
	680610	0,56	0,57	0,99	-0,43	-0,24	-0,28	-0,46	Group D-RSCA<0, TBI<0
	701939	1,78	1,81	0,32	1,49	0,75	0,28	0,60	Group A-RSCA>0, TBI>0
2018	400819	2,98	3,06	0,67	2,39	0,66	0,50	0,49	Group A-RSCA>0, TBI>0
	680610	1,00	1,01	0,97	0,05	0,02	0,00	-0,12	Group B-RSCA>0, TBI<0
	701939	2,29	2,34	0,42	1,92	0,75	0,39	0,63	Group A-RSCA>0, TBI>0
2019	400819	2,32	2,38	0,81	1,57	0,47	0,40	0,38	Group A-RSCA>0, TBI>0
	680610	0,72	0,72	0,91	-0,18	-0,10	-0,16	-0,19	Group D-RSCA<0, TBI<0
	701939	1,99	2,03	0,73	1,29	0,44	0,33	0,42	Group A-RSCA>0, TBI>0
2020	400819	2,35	2,40	1,09	1,31	0,34	0,40	0,20	Group A-RSCA>0, TBI>0
	680610	0,57	0,57	0,68	-0,11	-0,07	-0,27	-0,23	Group D-RSCA<0, TBI<0
	701939	1,99	2,03	0,67	1,37	0,48	0,33	0,42	Group A-RSCA>0, TBI>0
2021	400819	2,36	2,42	0,79	1,63	0,48	0,41	0,36	Group A-RSCA>0, TBI>0
	680610	1,48	1,50	0,69	0,82	0,34	0,19	0,28	Group A-RSCA>0, TBI>0
	701939	1,90	1,94	0,89	1,04	0,34	0,31	0,31	Group A-RSCA>0, TBI>0

Figure 2. Product mapping for 2001.

Figure 3 displays the product map results of the air conditioning sector and sub-product group for 2008. In 2008, the air conditioning sector was included in Group B in the product map. It has been determined that Türkiye has a comparative advantage in the air conditioning sector but is a net-importer. Likewise, products HS Code 840310 and HS Code 840410 are included in Group B. Products with HS Code 841891 and HS Code 841490 codes are located in Group C on the product map in 2008. Therefore, it is realized that these two products do not have a comparative advantage but are included in the net-exporter. Compared to 2001, the number of products in Group D has decreased. In this context, HS Code 851610, HS Code 680610, HS Code 841610, HS Code 701939, HS Code 902610, HS Code 840220, Products with HS Code 902511, HS Code 841989, HS Code 841430 and HS Code 841939 are located in Group D on the product map in 2008. In this context, it has been revealed that Türkiye does not have a comparative advantage in these 10 products and is a net-importer. When the 2008 Global Crisis is assessed from an economic perspective, it can be comprehended that the air conditioning industry is included in Group B and 10 products are involved in Group A. Therefore, it has been concluded that the air conditioning industry maintains its competitive structure despite the crisis period.

Figure 4 indicates the product mapping results of the air conditioning sector and sub-product group for 2012. According to the product mapping results of the air conditioning sector, it is involved in Group B. The explanation for this is that Türkiye has a comparative advantage in the air conditioning trade but is a net importer. The other product in Group B is HS Code 841939. HS Code 732211, HS Code 841850, HS Code 732181, HS Code 392111, HS Code 841891, HS Code 741220, HS Code 830710, HS Code 400819, HS Code 841460, HS Products numbered Code 391731, HS Code 840310, HS Code 841850 are included in Group A. Thus, Türkiye has both a comparative advantage and a net exporter position in the trade of these 11 products. Products with codes HS Code 841610, HS Code 841490 and HS Code 701939 are involved in Group C. In this context, this study revealed that Türkiye does not have a comparative advantage in these three products but is a net exporter. Products with codes HS Code 680610, HS Code 841520, HS Code 851610, HS Code 841439, HS Code 841430, HS Code 902610, HS Code 902511 and HS Code 840220 are included in Group D. It has been determined that Türkiye is a net importer with comparative disadvantage in these 8 products. In 2012, the HS Code 840410 product was positioned on the vertical axis between Group B and Group C. In this context, the relevant product does not have a comparative advantage since it is located on the southern axis.

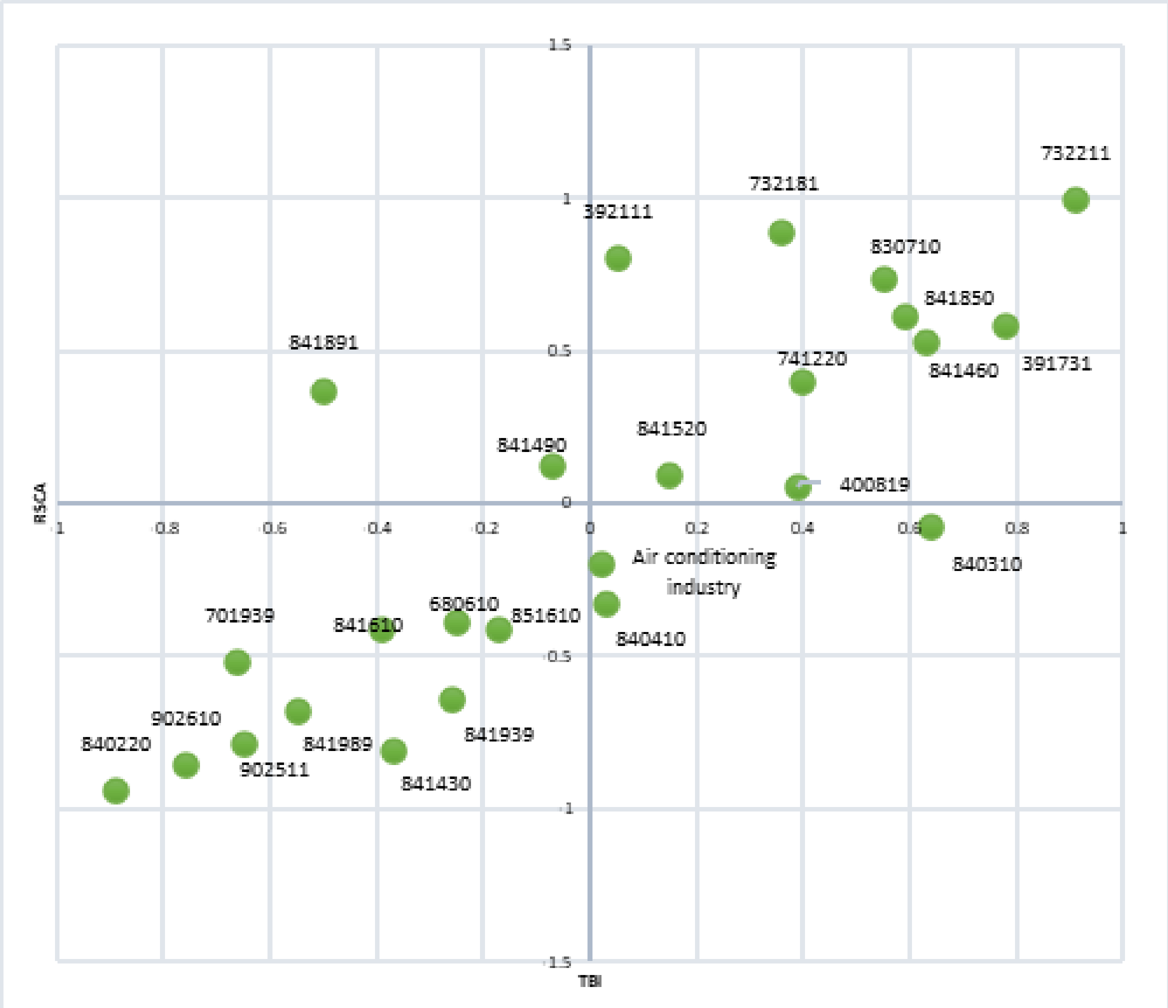

Figure 3. Product mapping for 2008.

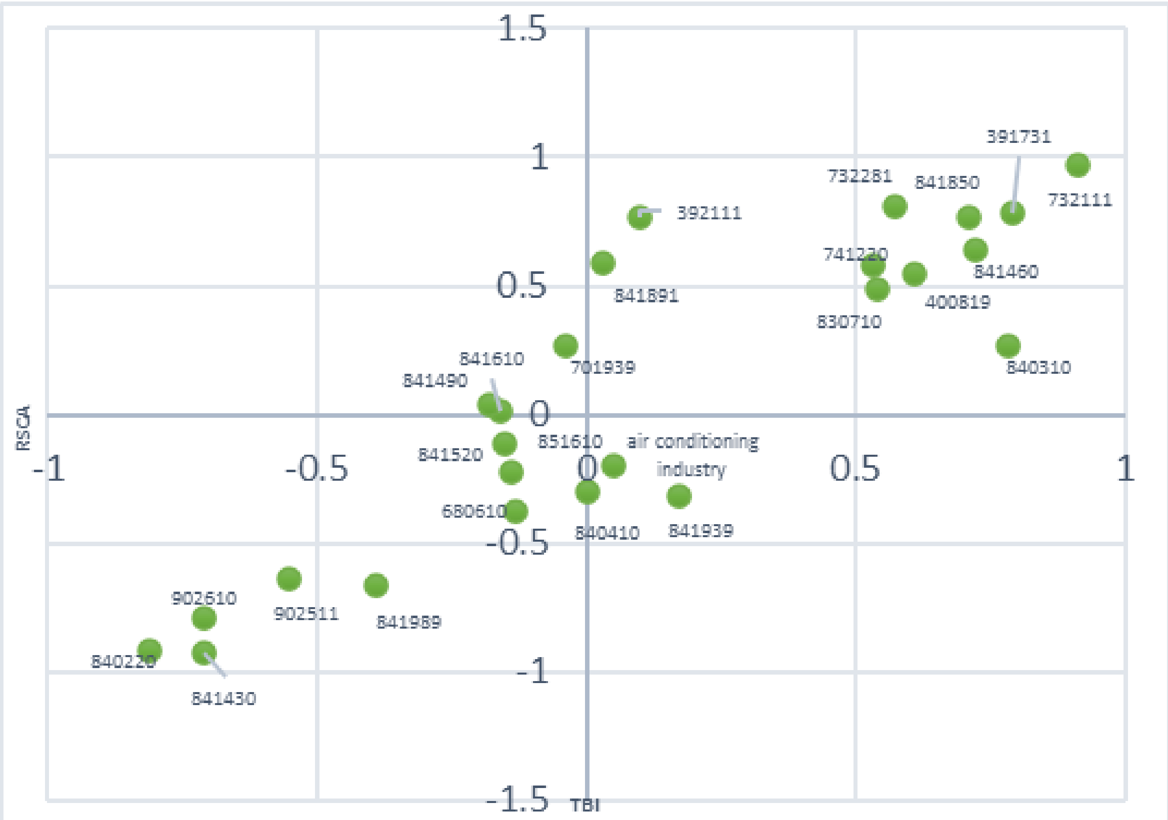

Figure 4. Product mapping for 2012.

Figure 5 indicates the product mapping results of the air conditioning sector and sub-product group for 2021. In 2021, the air conditioning sector is in Group B in product mapping. Therefore, it has been revealed that the sector has a comparative advantage but is in a net-importer. When the results of Türkiye's product mapping of 2001, 2008 and 2012 are compared, it can be realized in Figure 5 that the number of products in Group A increased in 2021. HS Code 732181, HS Code 392111, HS Code 841610, HS Code 680610, HS Code 701939, HS Code 841939, HS Code 400819, HS Code 830710, HS Code 840310, HS Code 841891, HS Code 391731, HS Code 741220 HS Code 841850, HS Code 732211 and HS Code 841460 products are included in Group A in the 2021 product mapping. In this context, it has been determined that Türkiye has a comparative advantage in these 15 products and is also a net-exporter. HS Code 841490 and HS Code 841410 products are included in Group C in the product mapping in 2021, therefore it is realized that these two products do not have a comparative advantage but are in a net-exporter. The number of products in Group D decreased in 2021. In this context, products coded HS Code 841520, HS Code 851610, HS Code 902511, HS Code 902610, HS Code 840220, HS Code 841430 and HS Code 841989 are included in Group D in product mapping in 2021. Therefore, Türkiye does not have a comparative advantage in these 7 products and is a net-importer. When evaluated in terms of the impact of the 2021 Foreign Exchange and Debt Crisis and the Covid-19 pandemic, it is comprehended that the air conditioning s industry is in Group B and 15 products are in Group A. Hence, it has been observed that the air conditioning industry maintains its competitive structure despite periods of crisis.

The average product mapping results of the air conditioning sector and sub-product group for the periods 2001-2021 are highlighted in Figure 6. According to the product mapping results, the air conditioning sector is in Group B. The explanation for this is that it has a comparative advantage however a net-importer is. HS Code 732211, HS Code 841850, HS Code 732181, HS Code 392111, HS Code 841891, HS Code 741220, HS Code 830710, HS Code 400819, HS Code 841460, HS Code 391731, HS Code 840310, HS Code 841850 products are included in Group A. Türkiye has both a comparative advantage and a net-exporter in the trade of these 11 products. Only the product with HS Code 701939 is included in Group C. This study revealed that Türkiye does not have a comparative advantage in this product, but is a net-exporter. HS Code 841490, HS Code 841610, HS Code 680610, HS Code 841520, HS Code 840410, HS Code 841939, HS Code 851610, HS Code 841439, HS Code 841430, HS Code 902610, HS Code 902511 and HS Code 840220, products are included in Group D. It has been concluded that Türkiye is a net- importer with comparative disadvantage in these 12 products.

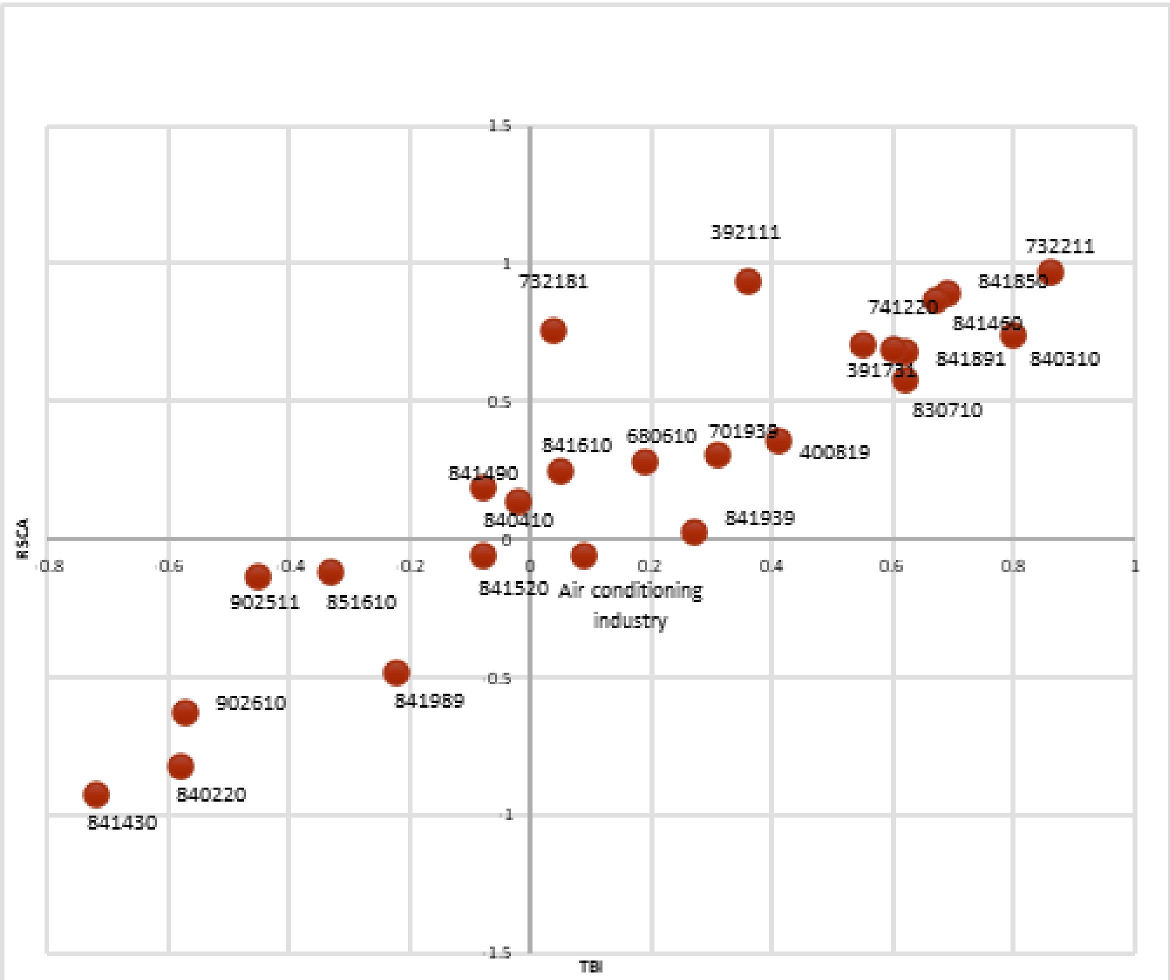

Figure 5. Product mapping for 2021.

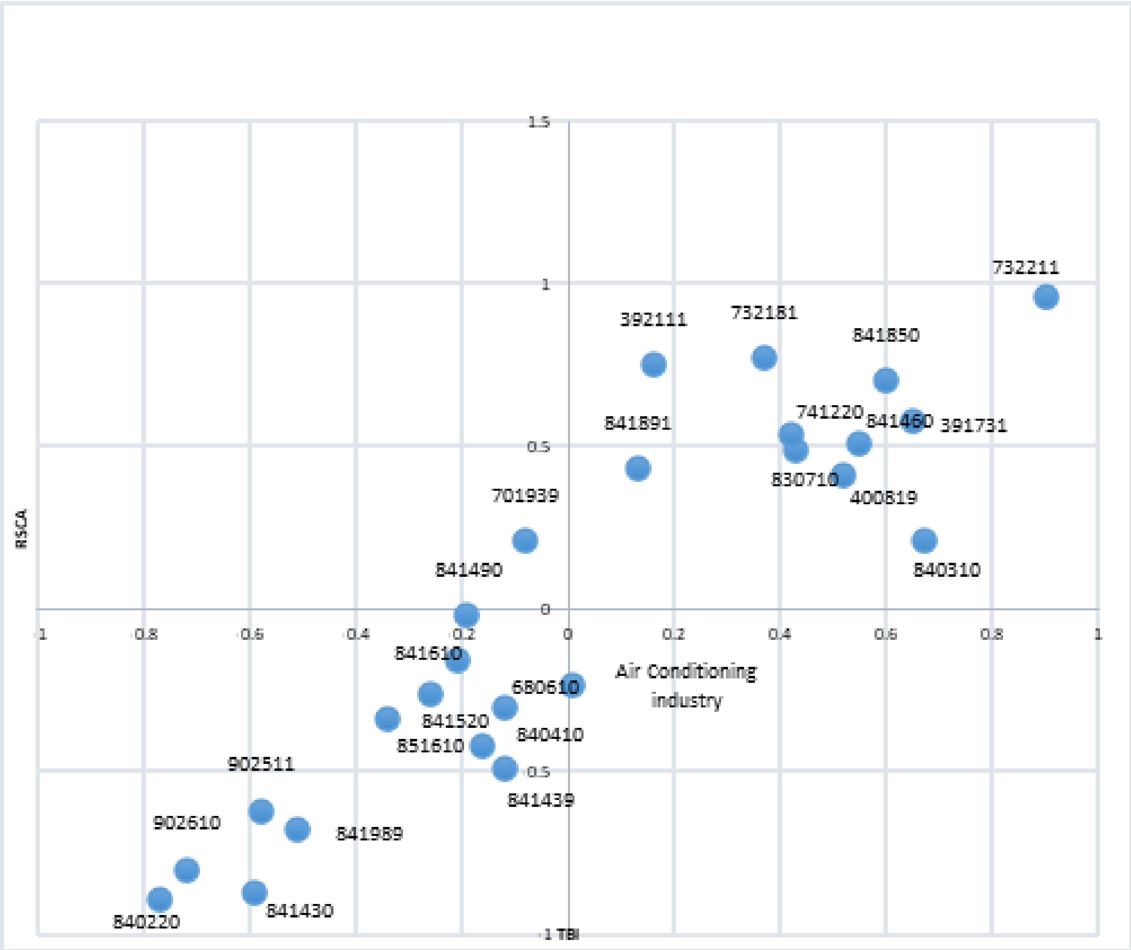

Figure 6. Average product mapping for the period of 2001-2021.

6. Conclusion and recommendations

Türkiye ranks 19th in global air conditioning exports and its share in world air conditioning exports is 3% [18]. Türkiye's air conditioning exports in 2022 amounted to 6 billion 680 million dollars. The number of companies operating in the air conditioning sector in 2022 is 20 thousand 762 [51]. The fact that the air conditioning sector has become a significant sector nowadays and in the future was an important factor in the creation of the study and was deemed suitable for research. In this context, the aim of the study is to research the international competitiveness of the Turkish air conditioning industry and its sub-product groups (heating, refrigeration, air conditioning, ventilation, installation and insulation) for the periods 2001-2021. In this study, Balassa's Revealed Comparative Advantage Index (RCA), Vollrath Indices (RXA, RMP, RTA, RC), Revealed Symmetric Comparative Advantage Index (RSCA), Trade Balance Index (TBI) and Product Mapping method were used. Turkish literature using the product mapping method is extremely limited [26-32]. Studies in the international literature on product mapping method are [33-39].

The contributions of this study to the literature are summarized. Alterations in specialization in the trade of the air conditioning sector and its sub-product group have been identified, products and sector with competitiveness have been revealed, and the mobility of the comparative advantage of the sector and sub-product group has been analyzed. Product mapping has been consisted of the first time in the literature for the air conditioning sector and its sub-product groups. According to the study findings, the average values of the RCA and RXA index results calculated in the 2001-2021 periods of the Turkish air conditioning industry are comprehended to be 1 and above, therefore it has been determined that the air conditioning industry has competitiveness and specializes in exports. According to the product mapping method, it was revealed that the air conditioning industry has a comparative advantage however is in a net-importer (GROUP B). The noteworthy point in the study is that it was determined that the air conditioning sector was not affected much by the 2008 Global Economic Crisis, the 2018-21 Türkiye Foreign Exchange and Debt Crisis, and the Covid pandemic, therefore it is sight that the air conditioning sector maintains its competitiveness and continues to grow despite the crises. In the sector report of TOBB [52], a competitive analysis of the air conditioning sector was analyzed using the Diamond Model developed by Porter and it has been concluded that the Turkish air conditioning sector has a high level of competitiveness. Therefore, the results are parallel to the results of this study. As in the study of Lehtonen and Sipilä [19], it is emphasized that the air conditioning sector will alter in recent years, the sector will grow and the importance of the sector will gradually increase.

The results for the sub-products of the Turkish air conditioning industry can be summarized as follows:

The results of the heating sub-product group indicate that it specializes in the export of three products (HS Code 732181, HS Code 732211, and HS Code 840310), and that these products are in a net-exporter (GROUP A) with comparative advantage. However, it was revealed that there was no specialization in the export of the other three products in the heating sub-product group (HS Code 840220, HS Code 841610, and HS Code 851610) and that these products were net-importers (GROUP D) with a comparative disadvantage. In the other two products (HS Code 840410, HS Code 841939), it is realized that the competitiveness is at the limit.

The results of the refrigeration sub-product group display that it specializes in the export of two products (HS Code 841891, HS Code 841850), and that these products are in a net-exporter (GROUP A) with comparative advantage. However, in the other two products (HS Code 841990, HS Code 841989) it has been determined that our country does not indicate specialization in exports. According to the product mapping method, it has been revealed that it is a net-importer (GROUP D) with a comparative disadvantage.

The results of the air conditioning sub-product group demonstrate that Türkiye did not specialize in exports of two products (HS Code 841430, HS Code 841520) and that these products were net-importers (GROUP D) with a comparative disadvantage.

Results of the ventilation sub-product group reveal that Türkiye specializes in exports in two products (HS Code 830710, HS Code 841460), and these products are involved in of net-exporter (GROUP A) with comparative advantage.

As a result of the installation, it has been obtained that our country specializes in exports in three products (HS Code 391731, HS Code 392111, HS Code 741220) and that it is a net-exporter (GROUP A) with a comparative advantage in these products. However, in the other two products (HS Code 902511, HS Code 902610), it has been revealed that Türkiye does not specialize in exports and that these products are net-importer (GROUP D) with a comparative disadvantage.

The results of the insulation sub-product group indicates that Türkiye specializes in exports of only one product (HS Code 400819) and that this product is a net-exporter (GROUP A) with a comparative advantage. On the other hand, it has been revealed that our country does not specialize in exporting only one product (HS Code 680610) and that this product is a net-importer (GROUP D) with a comparative disadvantage. Another product (HS Code 701939) has limited competitive power. It is the only product in Group C in Türkiye's product mapping.

The companies in the air conditioning sector should improve a product portfolio with high quality, high benefit and unique design. Businesses operating in the air conditioning sector should support to establish an effective competitive intelligence system and training programs should organize for this purpose. R & D for the sector should be integrated into the production processes and encouraged in nowadays world where technological progress is at its peak. E-commerce networks should be improved to market the sector and its sub-products, and social media platforms should be utilized to increase the recognition of the sector. Universities, vocational high schools and companies within the scope of the air conditioning sector should cooperate and carry out activities in coordination. Foreign fair support should improve for companies in the sector. Qualified workforce support should provide and the opportunity to own a global brand should offer.

A new study can conduct to determine the competitiveness determinants of companies operating in the air conditioning sector, which has a high market share in international market. In addition, a qualitative study can carry out by interviewing company managers to determine what kind of strategy the companies that are strong in the air conditioning industry have developed to maintain their competitiveness. Finally, air conditioning industry global competitiveness of different countries can analyze and compare with other countries by revealing their comparative advantage over Türkiye.

This study has two limitations. First, the period could have gone back earlier. This study covers the years 2001-2021. Secondly, this study, which was created using secondary data, could have been enriched with field work. Qualitative research can be conducted with sector managers on what can be done to increase the exports of the air conditioning sector.

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Author contributions

Fatma İzgi: Conceptualization, Methodology, Software Writing-Original draft preparation
Mustafa Kavacık: Data curation, Validation, Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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IVPF-AHP integrated VIKOR methodology in supplier selection of three-dimensional (3D) printers

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Abstract

Complex geometries, fine details, and various designs that are difficult to create using traditional methods can easily be turned into a tangible object with Three-Dimensional (3D) printers. 3D printers have advantages such as providing design flexibility, obtaining prototypes in the shortest possible time, allowing for personalization, and reducing waste through the use of advanced technology. These advantages emphasize the significance of 3D printers in a sustainable production model. The widespread usage of 3D printers leads to increased efficiency and cost reduction in production. When the literature is examined, it is observed that there are limited studies on the evaluation of supplier performances for company using 3D printers. The aim of this study is to address 3D printers, which are highly significant for sustainable production, and to reveal the criteria that companies utilizing these printers need to consider for determining their suppliers. As a result of the literature review and expert interviews, a model has been developed that gathers the criteria to be considered for supplier selection, which is an important cost factor for companies involved in designing and producing 3D printers under five main and 18 sub-criteria. The importance weights of the criteria have been determined using the Interval Valued Pythagorean Fuzzy Analytic Hierarchy Process (IVPF-AHP) method, and the most suitable supplier among alternative suppliers has been selected using the Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method. Finally, the supplier scores have been statistically analyzed to show the validation of the results of the proposed method. According to the results, it has been concluded that for company using 3D printers, quality and technical service criteria are more important in the supplier selection. Additionally, cost of the material/equipment, product price and easy maintenance criteria also play a critical role in the supplier selection of 3D printer.

1. Introduction

Additive manufacturing (AM) is the process of transforming a digitally designed model into a physical object by building it layer by layer. AM is used worldwide in various sectors due to its contribution to the advancement of production technology, enabling process automation and real-time evaluation of data. AM offers many advantages compared to traditional manufacturing techniques, such as unlimited design freedom, decentralized manufacturing, on-demand manufacturing, quality improvement, and the ability to produce small-volume products [1]. These advantages highlight the significance of AM technology for creating a sustainable production model that minimizes adverse environmental effects, preserves energy and natural resources, and aims to produce rational products. AM which focuses on innovation and creativity, should take its place in production processes as part of a comprehensive sustainability plan [2]. Some of the commonly used AM processes in the fabrication process are stereolithography (SL), selective laser sintering (SLS), fused deposition modelling (FDM), 3D printing (3DP), laminated object manufacturing (LOM), polyjet printing (PP), electron beam melting (EBM), and laser engineered net shaping (LENS) The key advantage of adapting 3D printing technologies to traditional manufacturing processes is the ability to create complex, customized, and high-precision models [3]. 3D printers work in a similar way to traditional printers, but they use powder that gradually transforms into an image on a layer-by-layer basis. The use of smart materials and layer-by-layer addition of materials reduces raw material waste. This also leads to an increase in efficiency. 3D printers utilize three-dimensional Computer Aided Design (3D CAD) software to create each layer of the object [4]. The workflow diagram for the 3D printing process is shown in Figure 1.

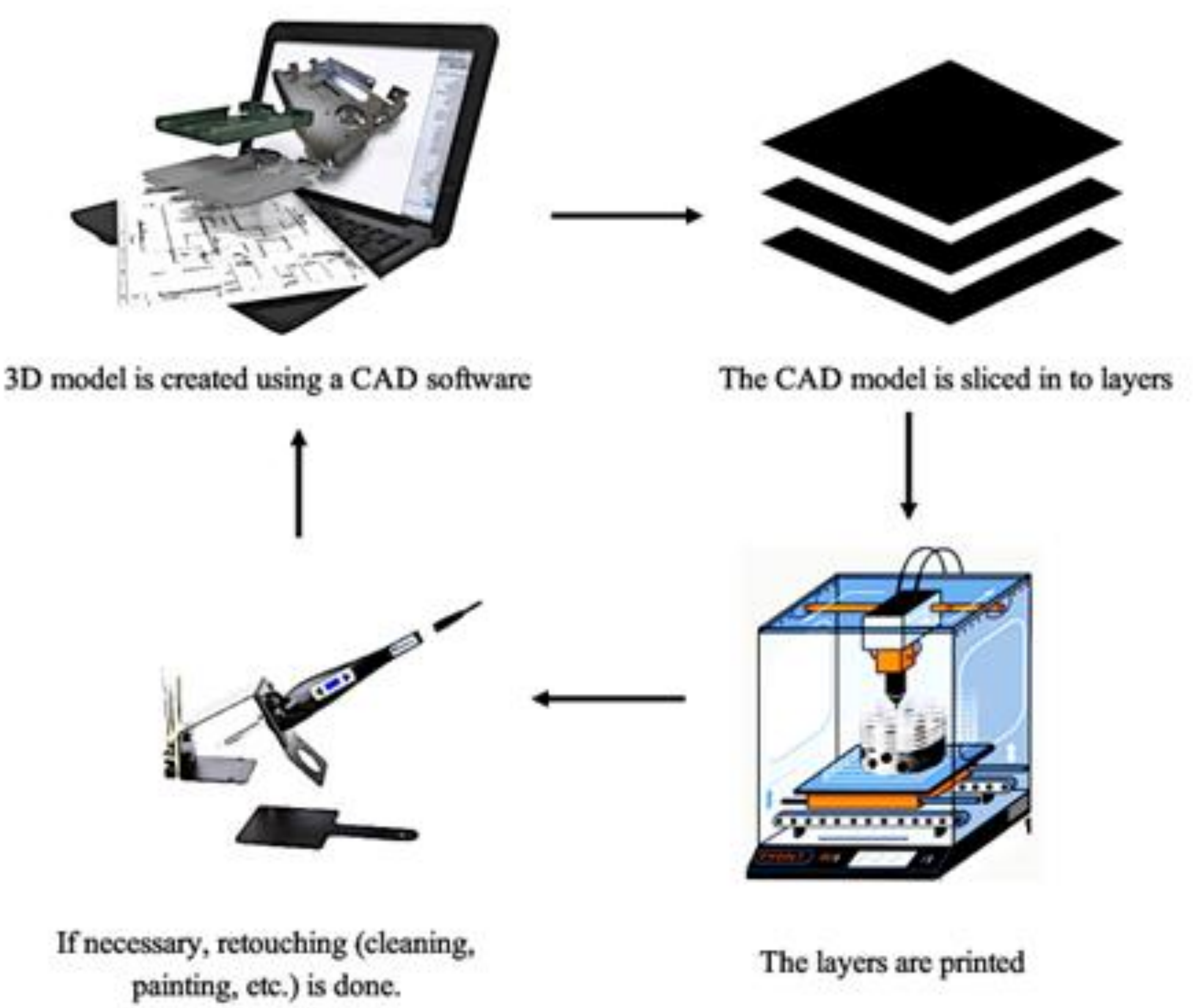

Figure 1. The workflow diagram of the 3D printing process [5].

Today, many 3D printers are produced to cater to different sectors. Such importance of 3D printers, which has the potential to meet the high-quality printing of all different sectors, makes the studies in this field valuable. The widespread use of 3D printers with high technology has led to the creation of many brands. Finding the most suitable supplier among these brands is critical for companies. Choosing the right supplier for the company will reduce the company's purchasing costs while increasing customer satisfaction and its competitive performance against its rivals in the market. For this reason, it is of great importance for the sector to determine the criteria that should be taken into account when choosing their own supplier among the suppliers of the companies that supply 3D printers.

In the competitive environment that develops in parallel with the developing technology in the business world, businesses offer their products and services by using their resources effectively in order to always be ahead of their competitors in the sector and to continue their existence for a long time. Choosing the most suitable supplier with minimum cost, in the fastest time and at the right time provides benefits in terms of increasing its profitability in line with increasing its competitive power [6].

Multi-Criteria Decision Making (MCDM) methods are divided into two categories: Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM). The MADM method is referred to as discrete MCDM, while MODM is called continuous MCDM. The goal of MADM methods is to model decision processes based on criteria, maximizing the utility that decision-makers will obtain at the end of the process. MADM methods are designed to determine the best alternative, classify alternatives into a few categories, and/or rank alternatives according to subjective preference order. There are many methods suggested in the literature for this purpose. Table 1 provides commonly used MADM methods in the literature [7].

Table 1. The most commonly used MADM methods in the literature [7].

MADM Methods	Abbreviation	References
Entropy Method	Entropy	Shannon [8]
Simple Additive Weighting	SAW	Churchman and Ackoff [9]
Multi Attribute Utility Theory	MAUT	Fishburn [10]
Elimination et choice Translating Reality	ELECTRE	Benayoun et al. [11]
Multi-Attribute Value Theory	MAVT	Fishburn [12]
Weighted Product Method	WPM	Miller and Starr [13]
Decision Making Trial and Evaluation Laboratory	DEMATEL	Fontela and Gabus [14]
Simple Multi-Attribute Rating Technique	SMART	Edward [15]
Analytic Hierarchy Process	AHP	Saaty [16]
Technique for Order Preference by Similarity to Ideal Solution	TOPSIS	Hwang and Yoon [17]
Preference Ranking Organization Methods for Enrichment Evaluations	PROMETHEE	Brans et al. [18-19]
Measuring Attractiveness by a Categorical Based Evaluation Technique	MACBETH	Bana e Costa and Vansnick [20]
Complex Proportional Assessment Mth.	COPRAS	Kaklauskas et. al [21]
Analytic Network Process	ANP	Saaty [22]
Gray Relation Analysis	GRA	Deng [23]
Vise Kriterijumska Optimizacija I Kompromisno Resenje	VIKOR	Opricovic and Tzeng [24]
Multi-objective Optimization by Ratio Analysis	MOORA	Brauers and Zavadskas [25]
Multiple Objective Optimization on the Basis of Ratio Analysis	MULTIMOORA	Brauers and Zavadskas [26]
Additive Ratio Assessment	ARAS	Zavadskas and Turskis [27]
Weighted Aggregated Sum Product Assessment	WASPAS	Zavadskas et al., [28]
Evaluation Based on Distance from Average Solution	EDAS	Ghorabaee [29]
Best-Worst Method	BWM	Rezaei [30]

Several studies have effectively addressed a range of decision-making problems using the MCDM methods. For instance, Menekse et. al. [31] presented an integrated MCDM approach using PFSs to assess AM alternatives in the automotive industry. Özgüner and Özgüner [2] analyzed the impact of AM technology on sustainable production using the DEMATEL method. According to the results, AM technology has been revealed to have a significant impact on sustainable production with contributions such as the development of sustainable solutions, ensuring green production, promoting the production of innovative products, and preventing excessive resource use. Büyüközkan and Göçer [32] utilized the CODAS method under Pythagorean fuzzy in selection of the right 3D printing technology. Sahoo and Goswami [33] examined current studies by reviewing the literature on selecting environmentally friendly suppliers. Amiri et. al. [34] employed BWM method for sustainable supplier selection in the supply chain. Więckowski et. al. [35] evaluated battery suppliers using fuzzy MCDM methods in a fuzzy environment, discussing the importance of transportation cost, delivery time, and warranty periods. El-Morsy [36] conducted a stock portfolio analysis by defining the risky return rate, portfolio risk amount, and expected return rates with PFNs. Yazdani et. al. [37] established a sustainable supplier evaluation framework using NSs. Stević et. al. [38] developed a novel measurement and ranking of alternatives for sustainable supplier selection in the healthcare sector using the COMpromise Solution (MARCOS) method. Su et. al. [39] utilized Grey and DEMATEL methods to ensure the development of the hierarchical structure of sustainable supply chain management and to reveal the relationship among the critical criteria and a specific supplier. Nagarajan et. al [40] employed NSs in the selection of the best 3D printer.

In this study, Interval-Valued Pythagorean Fuzzy Analytical Hierarchy Process (IVPF-AHP) and VIseKriterijumsa Optimizacija I Kompromisno Resenje (VIKOR) methods are used in an integrated way. Information can sometimes be ambiguous due to various restrictions. If the information is not precise and clear, it is not possible for the decision maker to choose with exact numbers [41]. Pythagorean fuzzy numbers (PFNs), one of the new fuzzy set extensions, play an important role in defining information according to traditional fuzzy numbers in cases where the information is incomplete, ambiguous, and uncertain. In the definition of PFNs, the inclusion of a non-membership function, in addition to the membership function, allows for a better representation of expert opinions. The sum of the membership and non-membership functions can be greater than 1, but the sum of their squares cannot exceed 1. This also provides experts with the flexibility of defining, thereby minimizing uncertainty. PFNs are easy to implement in real life than other new fuzzy set extensions. PFNs with interval values are a new and effective decision-making tool. Due to these advantages, IVPF-AHP method is used to find the significance weights of the criteria in the proposed approach. The Analytic Hierarchy Process (AHP) method has been also applied to demonstrate the validity of the proposed model. The criteria weights obtained as a result of the IVPF-AHP and the AHP methods have been analyzed for the proposed model in SPSS software. The results obtained by statistical analysis confirm that the proposed model produced meaningful results.

In the VIKOR method, linear normalization is used, while the TOPSIS method employs vector normalization. The VIKOR method addresses the proximity to the ideal solution using an aggregation function, while the TOPSIS method is defined with two reference points. The TOPSIS method does not take into account the relative importance of distances to these reference points. In the PROMETHEE method, the results are based on the maximum group benefit. In the VIKOR method, it combines maximum group benefit with minimum individual regret. ELECTRE and VIKOR methods are based on similar principles [42]. Additionally, the VIKOR method provides operational ease compared to the ELECTRE method. That is why the VIKOR method has been preferred. The VIKOR method is based on the principle of determining the most suitable option based on existing criteria and ranking the options according to their performance. Experts were asked to score between 0 and 100 when comparing suppliers, as it would be much more difficult to compare five alternative suppliers by each criterion using linguistic expressions. Criteria weights obtained from the IVPF-AHP method have been transferred to the VIKOR method and experts were asked to evaluate five alternative suppliers based on the criteria. The results obtained according to the evaluations of the experts have been examined. The supplier scores obtained by IVPF-AHP and AHP methods are analyzed by the Paired Sample t-Test. As a result, there are no statistically meaningful differences between the two methods.

In Section 2, the literature review about determining the criteria to be considered for the selection of the 3D printer supplier of a business is included, the decision-making model created is shown. In Section 3, IVPF-AHP and VIKOR methods used in the study are explained and the previous studies are presented. In Section 4, the implementation made in the study is included and Section 5 contains the statistical analysis results used in the comparison of methods. In Section 6, evaluations are made about the data obtained as a result of the implementation and suggestions are made for the future studies.

2. Evaluation criteria of 3D printer supplier selection

In this study, the supplier selection problem of 3D printers is studied. For this problem, the main and sub-criteria are searched by literature review and the most appropriate ones are determined by consulting with the experts. The experts are determined by considering their experiences the supplier selection problem. These criteria and their brief literature review can be seen in Table 2.

Table 2. Literature review for the supplier selection criteria of 3D printers.

Main Criteria	Sub-criteria	Sources
Cost (C)		[43-46]
	Product price (C_1)	[46-50]
	Cost of the material/equipment (C_2)	[45,46], [49-51]
	Energy consumption cost of 3D printers (C_3)	[1, 4], [52-53]
Quality (Q)		[54-58]
	The compatibility of materials such as filament and nozzle (Q_1)	[4,31,44], [47-49], [54,59,60]
	Customer satisfaction (Q_2)	[45], [55-57], [61,62]
	Different type of 3D printers (Q_3)	[47,58,63]
Accessibility to Technology (A)		[4, 47,48,61,62]
	Geometric complexity (A_1)	[44,47,49]
	Extruders (A_2)	[4,46,50,61]
	Layer thickness (A_3)	[44,46], [48-50], [61]
	Waste disposal (A_4)	[1,4,47,58]
	Build speed (A_5)	[31,44], [46-50], [54]
Logistics Support (L)		[62,64,65]
	Delivery lead time/On-time delivery (L_1)	[47,62,64,66]
	Delivery reliability/Perfect delivery (L_2)	[65,67,68]
Technical Service (T)		[1,4,61,62]
	Ease of assembly (T_1)	[55,61,62]
	Interface installation (T_2)	[1,4,61,69]
	Spare part (T_3)	[62,70,71]
	Easy maintenance (T_4)	[1,55,61,62]

In this study, the supplier selection problem of 3D printers is considered and classified five different main criteria as Cost (C), Quality (Q), Accessibility to Technology (A), Logistics Support (L) and Technical Service (T) through literature review and expert interviews. Cost (C) is one of the main criteria for selecting the right supplier. Due to the use of new technology and their limited availability in the market, the prices of 3D printers were quite high. The widespread adoption of 3D printers and the increase in product variety have led to a decrease in the selling prices. However, whether the suppliers can provide the proper service that meets the business needs should be considered, as well as the price [72]. The cost criterion has three sub-criteria; Product Price (C_1), Cost of the material/equipment (C_2) and Energy consumption cost of 3D printers (C_3). Quality (Q) is the second main criterion. In order for enterprises to maintain their dominance in the sector, they must produce both affordable and quality products. Quality criterion consists of four sub-criteria; The compatibility of materials such as filament and nozzle (Q_1), Customer satisfaction (Q_2) and Different type of 3D printers (Q_3). The compatibility of materials such as filament and nozzle (Q_1), Filament is one of the essential materials used in the 3D printing process. The quality and properties of the filament directly impact the quality and success of 3D printing. The nozzle directly affects the level of detail and precision in the 3D printing process. The proper selection of the nozzle is crucial for achieving high-quality prints. Customer satisfaction (Q_2), if the product meets customer requirements, and the customer is satisfied with the service provided, this leads to customer satisfaction. The understanding the needs and expectations of customers and planning how services can be delivered within this framework is so important. Different type of 3D printers (Q_3), it is very significant to find product options in different types and capacities according to the specifications of the customer in order to find the product that the customer desires. The Accessibility to Technology (A) is the third main criterion. 2D printers perform the process of printing existing objects' letters or visuals, while 3D printers enable the physical touch of objects. In this way, 3D printers have been designed using innovative technology [73]. The accessibility to technology criterion consists of five sub-criteria; Geometric complexity (A_1), Extruders (A_2), Layer thickness (A_3), Waste disposal (A_4) and Build speed (A_5). These criteria are crucial for 3D printers to operate at the desired performance level. Logistics Support (L) is the fourth main criterion. No matter how quality the product is or how well it is promoted, if the consumer has difficulty in finding that product, the desire for that product will decrease over time and the tendency towards alternatives will begin. The logistics support criterion has two sub-criteria; Delivery lead time/On-time delivery (L_1) and Delivery reliability/Perfect delivery (L_2). Delivery lead time/On-time delivery (L_1), the delay in this period also delays the delivery to the customer. The Delivery reliability/Perfect delivery (L_2) criterion is very important as it is a disadvantage for the company if the product is missing or damaged when delivering the product. The Technical Service (T) is the final main criterion. It is very important for after-sales service that the product is installed or assembled and running after purchases. The technical support criterion consists of four sub-criteria; Ease of assembly (T_1), Interface installation (T_2), Spare part (T_3) and Easy maintenance (T_4). Ease of assembly (T_1) by evaluating both the conditions at the installation site and all factors with which product can proceed more easily and quickly. The interaction between users and 3D printers produced with advanced technology will be enhanced thanks to a comprehensible interface installation (T_2), causing increased user satisfaction. It is significant to be able to detect and supply the required spare parts as soon as possible. Therefore, the Spare part (T_3) criterion plays an important role. There are different assembly types depending on the 3D printer models. With technological developments, devices are constantly being renewed. The precision of 3D printers produced with advanced technology necessitates careful attention to maintenance. Therefore, the importance of the technical team's knowledge in ensuring ease of maintenance (T_4) is significant.

3. Methods

The fuzzy set theory (FST) introduced to literature by Zadeh [74]. The FST is used in situations where information is uncertain, vague, and incomplete. The Fuzzy Sets (FSs) have a single membership function. Sometimes, a decision maker may not exactly give a decision about a subject. Therefore, intuitionistic fuzzy sets (IFSs) that contain both membership and non-membership functions are developed by Atanassov [75]. Unlike the IFSs, the sum of membership and non-membership degrees cannot exceed 1. Pythagorean fuzzy sets (PFSs) developed by Yager [76]. The PFSs also have membership and non-membership functions but sum of their square cannot be greater than 1. These extensions have enabled the more flexible and detailed representation of uncertainty in various decision-making processes. Figure 2 presents the FSs and its extensions chronologically.

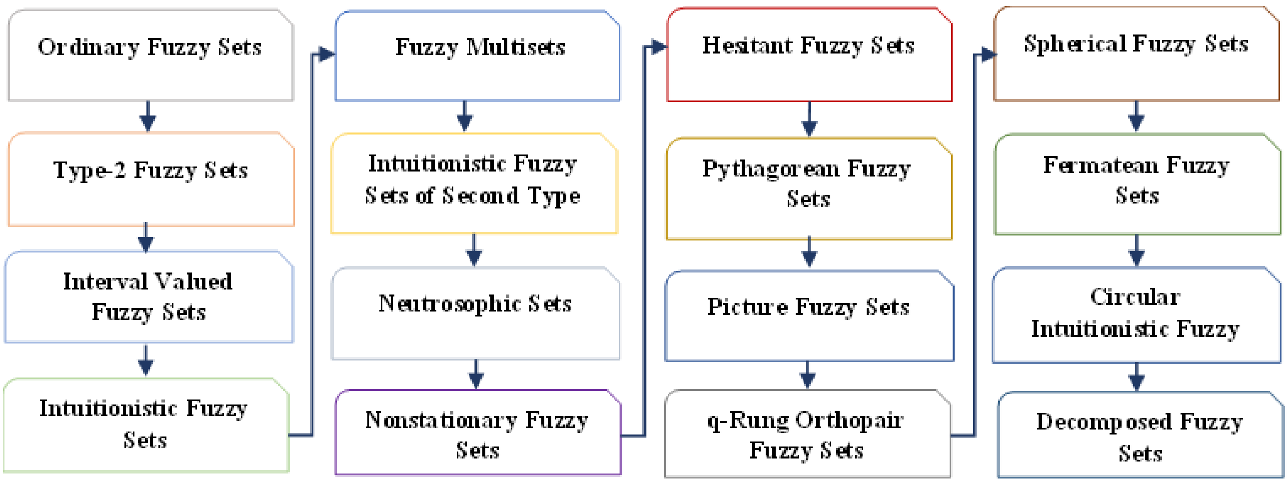

Figure 2. Fuzzy sets and its extensions [77].

PFSs are more flexible than other the FSs. Because of these advantages, PFSs are preferred in literature studies. AHP is used to determine the relative importance of activities in the MCDM problems. This method is based on pair-wise comparison of criteria or alternatives. Due to its popularity in decision-making problems, AHP has been expanded with new fuzzy set extensions to allow decision-makers to express uncertainty more effectively and in more detail in their linguistic evaluations [77]. F-AHP is extended of AHP method. It developed by Laarhoven and Pedrycz [78]. The details of the F-AHP method are not given owing to page count restriction, but the related reference is provided for readers in more detail about the method. PFSs integrated into the AHP method are implemented in situations where experts may not exactly decide and not fully reflect the thinking style of the experts.

Studies with PF-AHP method are summarized below: Karaşan et al. [79] used PF-AHP method for the selection of the most suitable clean energy technology. Otay and Jalley [80] evaluated wind energy farms in Türkiye using the PF-AHP method. İlkbahar et al. [81] examined renewable energy alternatives using Pythagorean Fuzzy WASPAS method. Mete [82] assessed occupational risks in pipeline construction by integrating PFSs into FMEA-based AHP-MOORA approach. Öz et al. [83] conducted a risk assessment for the cleaning and rating process of the natural gas pipeline project and used the PFSs based TOPSIS method to prioritize hazards. Bolturk and Kahraman [84] applied the Pythagorean fuzzy extension of CODAS method to select natural gas technology. Mete et al. [85] developed a decision support system based on Pythagorean fuzzy VIKOR method for occupational risk assessment of natural gas pipeline construction. Wood [86] made their supplier selection for oil industry facilities using flexible entropy weight and Intuitionistic fuzzy TOPSIS method. Yildiz et al. [87] determine best location for automated teller machine (ATM) via PF-AHP integrated Pythagorean fuzzy TOPSIS methodology. Coşkun et al. [88] have measured the marketing performance of an enterprise in the clothing industry using IVPF-AHP and interval-valued TOPSIS methods. Erdoğan et al. [89] measured the performance of retail companies by using Pythagorean Fuzzy TODIM methodology based on IVPF-AHP method.

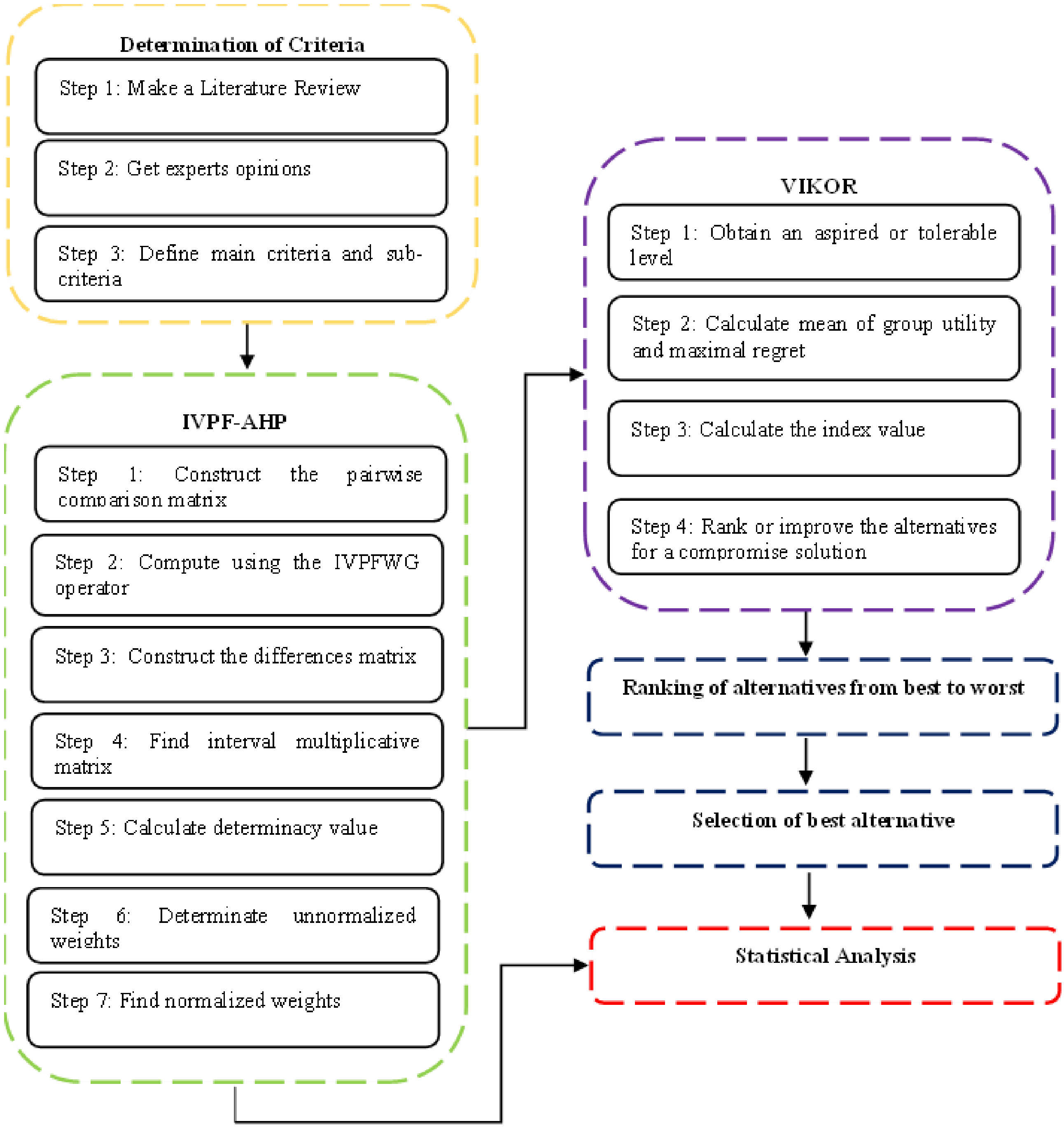

Figure 3. The proposed methodology.

When the literature is examined, it is observed that there are a limited number of studies with PFSs, which are new fuzzy sets extensions, neutrosophic sets (NSs) and hesitant fuzzy sets (HFSs) in the supplier selection of 3D printers. For this reason, interval-valued Pythagorean fuzzy sets (IVPFSs) have been used to find the importance weights of the criteria in the selection of a 3D printer supplier. IVPFSs, a new MDCM approach, expresses the uncertainty according to the degrees of membership and non-membership defined by flexible interval values. The VIKOR method has been used to compare alternative 3D printer brands. Finally, statistical analyses have been applied for the validation of the results of the proposed method in the study. The proposed methodology in the study is shown in Figure 3.

3.1. Interval-valued Pythagorean Analytic Hierarchy Process (IVPF-AHP)

3.1.1. Definitions of PFSs

In the decision-making process, decision-makers make their own evaluations for each of the alternatives. Some factors affecting decision-makers in an uncertain environment cause decision makers to be unable to make decisions with exact values. PFSs are applied to deal with these uncertainties. In PFSs, the membership and non-membership basic functions express uncertainty better. It helps to model the incomplete and subjective statements of decision makers in the best way [88].

The PFSs can be expressed as follows [90-94]:

Definition 1. Let X be a fixed set. A Pythagorean fuzzy set $\tilde{P}$ is defined as shown in Equation 1:

$$\tilde{P} \cong \{\langle x, \mu_{\tilde{P}}(x), v_{\tilde{P}}(x)\rangle; x \in X\} \tag{1}$$

A where $\mu_{\tilde{P}}(x): X \mapsto [0,1]$ defines the degree of membership and $v_{\tilde{P}}(x): X \mapsto [0,1]$ defines the degree of non-membership of the element $x \in X$ to $\tilde{P}$, respectively. Equation (2) is satisfied:

$$0 \le \mu_{\tilde{P}}(x)^2 + v_{\tilde{P}}(x)^2 \le 1; x \in X \tag{2}$$

The degree of hesitancy condition is as shown in Equation 3:

$$\pi_{\tilde{P}}(x) = \sqrt{1 - \mu_{\tilde{P}}(x)^2 - v_{\tilde{P}}(x)^2} \tag{3}$$

Definition 2. Let $\tilde{A} = \langle \mu_1, v_1\rangle$ and $\tilde{B} = \langle \mu_2, v_2\rangle$ be two Pythagorean Fuzzy Numbers (PFNs) and $\lambda > 0$. Then, the arithmetic operations of PFNs are as shown in Equation 4-7:

$$\tilde{A} \oplus \tilde{B} = \left(\sqrt{\mu_1^2 + \mu_2^2 - \mu_1^2\mu_2^2}, v_1 v_2\right) \tag{4}$$

$$\tilde{A} \otimes \tilde{B} = \left(\mu_1^2\mu_2^2, \sqrt{v_1^2 + v_2^2 - v_1^2 v_2^2}\right) \tag{5}$$

$$\lambda\tilde{A} = \left(\sqrt{1 - (1 - {\mu_1}^2)^\lambda}, {v_1}^\lambda\right) \tag{6}$$

$$\tilde{A}^\lambda = \left({\mu_1}^\lambda, \sqrt{1 - (1 - {v_1}^2)^\lambda}\right) \tag{7}$$

Definition 3. Let Int ([0,1]) denote the set of all closed subintervals of [0,1], and X be a universe of discourse. An IVPFS $\tilde{P}$ in X is given by Equation 8.

$$\tilde{P} = \{\langle x, \mu_{\tilde{P}}(x), v_{\tilde{P}}(x)\rangle; x \in X\} \tag{8}$$

where the functions $\mu_{\tilde{P}}(x): X \mapsto Int([0,1])$ $(x \in X \mapsto \mu_{\tilde{P}}(x) \subseteq [0,1])$ and $v_{\tilde{P}}(x): X \mapsto Int([0,1])$ $(x \in X \mapsto v_{\tilde{P}}(x) \subseteq [0,1])$ denote the membership degree and non-membership degree of the element $x \in X$ to the set $\tilde{P}$, respectively, and for every $x \in X$, $0 \le \left\{\sup(\mu_{\tilde{P}}(x))^2 + (v_{\tilde{P}}(x))^2\right\} \le 1$. Also, for each $x \in X$, $\mu_{\tilde{P}}(x)$ and $v_{\tilde{P}}(x)$ are closed intervals and their lower and upper bounds are denoted by $\mu_{\tilde{P}}^L(x), \mu_{\tilde{P}}^U(x)$, $v_{\tilde{P}}^L(x)$, $v_{\tilde{P}}^U(x)$, respectively. Therefore, $\tilde{P}$ can also be expressed in another style as shown in Equation 9:

$$\tilde{P} = \left\{\langle x, \left[\mu_{\tilde{P}}^L(x), \mu_{\tilde{P}}^U(x)\right], \left[v_{\tilde{P}}^L(x), v_{\tilde{P}}^U(x)\right]\rangle; x \in X\right\} \tag{9}$$

The degree of hesitancy condition is as shown in Equation 10:

$$\pi_{\tilde{P}}(x) = \sqrt{1 - \mu_{\tilde{P}}^U(x)^2 - v_{\tilde{P}}^U(x)^2}, \sqrt{1 - \mu_{\tilde{P}}^L(x)^2 - v_{\tilde{P}}^L(x)^2} \tag{10}$$

Definition 4. Let $\tilde{A}_i$, $i = (1,2,\ldots,n)$ be a collection of IVPFNs. Then, the Interval-Valued Pythagorean Fuzzy Weighted Power Geometric (IVPFWG) operator is as shown in Equation 11:

$$IVPFWG_w(\widetilde{A_1}, \widetilde{A_2}, \widetilde{A_3}, \ldots \widetilde{A_n}) = \left(\begin{array}{c}\left[\prod_{i=1}^{n}(\mu_{Ai}^L)^{w_i}, \prod_{i=1}^{n}(\mu_{Ai}^U)^{w_i}\right], \\ \left[\sqrt{1 - \prod_{i=1}^{n}(1 - (v_{Ai}^L)^2)^{w_i}}, \sqrt{1 - \prod_{i=1}^{n}(1 - (v_{Ai}^U)^2)^{w_i}}\right]\end{array}\right) \tag{11}$$

where $w = (w_1, w_2, \dots, w_n)^T$ is the weighted vector of $\widetilde{A}_i$, $i = (1,2,\dots,n)$ with $w_i \geq 0$ and $\sum_{i=1}^{n} w_i = 1$.

3.1.2. The Steps of IVPF-AHP

The steps of the IVPF-AHP method can be explained as follows:

Step 1: Construct the compromised pairwise comparison matrix $R_{(r_{ik})mxm}$ with respect to experts' opinions according to Table 3.

Step 2: Construct the differences matrix $D = (d_{ik})_{mxm}$ between lower and upper values of membership and non-membership functions by using Equation (12-13).

$$d_{ik_L} = \mu^2{}_{ik_L} - v^2{}_{ik_U} \tag{12}$$

$$d_{ik_U} = \mu^2{}_{ik_U} - v^2{}_{ik_L} \tag{13}$$

Step 3: Find the interval multiplicative matrix $S = (s_{ik})_{mxm}$ by using Equation (14-15).

$$s_{ik_L} = \sqrt{1000^{d_L}} \tag{14}$$

$$s_{ik_U} = \sqrt{1000^{d_U}} \tag{15}$$

Step 4: Calculate the determinacy value $\tau = (\tau_{ik})_{mxm}$ by using Equation (16).

$$\tau_{ik} = 1 - \left(\mu^2{}_{ik_U} - \mu^2{}_{ik_L}\right) - \left(v^2{}_{ik_U} - v^2{}_{ik_L}\right) \tag{16}$$

Step 5: Determinate unnormalized weights $\mathrm{T} = (\mathrm{t_{ik}})_{\mathrm{mxm}}$ by using Equation (17).

$$t_{ik} = \left(\frac{s_{ik_L} + s_{ik_U}}{2}\right)\tau_{ik} \tag{17}$$

Step 6: Find the normalized priority weights w_i by using Equation (18).

$$t_{ik} = \left(\frac{s_{ik_L} + s_{ik_U}}{2}\right)\tau_{ik} \tag{18}$$

Table 3. Weighing scale for the IVPF-AHP method.

Linguistic Terms	IVPFNNs			
	μ_L	μ_U	v_L	v_U
Certainly Low Importance (CLI)	0.00	0.00	0.90	1.00
Very Low Importance (VLI)	0.10	0.20	0.80	0.9
Low Importance (LI)	0.20	0.35	0.65	0.8
Below Average Importance (BAI)	0.35	0.45	0.55	0.65
Average Importance (AI)	0.45	0.55	0.45	0.55
Above Average Importance (AAI)	0.55	0.65	0.35	0.45
High Importance (HI)	0.65	0.80	0.20	0.35
Very High Importance (VHI)	0.80	0.90	0.10	0.20
Certainly High Importance (CHI)	0.90	1.00	0.00	0.00
Exactly Equal (EE)	0.1965	0.1965	0.1965	0.1965

3.2. VIKOR

The VIseKriterijumsa Optimizacija I Kompromisno Resenje (VIKOR) method was first developed by Opricovic and Tzeng [95] and for multi-criteria optimization of systems with complex structures. The VIKOR method helps to select the best alternative by using a multi-criteria ranking index to rank alternatives under a set of criteria. Development of the VIKOR method started with Equation (19) form of Lp-metric [96]:

$$L_i^p = \left\{\left[\sum_{j=1}^{n} w_j \left(\left|f_j^* - f_{ij}\right|\right) / \left(f_j^* - f_j^-\right)\right]^p\right\}^{1/p} \tag{19}$$

where, 1 ≤ p ≤ ∞; i = 1, 2, ..., m.

Within the VIKOR method $L_i^{p=1} (as\ S_i)$ and $L_i^{p=\infty} (as\ R_i)$ are used to formulate ranking measure. The solution obtained by S_i is with a maximum group utility ("majority" rule), and the solution obtained by min R_i is with a minimum individual regret of the "opponent".

The steps of the ranking algorithm VIKOR can be explained as follows:

Step 1: Calculate the best f_j^* values and the worst f_j^* values of all criterion functions *j = 1, 2, ..., n*. Assume that *j*[th] function denotes benefits (Equation 20-21):

$$f_j^* = \max_i f_{ij} \tag{20}$$

$$f_j^- = \min_i f_{ij} \tag{21}$$

Step 2: Compute the values S_i and R_i. S_i is the synthesized gap for all criteria and R_i is the maximal gap in *i* criterion for prior improvement (Equation 22-23).

$$S_i = \sum_{j=1}^{n} w_j \left(\left|f_j^* - f_{ij}\right|\right) / \left(f_j^* - f_j^-\right) \tag{22}$$

$$R_i = \max_j\left(\left|f_j^* - f_{ij}\right|\right) / \left(f_j^* - f_j^-\right) \tag{23}$$

Step 3: Calculate the values Q_i. (Equation 24).

$$Q_i = v\frac{(S_i - S^*)}{(S^- - S^*)} + (1 - v)\frac{(R_i - R^*)}{(R^- - R^*)} \tag{24}$$

where, $S^* = \min_i S_i$, $S^- = \max_i S_i$, $R^* = \min_i R_i$, $R^- = \max_i R_i$ and v is introduced as the weight for the strategy of "maximum group utility", $(1 - v)$ is the weight of the individual regret of the "opponent".

Step 4: Sort the alternatives by the value of S_i, R_i ve Q_i in descending order. Propose the alternative $A^{(1)}$ as a compromise solution which is arranged by the measure minQ_i if the two conditions are satisfied:

Condition 1: Acceptable advantage (Equation 25)*:*

$$Q(A^{(2)}) - Q(A^{(1)}) \geq 1/(m-1) \tag{25}$$

where, m refers to the number of alternatives and $A^{(2)}$ is the second position among the alternatives ranked by Q_i.

Condition 2: Acceptable stability in decision making: Alternative $A^{(1)}$ must also be the best ranked by S_i or/and R_i.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- Alternatives $A^{(1)}$ and $A^{(2)}$ if only condition 2 is not satisfied, or
- Alternatives $A^{(1)}, A^{(2)}, \ldots, A^{(M)}$ if condition 1 not satisfied; $A^{(M)}$ is determined by the relation $Q(A^{(M)}) - Q(A^{(1)}) < D(Q)$ for maximum M (the positions of these alternatives are close).

4. Real case application

With the widespread use of 3D printer in many sectors, the number of 3D printer suppliers has increased. It is crucial for businesses to find the most suitable supplier among these supplier companies. For this reason, it is of great importance for the sector to determine the criteria that should be taken into account when selecting their own supplier among the enterprises supplying 3D printer to the company. The integrated IVPF-AHP and VIKOR methods have been used in the study.

The necessary literature review is made for the criteria to be used in the selection of 3D printer supplier, and the criteria are determined in line with the interviews made with three expert teams with sufficient knowledge in the field. The criteria weights obtained using IVPF-AHP have been verified by the AHP method. Finally, the supplier scores obtained from the criterion weights of the two methods have been analyzed and their validity has been confirmed. The hierarchical structure of the application is shown in Figure 4.

In line with the evaluations of the experts, the 3D printers are separated according to their brands and the five preferred 3D printer brands are determined by the expert team. The identified brands are compared and ranked according to their performance levels. Criterion weights is found using the IVPF-AHP method. Criteria weights is transferred to the VIKOR method, and five alternative suppliers are evaluated with the VIKOR method. After that, the statistical analysis is done by Pearson Correlation Coefficient and Paired Simple t Test in SPSS software.

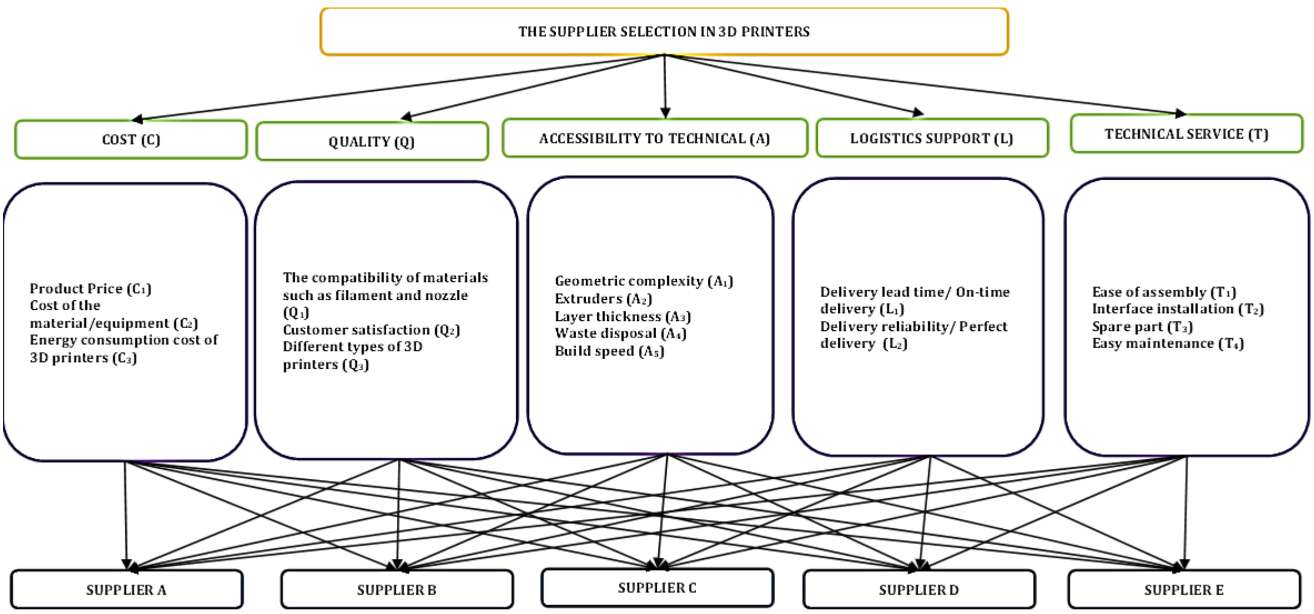

Figure 4. The hierarchical structure of the application

Experts were asked to evaluate the degree of influence of the criteria on each other with fuzzy linguistic expressions shown in Table 3. The impact assessment among the criteria by one of the experts is shown in Table 4. Linguistic expressions are translated into IVPFNs. PFNs with interval values corresponding to the linguistic evaluation of one of the experts are shown in Table 5. The consistency rates of each expert's evaluation matrix are calculated, and it is concluded that it is below 0.1. Criterion weights of the experts have determined as equally based on their years of experience in their field. Similarly, all evaluations made by the rest of the experts are translated into IVPFNs. IVPFNs are made into a single matrix using IVPFWG. The paired comparison matrix for the main criteria is shown in Table 6. The difference matrix shown in Table 7 is obtained by using the pairwise comparison matrix, Equation (12) and Equation (13). The interval multiplicative matrix shown in Table 8 is obtained by using the difference matrix, Equation (14) and Equation (15). Using Equation (16), certainty values are shown in Table 9. Unnormalized weight matrix is derived with certainty values. With the help of Equation (18), normalized priority weights are calculated and shown in Table 11.

According to the criterion weights obtained from the IVPF-AHP shown in Table 11, it is seen that the most important criterion to be considered in the selection of suppliers among the 3D printer brands in the sector is Quality. Supplier enterprises should focus on Quality and Technical Service criteria to increase their 3D printer sales.

Table 4. The evaluation values of one of the experts in terms of the effect between the main criteria.

	C	Q	A	L	T
C	EE	LI	LI	HI	AI
Q	HI	EE	EE	HI	EE
A	HI	EE	EE	AI	EE
L	LI	LI	AI	EE	LI
T	AI	EE	EE	HI	EE

Table 5. Corresponding IVPFNs for linguistic evaluation (CR = 0.041).

	C				Q				A				L				T			
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U
C	0.1965	0.1965	0.1965	0.1965	0.10	0.20	0.80	0.90	0.10	0.20	0.80	0.90	0.35	0.45	0.55	0.65	0.20	0.35	0.65	0.80
Q	0.8	0.90	0.10	0.20	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.80	0.90	0.10	0.20	0.1965	0.1965	0.1965	0.1965
A	0.8	0.90	0.10	0.20	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.65	0.80	0.20	0.35	0.1965	0.1965	0.1965	0.1965
L	0.55	0.65	0.35	0.45	0.10	0.20	0.80	0.90	0.20	0.35	0.65	0.80	0.1965	0.1965	0.1965	0.1965	0.10	0.20	0.80	0.90
T	0.65	0.80	0.20	0.35	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.1965	0.80	0.90	0.10	0.20	0.1965	0.1965	0.1965	0.1965

Table 6. Pairwise comparison matrix of main criteria.

	C				Q				A				L				T			
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U
C	0.20	0.20	0.60	0.60	0.15	0.26	0.91	0.96	0.22	0.29	0.80	0.88	0.43	0.55	0.69	0.81	0.24	0.38	0.90	0.96
Q	0.71	0.81	0.71	0.77	0.20	0.20	0.60	0.60	0.47	0.52	0.49	0.62	0.66	0.78	0.61	0.73	0.36	0.41	0.82	0.87
A	0.38	0.43	0.82	0.87	0.16	0.24	0.94	0.98	0.20	0.20	0.60	0.60	0.50	0.62	0.83	0.88	0.16	0.20	0.93	0.97
L	0.39	0.53	0.88	0.94	0.19	0.32	0.92	0.97	0.34	0.47	0.79	0.87	0.20	0.20	0.60	0.60	0.13	0.20	0.95	0.98
T	0.62	0.75	0.62	0.74	0.28	0.36	0.77	0.84	0.31	0.33	0.49	0.60	0.50	0.54	0.48	0.60	0.20	0.20	0.60	0.60

Table 7. Differences matrix of the main criteria.

	C		Q		A		L		T	
	d_{ikL}	d_{ikU}	d_{ikL}	d_{ikU}	d_{ikL}	d_{ikU}	d_{ikL}	d_{ikU}	d_{ikL}	d_{ikU}
C	-0.32	-0.32	-0.89	-0.76	-0.72	-0.56	-0.47	-0.19	-0.86	-0.67
Q	-0.10	0.15	-0.32	-0.32	-0.16	0.04	-0.11	0.23	-0.64	-0.51
A	-0.61	-0.49	-0.93	-0.83	-0.32	-0.32	-0.53	-0.31	-0.91	-0.83
L	-0.73	-0.49	-0.90	-0.74	-0.64	-0.41	-0.32	-0.32	-0.95	-0.86
T	-0.18	0.18	-0.63	-0.46	-0.26	-0.13	-0.11	0.07	-0.32	-0.32

Table 8. Interval multiplicative matrix of main criteria.

	C		Q		A		L		T	
	s_{ikL}	s_{ikU}	s_{ikL}	s_{ikU}	s_{ikL}	s_{ikU}	s_{ikL}	s_{ikU}	s_{ikL}	s_{ikU}
C	0.33	0.33	0.05	0.07	0.08	0.14	0.20	0.53	0.05	0.10
Q	0.71	1.69	0.33	0.33	0.58	1.13	0.69	2.22	0.11	0.17
A	0.12	0.18	0.04	0.06	0.33	0.33	0.16	0.34	0.04	0.06
L	0.08	0.18	0.05	0.08	0.11	0.24	0.33	0.33	0.04	0.05
T	0.55	1.85	0.11	0.20	0.41	0.64	0.69	1.25	0.33	0.33

Table 9. The determinacy values of main criteria.

	C	Q	A	L	T
	τ_{ik}	τ_{ik}	τ_{ik}	τ_{ik}	τ_{ik}
C	1.00	0.87	0.84	0.72	0.81
Q	0.75	1.00	0.80	0.66	0.87
A	0.88	0.90	1.00	0.78	0.92
L	0.76	0.85	0.77	1.00	0.92
T	0.65	0.83	0.87	0.83	1.00

Table 10. The unnormalized weights of the main criteria.

	C	Q	A	L	T
	τ_{ik}	τ_{ik}	τ_{ik}	τ_{ik}	τ_{ik}
C	0.33	0.05	0.10	0.26	0.06
Q	0.90	0.33	0.69	0.97	0.12
A	0.13	0.04	0.33	0.20	0.05
L	0.10	0.05	0.14	0.33	0.04
T	0.78	0.13	0.45	0.80	0.33

Table 11. The normalized weights for each criterion.

Main Criteria	w (%)
Cost	10.41
Quality	38.92
Accessibility to Technology	09.78
Logistic Support	08.58
Technical Service	32.31

When examined in terms of supplier selection in the additive manufacturing, it is observed that especially Cost and Accessibility to Technology criteria come well after Quality and Technical Service criteria.

For this reason, these two criteria are among the determining factors in supplier selection. The steps applied in the IVPF-AHP method for the main criteria are also applied for the sub-criteria, and the significance weights of the sub-criteria are shown in tables.

When the sub-criteria are examined, it is seen in Table 12 that the cost of the material/equipment and product price are more important than the energy consumption cost of 3D printers in the selection of suppliers based on cost criteria. When Table 13 is analyzed based on quality criteria, it is concluded that the compatibility of materials such as filament and nozzle is of critical importance when compared with other criteria. When Table 14 is examined, based on accessibility to technology criteria, it is noticed that build speed and layer thickness are very important compared to other criteria. When Table 15 is analyzed on the basis of logistic support criteria, it stands out that the delivery reliability and perfect delivery of products is more important than other criteria when choosing a supplier. The delivery of the product in non-damaged condition and ensuring the delivery reliability of the product enhances the customer's trust in the supplier, as it prevents adventure the security of the product. When Table 16 is assessed on the basis of technical service, it is seen that the easy maintenance is more important than the interface installation criteria. The reason for this is the production of 3D printers with new and different technologies, which results in higher costs. This study revealed that 3D printer suppliers should especially strengthen their Quality and Technical Service infrastructure to increase their customers. When the literature is also reviewed, it is seen that the results of this study are in line with the literature.

The criteria weights used in the VIKOR method come from the IVPF-AHP method, as the methods are used in an integrated manner. In the IVPF-AHP method, experts are asked to evaluate the criteria according to their importance with the fuzzy linguistic expressions shown in Table 3. For this reason, the criteria weights used in VIKOR are fuzzy. No deterministic action has been taken in criterion weights. Experts are asked to score between 0-100 when comparing suppliers, as it would be much more difficult to compare five different 3D printer suppliers, which we define as A, B, C, D, E, according to each criterion with linguistic expressions. For this reason, the VIKOR method has been preferred. The scores and the maximum and minimum scores of each criterion are shown in Table 17 where 0 is very bad and 100 is very good. The results obtained by calculating the group benefit average and maximum regret average of each supplier are listed in Table 18.

Table 12. The pairwise comparison matrix of all the expert evaluations, and the sub-criteria weights of cost criterion.

	C1				C2				C3				w (%)
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	
C1	0.20	0.20	0.60	0.60	0.29	0.41	0.87	0.92	0.39	0.44	0.72	0.79	23,69
C2	0.58	0.70	0.72	0.80	0.20	0.20	0.60	0.60	0.62	0.75	0.62	0.74	58,15
C3	0.29	0.34	0.84	0.89	0.24	0.38	0.90	0.96	0.20	0.20	0.60	0.60	18,16

Table 13. The pairwise comparison matrix of all the expert evaluations, and the sub-criteria weights of quality criterion.

	Q1				Q2				Q3				w (%)
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	
Q1	0.20	0.20	0.60	0.60	0.31	0.33	0.49	0.60	0.44	0.49	0.51	0.63	50.14
Q2	0.16	0.20	0.93	0.97	0.20	0.20	0.60	0.60	0.28	0.29	0.61	0.63	26.38
Q3	0.19	0.26	0.94	0.97	0.24	0.26	0.65	0.68	0.20	0.20	0.60	0.60	23.48

Table 14. The pairwise comparison matrix of all the expert evaluations, and the sub-criteria weights of accessibility to technology criterion.

	A1				A2				A3				A4				A5				w (%)
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	
A1	0.20	0.20	0.60	0.60	0.24	0.26	0.82	0.87	0.24	0.31	0.85	0.91	0.47	0.63	0.87	0.93	0.16	0.24	0.94	0.98	10.88
A2	0.28	0.29	0.71	0.77	0.20	0.20	0.60	0.60	0.34	0.39	0.75	0.81	0.53	0.66	0.82	0.88	0.20	0.29	0.89	0.95	15.21
A3	0.41	0.47	0.71	0.78	0.34	0.39	0.83	0.88	0.20	0.20	0.60	0.60	0.49	0.54	0.59	0.61	0.24	0.31	0.88	0.94	22.53
A4	0.24	0.38	0.78	0.89	0.28	0.43	0.81	0.89	0.00	0.00	0.83	1.00	0.20	0.20	0.60	0.60	0.15	0.26	0.91	0.96	09.98
A5	0.47	0.52	0.49	0.62	0.44	0.50	0.60	0.72	0.41	0.47	0.62	0.73	0.71	0.81	0.71	0.77	0.20	0.20	0.60	0.60	41.40

Table 15. The pairwise comparison matrix of all the expert evaluations and the sub-criteria weights of logistic support criterion.

	L1				L2				w (%)
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	
L1	0.20	0.20	0.60	0.60	0.16	0.20	0.93	0.97	19.16
L2	0.31	0.33	0.49	0.60	0.20	0.20	0.60	0.60	80.84

Table 16. The pairwise comparison matrix of all the expert evaluations, and the sub-criteria weights of the technical service criterion.

	T1				T2				T3				T4				w (%)
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	
T1	0.20	0.20	0.60	0.60	0.62	0.72	0.72	0.79	0.22	0.29	0.80	0.88	0.16	0.24	0.91	0.96	20.71
T2	0.23	0.34	0.89	0.94	0.20	0.20	0.60	0.60	0.00	0.00	0.87	1.00	0.00	0.00	0.94	1.00	09.47
T3	0.38	0.43	0.82	0.87	0.59	0.71	0.82	0.87	0.20	0.20	0.60	0.60	0.22	0.29	0.93	0.97	16.36
T4	0.47	0.52	0.59	0.71	0.72	0.86	0.59	0.72	0.38	0.43	0.56	0.68	0.20	0.20	0.60	0.60	53.46

Table 17. Evaluation scores of 3D printer suppliers belonging to different brands according to the criteria.

	A	B	C	D	E	f_j^*	f_j^-
C1	22	24	60	62	37	62	22
C2	38	25	61	47	39	61	25
C3	77	40	20	25	12	77	12
Q1	72	44	14	18	18	72	14
Q2	81	49	29	20	32	81	20
Q3	76	43	28	56	33	76	28
A1	74	17	24	31	16	74	16
A2	62	39	35	15	13	62	13
A3	61	38	44	21	17	61	17
A4	69	41	29	24	23	69	23
A5	68	45	29	12	28	68	12
L1	65	12	39	63	27	65	12
L2	54	13	53	60	42	60	13
T1	77	20	50	17	14	77	14
T2	75	35	34	12	13	75	12
T3	69	38	18	56	45	69	18
T4	75	50	37	34	39	75	34

Table 18. Ranking of 3D printer suppliers belonging to different brands according to the criteria weights obtained from the IVPF-AHP.

S_i	Rank	R_i	Rank	Q_i	Rank
0.072	A	0.039	A	0.000	A
0.660	B	0.105	B	0.608	B
0.732	D	0.182	D	0.902	D
0.734	C	0.183	E	0.945	C
0.816	E	0.195	C	0.962	E

By examining Condition 1 (acceptable advantage) and Condition 2 (an acceptable advantage in decision making) in the VIKOR method, according to Condition 1 and Condition 2, among the listed suppliers Qi, supplier A with the smallest value has been chosen due to its highest performance level.

5. Comparative analysis

A statistical analysis is important to prove the validity of the model in MCDM methods. For this, the results of the methods can be tested using various statistical analyses. SPSS is a statistical software package that allows the many different types of analysis, transformation, and forms of output of complex data. In addition to statistical analyses, it also provides various tools for data visualization, data manipulation, and reporting [97-98]. The relationship between the criteria weights obtained by MCDM methods can be analyzed using the correlation coefficient. The analysis of the results in determining the best alternative obtained from different criteria weights can be analyzed by the correlation coefficient or paired sample t-Test in the VIKOR method.

When Figure 5 is examined, both methods give similar results. However, decision-makers may not always have complete knowledge about a subject, and information is often uncertain in real-life problems. In such situations, the AHP method needs to be revised. The IVPF-AHP is more successful than the AHP method due to its flexibility in defining for decision-makers and its success in modeling uncertainty in real-life problems.

The correlation coefficient or r coefficient is a statistical tool used to measure the degree or strength of the relationship between two different variables. The correlation coefficient is considered to represent ≤ 0.35 weak correlations, 0.36 to 0.67 modest correlations, 0.68 to 1.00 high correlations and ≥ 0.90 very high correlations [99].

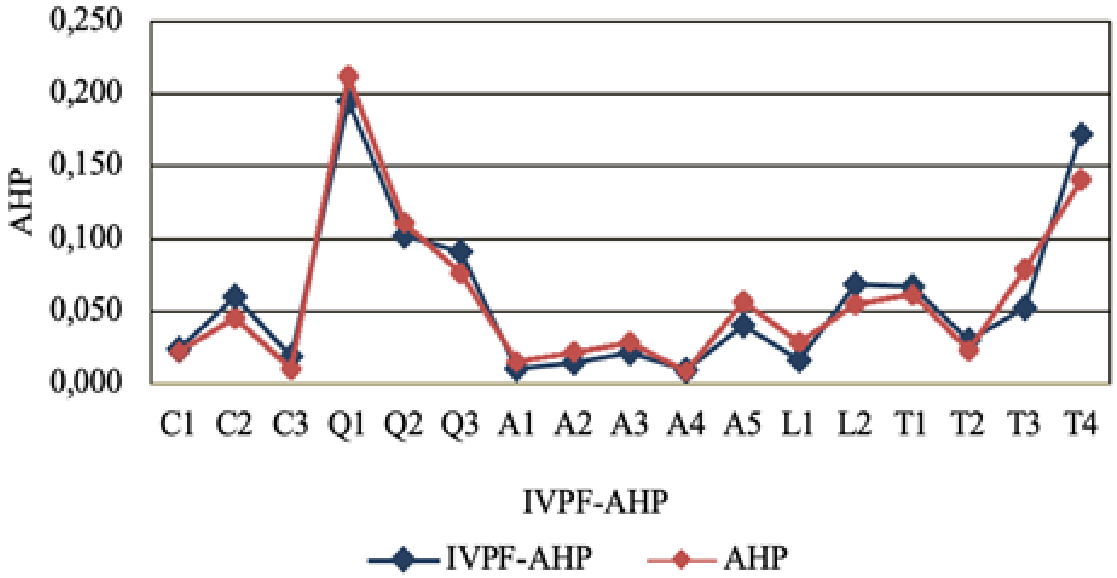

Figure 5. Comparison of the criteria weights obtained from the methods.

According to Figure 6, the correlation coefficient and test significance value of the methods are 0.9302 and 0.000, respectively. A very strong statistically positive correlation has been found between the criteria weights obtained from IVPF-AHP and the criteria weights obtained from AHP (P <.001).

The supplier scores determined using different methods in Table 19 is analyzed with a paired sample t-Test. It tests whether there is a significant difference between the two groups. The five supplier scores are analyzed by paired sample t-Test.

According to Table 20 and Table 21, 99% confidence level, test statistic and significance values are 1.633 and 0.178, respectively. As a result of the analysis, there are no statistically significant differences between the results of the two methods. The correlation coefficient according to the total scores of 3D printer suppliers with IVPF-AHP and AHP methods is 1.000. Thus, the proposed approach can be used for the 3D printer supplier selection.

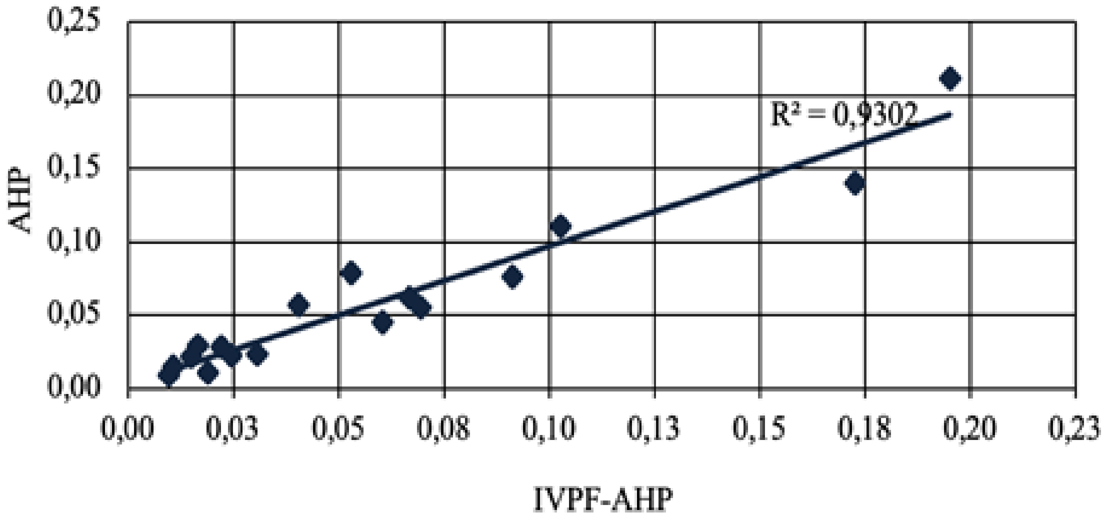

Figure 6. Correlation graph of the criteria weights obtained from the methods.

Table 19. Total scores of 3D printer suppliers according to the IVPF-AHP and the AHP methods.

		A	B	C	D	E
IVPF-AHP	C	04	03	06	05	03
	Q	29	17	08	11	10
	A	06	04	03	02	02
	L	05	01	04	05	03
	T	24	13	12	10	10
	Total	69	38	33	33	29
AHP	C	3	2	4	4	3
	Q	30	18	8	10	10
	A	9	5	4	2	3
	L	5	1	4	5	3
	T	23	12	11	11	10
	Total	69	38	32	32	29

Table 20. Analysis of the criteria weights of IVPF-AHP and AHP methods with paired sample t-Test in five suppliers.

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	99% Confidence Interval of the Difference: Lower	99% Confidence Interval of the Difference: Upper			
IVPF-AHP & AHP	.40000	.54772	.24495	-.28009	1.08009	1.633	4	.178

Table 21. Correlation coefficient according to the total scores of 3D printer suppliers.

	Correlation Coefficient	Sig.
IVPF-AHP & AHP	1.000	.000

6. Conclusion

In the business world where competition is increasing day-by-day in parallel with the changing technological developments, companies must be superior to their competitors and more open to innovations to increase their profitability and maintain their continuity. At this point, the decision-making process constitutes the most important stage. When the developing technology, printers have also begun to evolve and change. This transformation has led to the emergence of many 3D printer brands.

Selection supplier for 3D printer has become crucial for businesses that want to choose their own supplier. In this study, the criteria to be considered to choose the best among the 3D printer suppliers are collected under five main criteria and 17 sub-criteria, and a model is created. The criteria determined are evaluated, and their opinions are received by a team of three experts who have a command in the field. The criteria weights are determined, and the result is assessed by listing the criteria according to their importance. This study revealed that supplier enterprises operating in the 3D printer should strengthen their quality and technical service infrastructures to increase their sales. It has been concluded that the criteria regarding the cost of the material/equipment, the compatibility of materials such as filament and nozzle, the ability of delivery reliability of products, easy maintenance are more important than other criteria. The suppliers are evaluated with the VIKOR method, and supplier A with the highest performance level is selected among the suppliers. According to the result of the statistical analysis, the proposed approach can be preferred for the 3D printer supplier selection.

It is seen that all enterprises the 3D printer can benefit from the results obtained from this study. In addition, it is clearly seen that the work done is valuable due to the importance of the 3D printer in today. 3D printers offer various advantages, including good fabrication speed, low material costs, and contributions to sustainable manufacturing. However, there are limitations in the potential to create large-scale models. Although mass production of identical parts is possible, challenges such as printing speed and cost can be obstacles. Additionally, issues like surface finish, moderate strength, and material availability can cause difficulties for suppliers. In future studies, these problems could be addressed with the integration of artificial intelligence technologies. The criteria created can be increased, more suppliers can be examined, and studies can be conducted with neutrosophic sets and hesitant fuzzy sets, which are the extension of new fuzzy sets and are more successful in defining uncertainty than traditional fuzzy sets. Furthermore, the effect of supplier selection on a supply chain can be investigated.

Conflicts of interest

The authors declare no conflicts of interest.

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Development of a sensitivity analysis tool for the trajectory of multistage launch vehicles

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Abstract

The primary objective of this work is to create a highly accurate sensitivity analysis tool for multi-stage launch vehicle trajectories. This tool is designed to assess the impact of various parameters on the trajectory and performance of multi-stage launch vehicles. To achieve this, we have developed high-fidelity simulation software that considers all translational and angular movements by modelling the six-degrees-of-freedom (6DOF) equations of motion. The validation of this software is based on experimental data. An essential aspect of this work is the utilization of the developed sensitivity analysis tool to determine how different parameters affect the trajectory of multi-stage launch vehicles. Through the sensitivity analysis conducted using the developed tool, it is possible to identify which parameters are of critical importance during the design phase. We apply a generic mission profile for the Minotaur-I launcher to obtain parametric dependencies of the flight path. Through a comprehensive parametric study, we evaluate a range of critical parameters, including gross lift-off weight, a specific impulse of each stage, pitch-over manoeuvre initial time and angle, and ignition impulse of each stage. These parameters significantly influence the trajectory, performance, and reliability of the launch vehicle for mission design and success. The results of the sensitivity analysis underscore that even minor variations in these parameters can result in substantial deviations from the nominal insertion altitude. The acceptability of errors in specific impulse changes varies across stages, with maximum changes of 6.07%, and the fourth stage showing less sensitivity at 0.13%. However, it's important to note that variations in the parameters of the first stage tend to be challenging to rectify once they occur, with maximum changes in specific impulses reaching 75.57%. Another noteworthy discovery is that the acceptability of changes in pitch-over manoeuvre initiation times depends on the rate of change; they can be deemed either acceptable or unacceptable based on this factor, with changes ranging between 17.90% and 98.38%.

1. Introduction

Launch vehicles, also known as carrier rockets, serve the purpose of transporting one or more payloads from Earth's surface to space. They play a crucial role in various missions, including commercial and military satellite deployments, meteorological observation, and experimental research.

Throughout the history of the space race, a diverse range of launch vehicle systems has been developed. These systems are designed not only to access space but also to achieve their designated missions, contributing to the global prestige of the countries and organizations involved in space exploration.

The advancement of technology has amplified the significance of designing and determining trajectories for launch vehicles, particularly due to the intricate structures of modern launchers. Achieving a higher level of sophistication and success in specific missions necessitates precise modelling, simulation, and analysis of these launchers.

Various simulation tools for aerospace vehicles have been developed by numerous companies, agencies, and institutes. The objectives of these developers can vary. For instance, research centres at NASA have enhanced simulation tools like Core [1], JEOD [2], LaSRS++ [3], MAVERIC [4], POST2 [5], VMSRTE [6], and OTIS [7]. These tools offer distinctive features such as design and flight performance analysis, modelling of object-oriented concepts and different vehicles in the same simulation platform, vertical motion simulation encompassing rotorcraft, trajectory generation, targeting, and optimization.

Additionally, simulation tools developed by Analysis, Simulation and Trajectory Optimization Software (ASTOS) Solutions GmbH and Artificial General Intelligence (AGI), namely ASTOS [8] and Systems Tool Kit (STK) [9], can conduct mission performance analysis, concept analysis, guidance, navigation, and control (GNC) design, modelling with high temporal and spatial accuracy, and employ cloud and server-based architecture while also facilitating vehicle orientation. In the existing literature, despite the availability of numerous simulation tools, it is important to note that many of them cannot perform sensitivity analysis.

The flight path and performance of a vehicle are influenced by a multitude of design and event parameters as well as modelling parametrization. Sensitivity analysis is a crucial step in understanding how vehicle performance is linked to these parameters. In essence, sensitivity analysis entails assessing how alterations in the input variables of a mathematical model or system impact the output variables under specific conditions. This analysis helps engineers and decision-makers understand the impact of uncertainties and variations in design parameters.

The performance sensitivity of a launch vehicle is multifaceted, encompassing various factors that influence its overall effectiveness. m_{pl} analysis delves into how alterations in payload mass (m_{pl}) can impact critical aspects like the maximum achievable orbit and payload capacity [10]. Similarly, propellant mass (m_p) fraction examination explores the launch vehicle's performance sensitivity to changes in the ratio of (m_p) to total mass (m_t). In terms of cost sensitivity, manufacturing costs, encompassing materials and production processes, are scrutinized for their impact on the overall launch vehicle cost. Operational costs, including launch site expenses and maintenance, are also analysed to understand their influence on the total cost of a launch [11]. Design parameter sensitivity involves studying the launch vehicle's structural response to variations in parameters like material strength, thickness, and geometry [12]. Environmental sensitivity considers the impact of weather conditions, such as wind and temperature variations, on launch vehicle performance and safety [13]. Additionally, the choice of launch site is assessed for its effect on performance, considering different atmospheric conditions and geographic considerations. System reliability sensitivity examines the overall launch system's reliability concerning variations in the reliability of individual components or subsystems. Finally, regulatory and policy sensitivity explores how changes in regulatory requirements, compliance standards, and government policies or international regulations can influence the design and operational aspects of the launch vehicle program [14].

Several sensitivity analysis methods, such as differential, factorial, and One-at-a-Time (OAT), are available. However, sensitivity analysis studies for multistage launch vehicles are notably scarce in the existing literature. While sensitivity analysis has been conducted in fields like aeroelasticity [15], structural loads [16], and cost modelling [17], only a single study exists that focuses on the sensitivity analysis of launch vehicle trajectories [18]. It's worth noting that this study employs a three-degrees-of-freedom (3DOF) flight mechanics model, which may not capture the true trajectory accurately. To achieve a precise trajectory estimation, accurate subsystem modelling, and sensitivity analysis are indispensable. Moreover, none of these studies include sensitivity analysis for trajectory or performance parameters.

To address this gap in the literature, a sensitivity analysis tool has been developed within the scope of this paper to derive flight, mission performance, and parametric dependencies of launch vehicles. The initial step involves modelling the Minotaur-I launch vehicle produced by the American Company, Orbital Sciences Corporation (OSC). This model serves to validate and verify the developed tool by comparing it with reference data from the launch vehicle's user guide.

Following the validation, a Six degrees-of-freedom (6DOF) flight mechanics model is implemented to ensure the tool's accuracy. Subsequently, the developed tool is employed to perform sensitivity analysis on the Minotaur-I launch vehicle. This analysis seeks to determine the impact of input parameters on the vehicle's trajectory and assess how accuracy varies with different input parameters.

The OAT method is selected for the sensitivity analysis, as it involves altering one input parameter at a time in each run, ensuring simplicity and clear attribution of observed changes in the mathematical model or system to the specific input parameter modifications.

In this study, a 6DOF comprehensive trajectory model is implemented and validated using Minotaur-I launch vehicle reference mission data. With the validated model, launch vehicle trajectories can be modelled without the need for high-cost or hard-to-access programs, allowing for the rapid generation of detailed results during the design phase. Furthermore, the model is user-friendly, innovative, and entirely under user control, making it adaptable to specific needs. In this context, a sensitivity analysis tool has been added to the model, enabling the examination of the sensitivity of different design and event variables and their effects on-orbit target parameters. This allows for an investigation into the impact of the user-desired parameters.

In the present study, the details of the modelling conducted are determined in Section 2 while the validation of the developed tool is given in Section 3. Section 4 involves sensitivity analysis, and the discussion and conclusion are given in Section 5.

2. Modelling

To create a sensitivity analysis tool, it is essential to establish a foundation comprising a generic flight dynamics model and environment models, including gravity and atmosphere models. Furthermore, a precise implementation of subsystem models is required to accurately capture the characteristics of the launch vehicle. This necessitates the development of a 6DOF simulation model and the incorporation of environment models, which have been achieved through the utilization of MATLAB 2017b.

The tool also integrates propulsion, structural, and aerodynamic models for the launch vehicle. Specifically, the propulsion, structural, and aerodynamic models have been incorporated into the tool to enable comprehensive analysis.

In practice, the developed tool is employed to conduct sensitivity analysis for a specific launch vehicle. In this case, the Minotaur-I launch vehicle, produced by OSC, is selected as an exemplary launch vehicle to illustrate the tool's capabilities.

2.1. System dynamics

The trajectory model within simulation tools holds paramount importance, as it encompasses the entire set of equations of motion and transformation functions. Any inaccuracies or errors in the implementation of this model or the coupling of equations can result in irreparable consequences.

In the literature, various coordinate systems are available, and the Direction Cosine Matrix (DCM) is frequently employed for the conversion between these coordinate systems. In this study, the transformations considered are from Earth-Centered Earth-Fixed Frame (ECEF) to Earth-Centered Inertial Frame (ECI) and from ECEF to North-East-Down Frame (NED). The remaining frame rotation matrices are derived using either q-to-DCM or Euler angles-to-DCM functions, as documented in references [19–25].

In this study, an enhanced 6DOF modelling and simulation tool has been developed for aerospace vehicles. This tool encompasses both translational and angular motion aspects. Specifically, the study focuses on deriving the equations of rotational dynamics, which account for variations in time orientation. Additionally, it establishes the relationship between the derivative of the translational vector and angular velocity (ω).

The Moment vector (M) primarily results from the combined effects of aerodynamic forces and propulsion forces that do not act through the centre of mass. Furthermore, it incorporates the role of attitude control devices. Equation 1 demonstrates that the derivative of the angular momentum (h) of a rigid body, as measured in the inertial frame, is equivalent to the moment vector acting about the vehicle's centre of mass [26].

$$M = {}^{i}\dot{h}_{cm/i} \quad (1)$$

The notation, ${}^{i}\dot{h}_{cm/i}$ refers to the vector derivative of the ω of the body concerning the inertial frame, as observed from the inertial frame.

To derive the state equations for ω in body-fixed components, it is essential to introduce the Coriolis term to account for the rotation of the frame. This equation underscores the well-established fact that the angular momentum is equivalent to the product of the inertia matrix (J) and the ω. This understanding enables us to rearrange and substitute these terms into Equation 1 [26].

$${}^{b}\dot{\omega}_{b/i}^{bf} = \left(J^{bf}\right)^{-1}\left[\mathrm{M}^{bf} - \omega_{b/i}^{bf} \times J^{bf}\omega_{b/i}^{bf}\right] \quad (2)$$

In Equation 2, ${}^{b}\dot{\omega}_{b/i}^{bf}$ represents the components in the body coordinate system of the derivative taken in the body frame of the ω of the body concerning the inertial frame. Additionally, J^{bf} denotes the J for the rigid body. It's important to note that this matrix remains constant for an unchanging centre of mass (cm); however, it changes due to propellant consumption.

To derive the equation for translational motion, the second law of Newton is employed, aiming to calculate state parameters like the position and velocity vector (v) of a body. These calculations consider the impact of various forces such as aerodynamics, propulsion, gravitational attraction, and other disturbance forces.

However, it is also essential to account for centripetal and Coriolis accelerations, which arise due to the Earth's rotation and the movement of the frame. Following mathematical operations, the derivatives of the body's **v**, as observed in the body frame regarding the ECEF frame, have been determined, as expressed in Equation 3 [26].

$${}^{e}\dot{\mathbf{v}}_{cm/e} = \frac{1}{m}\mathbf{F} + \mathbf{G} - \omega_{e/i}x\left(\omega_{e/i} \times \mathbf{P}_{cm/O}\right) - 2\omega_{e/i}x\mathbf{v}_{cm/e} \quad (3)$$

where F is the sum of forces vector, G is the gravitation vector of Earth, O is the cm of Earth, m is body mass and $\mathrm{P}_{cm/O}$ is body cm position with respect to O. In addition, the matrix form of state equations is given in Equation 4.

$$X = \left[q_{b/e}, \mathbf{P}_{b/e}^{e}, \mathbf{v}_{b/e}^{e}, \omega_{b/i}^{e}\right]^{T} \quad (4)$$

where $q_{b/e}$ is quaternions of the body concerning ECEF, $\mathrm{P}_{b/e}^{e}$ is the components in the ECEF frame of the P of the body concerning ECEF, $\mathrm{v}_{b/e}^{e}$ is the components in the ECEF frame of the v of the body about ECEF and, $\omega_{b/i}^{e}$ is the components in ECEF frame of the **h** of the body concerning to ECI. The fourth-order Runge-Kutta Integration Method is used to solve differential equations [27].

2.2. Environment models

Environmental changes significantly impact the performance and stability of aerospace vehicles. The influence of these changes depends on various factors specific to the type of vehicle. In the case of launch vehicles, two paramount factors are the Earth's atmosphere and its gravity field. As a result, the tool incorporates models for both gravity and atmosphere to address these key considerations.

To achieve a trajectory that accurately replicates the behaviour of aerospace vehicles as they move across the Earth's surface, it is imperative to possess a precise model for the Earth's shape. *The World Geodetic System 1984* Model plays a crucial role in providing highly accurate information about the ellipsoidal shape of the Earth. Over the years, this model has seen refinements, with the most recent update in 2013 boasting an impressive accuracy of 1 cm [28].

The parameters that define the Earth's oblate spheroid shape, along with their most widely recognized abbreviations, are detailed in Table 1 [29]. It's worth noting that the gravitational constant in this context is geocentric and accounts for the mass of Earth's atmosphere.

Table 1. The WGS-84 parameters [29].

Parameter	Abbreviation	Value	Unit
Semi-major axis	a	6378137	m
Semi-minor axis	b	6356752	m
Angular velocity	ω	7.292115 x 10^{-5}	rad/s
Flattening	f	1/298.2572235	-
Gravitational constant	GM	3986.5	km^3/s^2
Eccentricity	e	0.081819190	-

In recent years, significant advancement has been made in the form of the EGM2008 Gravity Model, which is a global high-degree potential model [30]. This model has proven to be crucial for accurately calculating the trajectory of aerospace vehicles.

To facilitate the utilization of this model, the parameters listed in Table 1 are employed. By simplifying the gravitational potential function, a function for gravitational acceleration concerning the ECEF frame is derived. This function is then integrated into the tool, and it is represented in Equation 5 [31].

$$G_{J_2}^{ECEF} = -\frac{3}{2}J_2\left(\frac{\mu}{r^2}\right)\left(\frac{a}{r}\right)^2\begin{bmatrix}\left(1-5\left(\frac{z}{r}\right)^2\right)\frac{x}{r}\\ \left(1-5\left(\frac{z}{r}\right)^2\right)\frac{y}{r}\\ \left(1-5\left(\frac{z}{r}\right)^2\right)\frac{z}{r}\end{bmatrix} \tag{5}$$

where x, y, and z are ECEF position, μ is Earth's gravitational constant, r is the distance from the centre of mass of Earth, a is the semi-major axis of WGS84 ellipsoid and J_2 is the zonal harmonic coefficient.

Two categories of atmosphere models exist: reference and standard atmosphere models. While standard atmosphere models primarily consider the vertical distribution of atmospheric properties solely about h_{alt}, reference models encompass a broader range of factors, including seasonal, geomagnetic, solar, and latitude effects. Consequently, reference models tend to offer higher accuracy than standard models.

In the context of this study, the US1976 Standard Atmosphere Model has been adopted. The additional influences covered by reference models are not deemed critical to the research objectives. In this model, h_{alt} is the sole input parameter, while absolute temperature in Kelvins (T), Pressure (P), speed of sound (u), and atmospheric density (ρ) are the resulting outputs. These outputs are used to calculate parameters such as Mach number (M) and dynamic pressure (P_{dyn}).

The model can provide data up to a h_{alt}=84 km [32]. For h_{alt} beyond 84 km, the model relies on a look-up table. To extend its applicability, new functions have been created through a curve-fitting method using the data from this table. As a result, the implemented model remains valid up to a h_{alt}=1000 km [32].

For speed of sound (Equation 6) [33],

$$u = \sqrt{\frac{\gamma_{ad}RT}{M}} \tag{6}$$

where adiabatic index $(\gamma_{ad}) = 1.4$, universal gas constant $(R) = 8314.15$ Nm/kmolK, molecular mass $(M) = 28.95$ kg/kmol.

For Mach number (Equation 7) [33],

$$\mathrm{M} = \frac{V}{u} \tag{7}$$

For M which is used in the calculation of ρ is obtained by curve fitting. The density equation is given in the Equation 8 [34].

$$\rho = \frac{P_{atm}M}{RT} \tag{8}$$

The dynamic pressure equation is given in Equation 9 [34].

$$P_{dyn} = \frac{1}{2}\rho V^2 \tag{9}$$

here, V is the velocity magnitude of the vehicle.

2.3. Propulsion model

The Minotaur-I launch vehicle, which is the subject of this study, comprises four stages powered by solid propellant. The vehicle's properties are detailed in Table 2 [35]. Furthermore, it's noteworthy that this launch vehicle has undergone a total of eleven launches, and each mission has achieved success.

The choice to focus on a multistage launch vehicle with solid motors is deliberate. This selection is driven by the need to implement a sloshing model, which is particularly relevant for liquid and hybrid rocket motors and is expected to enhance the overall accuracy of the study.

Changes in h_{alt} have a direct impact on the total thrust generated by the launch vehicle, mainly because atmospheric pressure (P_{atm}) varies in h_{alt}. To ensure precision in the results, a P correction is applied by utilizing the vacuum thrust (T_{vac}) data for each stage, which is available from the vehicle's user guide [36].

The actual thrust magnitude (T_{thrust}) concerning h_{alt} is expressed in Equation 10 [33]. This equation is instrumental in determining how thrust varies with changing h_{alt}.

$$T_{thrust} = T_{vac} - p_3A_2 \tag{10}$$

Furthermore, the amount of propellant necessary for mission manoeuvres is easily calculated using the Tsiolkovsky rocket equation. This calculation is succinctly presented in Equation 11 [33].

In Equation 11, m_p is the propellant mass consumed to produce the needed v, and ΔV is the v increase of the vehicle and mi is the initial vehicle mass.

$$m_p = m_i \left[1 - \exp\left(-\frac{\Delta V}{g_0 I_{sp}}\right)\right] \quad (11)$$

Table 2. Minotaur I Launch vehicle characteristics [35].

	Stage 1 MM 55A1	Stage 2 MM SR19	Stage 3 Orion 50XL	Stage 4 Orion 38
Dimensions				
Length (m)	7.49	4.12	3.07	1.34
Diameter (m)	1.67	1.33	1.28	0.97
Mass (each)				
Propellant mass (kg)	20,785	6,237	3,645	770,2
Gross Mass (kg)	23,077	7,032	4,036	872,3
Structure				
Type			Monocoque	Monocoque
Case Material	D6AC Steel	6Al-4V Titanium	Graphite Epoxy	Graphite Epoxy
Propulsion				
Propellant	Solid TP-H1011	Solid ANB-3066	HTPB	HTPB
Thrust (kN) (Vacuum)	792	267.7	194.4	36.9
Isp (sec) (Vacuum)	262	288	289	287
Control-Pitch, Yaw	TVC ±8o	LITVC	EMA ±3 o	EMA ±3 o
Roll	TVC ±8 o	Warm gas RCS	Nitrogen cold gas RCS	Nitrogen cold gas RCS
Events				
Nominal Burn Time (sec)	61.3	66	71	66.8
Stage Shutdown	Burn to depletion	Burn to depletion	Burn to depletion	B-urn to depletion
Stage Separation			Spring ejection	Spring ejection

2.4. Structural model

The vehicle's structure serves as both a mechanical interface connecting the launch vehicle stages and the primary structural support for all subsystems. As a result, it's crucial to determine the most optimal structural configuration for the vehicle to meet mission requirements.

The modelling of the vehicle is carried out using CATIA V15R19 product design software. Given that the materials for each stage are known, the volumes of the structural components can be determined. Additionally, propellant volumes and heights are calculated based on the propellant density and the volume of the structural parts. This comprehensive approach allows for precise design and configuration of the vehicle's structure to meet the specific mission requirements.

2.5. Aerodynamics model

During the flight of launch vehicles, the three components of aerodynamic forces and moments acting on the vehicle are influenced by a combination of factors, including the vehicle's configuration, environmental properties, and its attitude relative to the free stream velocity [37]. Specifically, this study considers three aerodynamic forces: drag, lift, and side force, as well as three aerodynamic moments: rolling, pitching, and yawing moment, which all act on the launch vehicles.

The aerodynamic coefficients, which play a significant role in these forces and moments, depend on various parameters. However, for this study, they are modelled to be dependent on three primary parameters: α, β, and M. The angle of attack (α) and sideslip angle (β) are considered within the range of -20 to 20 degrees, while the M spans from 0 to 50. These parameters are central to the modelling of aerodynamic behaviour in the study.

In the early stages of aircraft design, engineers use the DATCOM semi-empirical aerodynamic prediction tool to obtain crucial aerodynamic characteristics. This tool combines theoretical methods with empirical data from wind tunnel tests and flight experiments, providing a relatively quick and accurate estimation of aerodynamic properties [38]. Consequently, parameters like mesh structure and flow domain, common in Computational Fluid Dynamics (CFD) solutions, cannot be addressed. While more detailed aerodynamic coefficient predictions can be achieved with CFD in later design stages, this study focused on the early design phases. The launch vehicle, experiencing intense aerodynamic effects in a short time, prompted the use of the DATCOM tool for a swift and efficient solution.

For this study, the aerodynamic coefficients are derived using DATCOM Revision 2011, employing the example configuration of the Minotaur-I launch vehicle, as depicted in Figure 1. DATCOM is a widely utilized semi-empirical aerodynamic prediction tool, capable of projecting aerodynamic forces, moment coefficients, and stability derivatives as functions of the α and M [38].

The process involves inputting the vehicle's configuration into DATCOM, and then the code is executed multiple times to obtain coefficients for varying β values. Furthermore, the aerodynamic computations for the launch vehicle encompass the incorporation of stability derivatives of these coefficients.

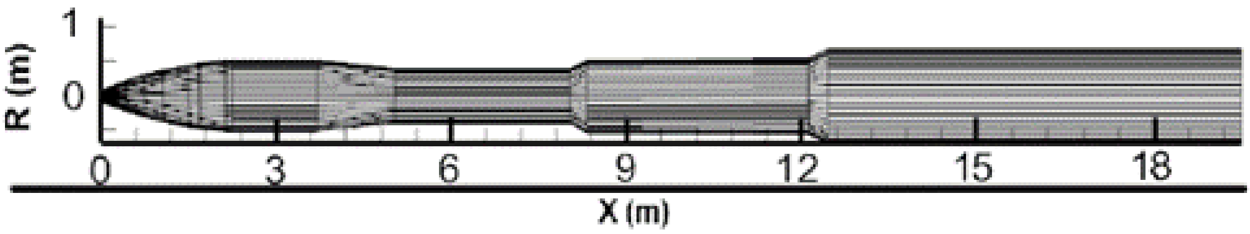

Figure 1. Minotaur-I vehicle configuration.

3. Reference mission and verification

The Minotaur-I launch vehicle is designed to transport payloads into both Low Earth Orbit (LEO) and Sun-Synchronous Orbit (SSO). To facilitate the sensitivity analysis, it's essential to validate the developed tool. For this purpose, a specific mission is selected from the launch vehicle's user guide [36]. In this mission, the vehicle is launched from Vandenberg Air Force Base Launch Platform, situated at a longitude of 120° 37' 56.57" W, a latitude of 34° 34' 34.86" N, and a h_{alt}=117 meters above sea level. The payload for this mission weights 302 kg, and the objective is to place it in a circular SSO with an inclination (i)=98°.3°, at a h_{alt}=741.3 km, and a **v**=7482.2 m/s [36]. A SSO is a nearly polar orbit around a planet. In this orbit, a satellite passes over any given point on the planet's surface at the same local mean solar time. On the other hand, the LEO region refers to the area of space below a h_{alt}=2,000 km, which is approximately one-third of Earth's radius. It is selected because SSO is a special type of LEO, and the experimental data used in the study are accessible for open access. The proposed study can be applied to all LEO missions that do not require agile manoeuvres of the launch vehicle for placing the satellite into orbit.

Simulation outputs for the reference mission were obtained from the developed tool. To validate the tool, the efficiency of using the v and h_{alt} values of nine reference points extracted from the user's guide's reference case, provided by the manufacturer, as verification data, is evident when comparing the results obtained. The comparison of h_{alt} reference data and the results obtained from the developed tool is shown in Figure 2, while the v comparison is illustrated in Figure 3. Different colours and line styles are used for each stage of the launch vehicle in the figures, while "x" markers are employed for reference data.

Additionally, to accurately position the payload into its target orbit, it's crucial to achieve a γ of approximately zero degrees. The flight path angle (γ) is calculated as the difference between pitch angle (θ) and α, as expressed in Equation 12.

$$\gamma = \theta - \alpha \tag{12}$$

The result of the tool for γ is given in Figure 4. When examining the figures, it is observed that the marked reference data aligns with the results of the developed tool for h_{alt} and v. At the final stage, particularly when reaching stage 4, simulation results should meet the target parameters. The developed tool has calculated the final values for γ to be approximately 0.015°, h_{alt} to be 741.5 km, and v to be 7496 m/s. These values closely align with those specified in the vehicle's user guide.

Figure 2 illustrates that as the simulation progresses, altitude increases, reaching the targeted orbit altitude, and drop altitudes for each stage are observed. In Figure 3, it is evident that fuel consumption increases the velocity for each stage, followed by a gradual decrease after the end of combustion until reaching the targeted speed. In Figure 4, the launch vehicle initially rises vertically upon liftoff, undergoes a gravity turn maneuver, and approaches a flight path angle near zero when reaching the targeted orbit altitude. Points marked with x for γ, h_{alt}, and **v** parameters have error rates calculated concerning reference values, revealing a maximum difference of 1.7% between simulation results and reference points for all three parameters. Due to the significantly low maximum difference, it is evaluated that the developed tool exhibits high accuracy and can be utilized in precision analysis. Since there is no reference value for the flight path angle, its proximity to zero upon reaching the targeted orbit is crucial. Table 3 presents a comparison of Minotaur-I launch vehicle simulation results and experimental results, including error values for altitude and velocity.

The injection accuracy, as expected [36], is smaller than the resolution for accuracy, with a margin of ± 55.6 km for mean h_{alt} and ±0°.2 for i. These slight deviations can be attributed to numerous unknown parameters involved in the modelling process, including environmental perturbations and aerodynamic inconsistencies.

For instance, variations may arise from differences in aerodynamic coefficient inputs, such as the α and β. Other crucial factors in the aerodynamic model include the choice of atmosphere model and M.

It is important to emphasize that the accuracy of the results depends on faithfully implementing the vehicle's configuration and properties. Therefore, this tool proves valuable for sensitivity analysis due to its precision, reliability, and efficiency. Furthermore, it offers the advantage of easier user-friendly improvements compared to commercial software.

Table 3. Comparison of Minotaur-I launch vehicle simulation results and experimental results.

Parameter	Simulation result	Experimental results	% Error
Altitude (km)	741.5	741.3	0.027
Velocity (m/s)	7496	7482.2	0.184

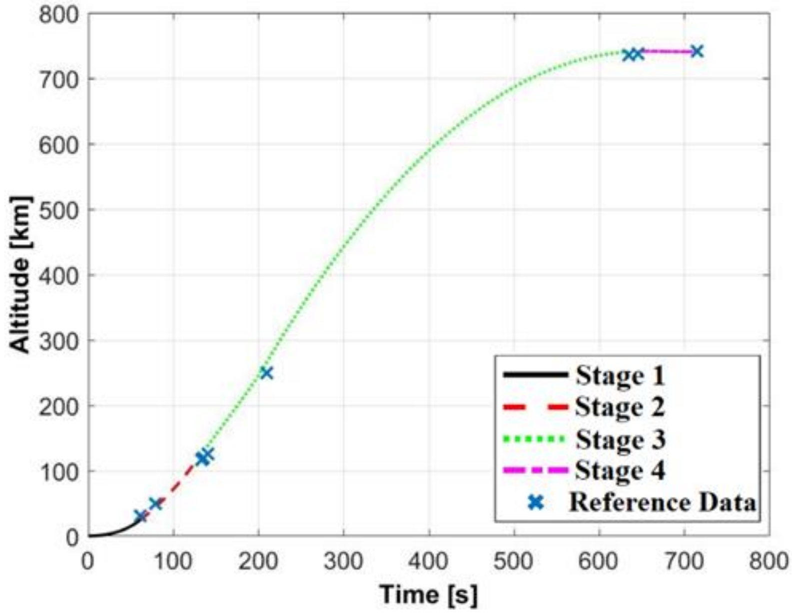

Figure 2. Altitude comparison of Minotaur-I launch vehicle for reference case.

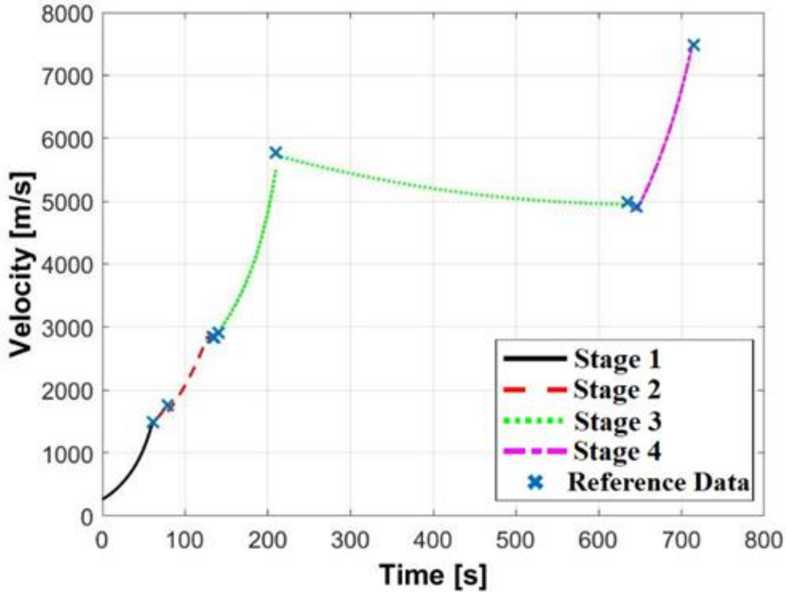

Figure 3. Velocity comparison of Minotaur-I launch vehicle for reference case.

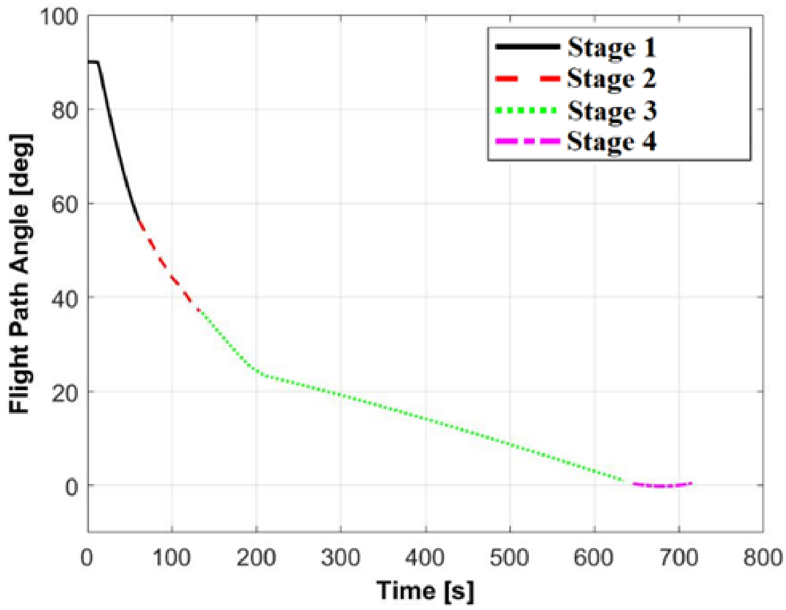

Figure 4. Minotaur-I flight path angle results with respect to time for reference case.

4. Sensitivity analysis

A sensitivity analysis was conducted for the Minotaur-I launch vehicle using the vehicle's implemented subsystem models. The vehicle's trajectory and performance are influenced by numerous design and event parameters. To assess the impact on the mission, the analysis considered factors such as the gross lift-off weight, I_{sp} of each stage, pitch-over manoeuvre starts time, ignition time of upper stages, and pitch-over manoeuvre angle.

Although changes in these parameters affect the entire set of state variables, the results are presented in h_{alt} relative to the variation parameter graph. h_{alt} is the preferred parameter for illustrating such variations and is most comprehensible to readers. The parameters and their variations used in the sensitivity analysis are summarized in Table 4.

Table 4. The summary of sensitivity parameters.

Symbol	Parameters	Variation
x_1	GLOW	(-100) - (50) kg
x_2	I_{sp_1}	(-4) % - (4) %
x_3	I_{sp_2}	(-4) % - (4) %
x_4	I_{sp_3}	(-4) % - (4) %
x_5	I_{sp_4}	(-4) % - (4) %
x_6	pitch-over final time	(-10) - (10) s
x_7	pitch-over start time	(-10) - (10) s
x_8	stage 2 ignition	(-10) - (10) s
x_9	stage 3 ignition	(-10) - (10) s
x_{10}	stage 4 ignition	(-10) - (10) s
x_{11}	TVC angle	(-1)-(1) deg

The Gross Lift-Off Weight (GLOW) is a crucial measure encompassing the total weight of the launch vehicle at the lift-off stage, including the main rocket structure, propellant, payload, and boosters. This parameter holds significant importance in trajectory planning and launcher design. The Minotaur-I launch vehicle, for example, weights approximately 32 tonnes [36].

Another key parameter under scrutiny is the specific impulse at vacuum, denoted as I_{sp}. It is examined with variations of ±8% from its actual value for each stage individually. Alongside design variables, the control parameters for various events play a critical role in determining the vehicle's trajectory.

The launch vehicle initiates its ascent vertically from the Earth's surface and must perform a pitch-over manoeuvre to achieve the target orbit with the required γ. Therefore, precision in manoeuvre timing is vital for mission success. The second control parameter involves the ignition time of the upper stages. These stages commence their burn once the lower stages separate and reach the necessary h_{alt} as dictated by the mission. Failure to ignite at the precise moment could lead to the payload missing the target orbit.

Furthermore, the Thrust Vector Control (TVC) angle is employed following the initial vertical ascent to initiate the gravity turn manoeuvre, which is essential for achieving the desired γ. Failing to maintain the correct angle could result in the payload not reaching the intended orbit. The results of these sensitivity parameters are depicted in Figure 5.

The sensitivity analysis encompasses various design parameters, including the GLOW and the I_{sp} of each stage, as well as event-related parameters like ignition times, pitch-over manoeuvre initiation times, and manoeuvre angles.

It's seen that any deviations in mass can lead to mission failure, but a control mechanism can be employed to achieve the target parameter. The I_{sp} value of the first stage holds greater significance due to its substantial influence on the trajectory. As we progress from stage 1 to stage 4, the number of values within the accuracy limits increases because the vehicle's mass generally decreases, and the final stage is responsible for orbit injection.

The timing of the initiation has a vital impact on the launch vehicle's flight path, particularly when the vehicle maintains motion with a large γ, resulting in a h_{alt} higher than nominal. For example, a deviation of about 10 seconds, whether early or delayed, in the manoeuvre initiation, is intolerable due to accuracy constraints. However, a 2-second deviation remains within acceptable limits.

The ignition times of the stages significantly affect the trajectory, with the second stage ignition time having the most pronounced impact. The dependency decreases as we move from stage 1 to stage 4. To illustrate, a 5-second delay in the ignition of the second stage is unacceptable, while it may be allowable for the fourth stage.

In this mission simulation, the nominal value for the manoeuvre angle is 4.75 degrees. Results indicate that even a 0.5-degree deviation from the actual value can lead to significant changes in apogee h_{alt}. The most substantial deviation is observed in the first stage and the pitch-over manoeuvre angle, as per the sensitivity analysis results. Small variations in these parameters can result in critical consequences, such as accidents resulting in fatalities or mission failure. Consequently, achieving a higher level of modelling accuracy is imperative for mission success.

The errors in trajectory can stem from various sources, including motor performance, uncertainties in the guidance algorithm, and navigation issues. In many instances, deviations in injection h_{alt} can be accommodated within the Minotaur-I launch vehicle's specified accuracy limits. However, most cases analysed in the sensitivity study exceed these limits and cannot be dismissed as negligible.

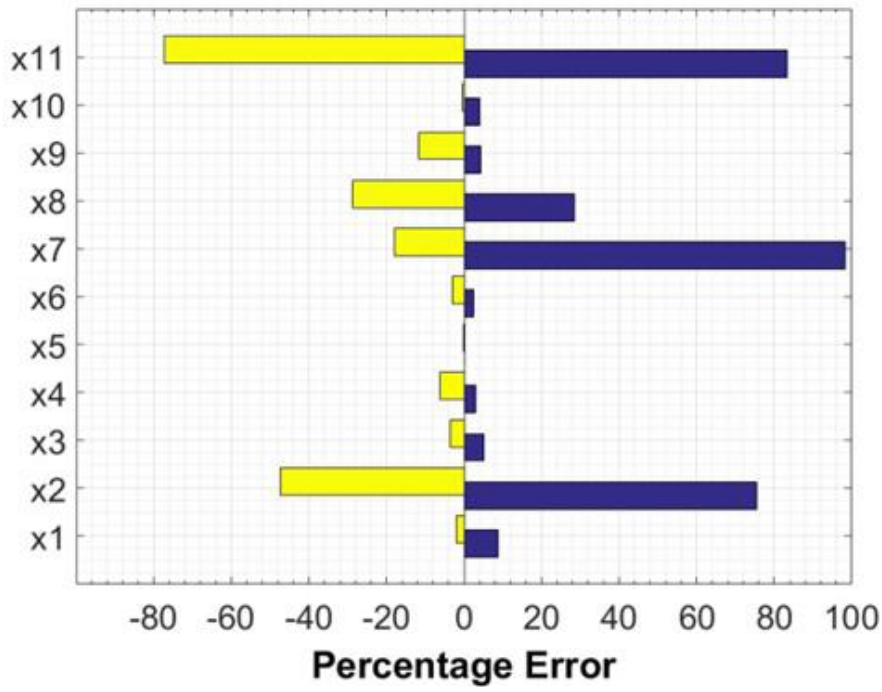

Figure 5. The results of sensitivity analysis.

Conversely, certain scenarios, such as those involving the fourth stage, could have noticeable implications. This is particularly relevant because the final stage is typically employed to achieve specific payload orbit parameters rather than gaining h_{alt}.

Addressing these potential errors necessitates a meticulous approach, involving careful design, pre-flight analysis, Monte-Carlo simulations, and control systems aligned with the predetermined trajectory to mitigate and manage issues effectively.

5. Discussion and Conclusion

During this study, a sensitivity analysis tool was developed, which includes a 6DOF trajectory model for aerospace vehicles. This tool can predict the trajectories of both currently operational and under-development launch vehicles designed for LEO with a high degree of accuracy within a short time frame.

ASTOS emerges as a prominent aerospace modelling tool, excelling in orbit and trajectory analysis, which proves indispensable for meticulous space mission planning and optimization. Its advanced spacecraft dynamics modelling capabilities, accurately representing propulsion systems and mission profiles, position ASTOS as the preferred choice for intricate space missions. Notables are ASTOS optimization features, allowing users to fine-tune trajectories based on diverse constraints. However, challenges include a steeper learning curve and a specialization in space mission analysis, potentially limiting its adaptability for broader aerospace applications like aircraft flight dynamics [39]. In contrast, the STK distinguishes itself with versatility, supporting multi-domain simulation across space missions, aircraft, unmanned aerial vehicles (UAVs), missiles, and ground systems. Yet, it may not match the detailed spacecraft dynamics modelling of specialized tools like ASTOS, and its optimization capabilities may lack the specificity required for intricate trajectory planning [40]. On the other hand, NASA and ASTOS programs are high-cost and difficult or inaccessible programs. In the developed tool, there is modelling and simulation capability for satellite launch vehicles that require manoeuvres such as gravity turn and capability of TVC, compared to other programs. In addition, its advantages compared to other programs include the ability to provide the user with the option to choose a method or integrate their algorithm according to the user's needs for optimization or integration solutions. Furthermore, it enables sensitivity analysis by incorporating comprehensive models as needed by the user.

The developed tool not only provides rapid solutions but also opens possibilities for using it during the development phase of launch vehicles to optimize their trajectories according to specific requirements. To validate the tool, it was compared with reference mission data obtained from the user's guide for the Minotaur-I launch vehicle.

This analysis encompasses a wide range of design and event parameters, utilizing the properties and subsystems of the Minotaur-I launch vehicle. The translational and rotational equations of motion are based on Newtonian principles, incorporating Earth's rotation and ellipsoidal shape. Quaternion updates are employed for attitude orientation during rotational motion, and a fourth-order Runge-Kutta integration method is used for system dynamics calculations. To simulate the environment, gravity, and atmospheric models are utilized. The EGM2008 gravity model is chosen for its precision, and the US Standard Atmosphere Model 1976, considering h_{alt}, is used due to its simplicity and lack of seasonal effects.

For the reference mission verification, the Minotaur-I thrust profile was determined, accounting for factors such as P corrections and structural property changes, including the J, m, and centre of gravity. Structural properties were obtained using CATIA V15R19 product design software, while aerodynamic coefficients were determined using DATCOM Revision 2011 for all stages. The analysis does not assume any simplifications and considers all three axes of aerodynamic forces and moments acting on the vehicle. When the tool results and reference data are compared, it has been observed that the tool results align with the reference Minotaur-I mission data.

After verifying the developed tool by comparing it to reference mission data, sensitivity analysis has been carried out using the verified tool. The results of the sensitivity analysis highlight that even minor variations in these parameters can lead to significant differences in insertion h_{alt} compared to the nominal value. While GLOW changes can be tolerated for slight variations, changes in pitch-over manoeuvre angles are less forgiving. Like GLOW, the acceptability of errors in I_{sp} changes for the second and third stages varies, with errors being more negligible for the fourth stage. However, variations in the first stage parameters are generally irrecoverable.

Another significant finding is that changes in pitch-over manoeuvre initiation times can be either acceptable or unacceptable, depending on the rate of change. These errors may result from a range of factors, including motor performance, uncertainties in guidance algorithms, and navigation problems, and their tolerance is determined based on vehicle accuracy limits and control system properties.

In summary, the study has developed a sensitivity analysis tool for aerospace vehicles, demonstrating that accurate modelling of subsystems can yield real trajectories and provide insights into vehicle performance and parameter dependencies. Precise modelling is of utmost importance for mission success. During the design phase, the validated model streamlines the modelling of launch vehicle trajectories without the requirement for high-cost or hard-to-access programs, facilitating the swift generation of detailed results. Furthermore, the model, known for its user-friendly interface, innovation, and complete user control, ensures adaptability to specific needs. Within this framework, the model integrates a sensitivity analysis tool, allowing for the examination of various design and event variables and their effects on-orbit target parameters. This arrangement facilitates an investigation into the impact of user-desired parameters.

6. Future works

The possible further studies are listed as:

- Expanding the simulation and analysis beyond solid propellants to include a sloshing model for liquid propellants, which can significantly impact the system dynamics of launch vehicles.
- Integration of a disturbance model into the environment model to account for atmospheric conditions.
- Implementation of Guidance, Navigation, and Control (GNC) algorithms to enhance the fidelity of simulations.

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Author contributions

Ukte Aksen: Conceptualization, Methodology, Visualization, Validation, Writing. **Alim Rüstem Aslan:** Conceptualization, Methodology, Writing-Reviewing and Editing. **Ümit Deniz Göker:** Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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Restoration manager: Adapting project delivery methods for the restoration of architectural heritage

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Abstract

The restoration of architectural heritage is a complex process and presents intricate and formidable challenges. The project delivery method plays a pivotal role for the success of the restoration process. There exists a diverse array of project delivery methods, each characterized by its distinct set of advantages and disadvantages. In the context of architectural heritage restoration, given its distinct characteristics, these advantages and disadvantages encompass a wide spectrum. Current project delivery methods, while effective for certain contexts, often fall short in addressing the unique requisites of restoration projects. Acknowledging this inadequacy, this article undertakes a research that includes a literature review that not only examines prevailing project delivery methods but also articulates the need for a tailored framework within the restoration field. This article is produced from the doctoral thesis titled "Development of a Sustainable Integrated Management System for the Conservation of Architectural Heritage", which is in the process of preparation. In the light of the results of the survey which is conducted within the scope of the first author's doctoral study in order to examine the project delivery approach preferred among the participants that are working in the field of the conservation of architectural heritage, a project delivery method called "Restoration Manager", which has been precisely prepared to meet the requirements inherent in restoration initiatives, is presented. This comprehensive project delivery method seeks to fill the void by addressing the distinct needs and challenges encountered in restoration projects. The essence of this work is to create an appropriate project delivery system that adapts to the nuances of the restoration works, and through this project delivery framework, the restoration processes and outcomes will successfully be completed.

1. Introduction

The construction industry is a complex and challenging field that requires careful planning and execution to ensure successful project delivery [1]. Project delivery methods (PDMs) define the roles and responsibilities of the parties involved in a project and also form an execution framework in terms of the sequencing of design, procurement, and construction [2]. These PDMs may be expressed as the methods delineating the interactions and obligations among involved stakeholders while detailing the procedures for meeting their respective responsibilities. In construction, a project delivery method may be defined as “a process by which various stakeholders like building owners, occupants, architects, engineers, constructors work together to deliver a building; it is generally distinguished by two key characteristics such as the contractual relationships between project stakeholders and their engagement in the project.” [3].

Project delivery methods are an essential aspect of construction works that can significantly impact the success of a project. Studies by Hong et al. [4]; Ojiako et al. [5]; and Oyetunji and Anderson [2], suggest that selecting an appropriate project delivery method improves project performance and the reasonable choice of a proper project delivery method is one of the key links to project success.

The construction industry is dynamic and constantly evolving, and project managers face the challenge of selecting the most appropriate project delivery method (PDM) for successful project completion. The choice of PDM significantly impacts key performance indicators such as cost, schedule, quality, project execution, and safety [6]. The appropriate project delivery method (PDM) is seen as a vital factor to ensure good performance of construction project by Noor et al. [7]. He also states that numerous researches have been conducted to develop a structured and descriptive decision-making framework for selecting an appropriate PDM for decades.

Kubba [8] states that there is a wide range of construction project delivery systems. Similarly, Khan indicates there are many project delivery methods to match the variety of projects in today's competitive construction market, but at the same time, reminds that tailoring your choice to the individual project's specifications and circumstances can help ensure success [9].

The literature reviews unveil that various types of project delivery methods (PDMs) adopted within the construction industry can be categorized based on the fundamental concept of PDM. These categories include segmented, integrated, packaged, and collaborative approaches [10-11]. The segmented delivery approach, commonly known as Design-Bid-Build (DBB) or the traditional delivery method, stands out as the most widely used PDM for construction projects [12-13]. In contrast, the global construction industry occasionally employs alternative project delivery methods such as Design-Build (DB), construction management at risk (CMR), construction management agency (CMA), construction management multiprime (CMMP), Public-Private Partnership (PPP), and Integrated Project Delivery (IPD) [14-15].

The characteristics and functions of these PDMs are outlined based on the project's organizational structure in terms of roles and relationships, contractual framework defining assignments and responsibilities, and operational systems including working methods and strategies. It's essential to note that each PDM comes with distinct success factors, strengths, and weaknesses, significantly influenced by the specific characteristics of the project and the overall nature of the construction industry [16].

The distinction between construction works and the restoration of architectural heritage transcends the mere dichotomy of building a new versus preserving what already exists [17]. While both endeavours fall within the realm of the built environment, their underlying principles, goals, and processes diverge significantly. One of the most prominent disparities rests in the fundamental objectives each pursuit seeks to achieve. Construction work revolves around the genesis of novel edifices, manifesting as the creation of skyscrapers, residential complexes, bridges, and other modern architectural marvels. In these projects, innovation, functionality, and contemporary design often take precedence. Conversely, the restoration of architectural heritage takes on a profoundly different mission. This intricate process embarks on a journey to safeguard historical, cultural, and architectural legacies, ensuring they endure for generations to come. A prime illustration of this contrast emerges when considering the restoration of an architectural heritage; its timeworn façade, intricate detailing, and historical significance demand meticulous efforts to revive its original splendour, often requiring the use of traditional construction methods and the expertise of skilled artisans. The restoration of architectural heritage encompasses a broad spectrum, ranging from locally significant structures to those globally recognized and listed as World Heritage. Adhering to the principles outlined in the Venice Charter, each cultural property necessitates evaluation within its unique context. It is imperative to recognize that even regional restoration initiatives, when considered part of a larger cultural narrative, should align with international conservation conventions, and adhere to ICOMOS principles under the auspices of UNESCO.

Thus, construction and restoration, owing to their intrinsic dissimilarities, necessitate distinct approaches when it comes to project delivery methods. As Kubba emphasizes [18] that since each construction project is different, the project delivery system should be tailored to the individual requirements of that unique project, and the divergence in operational requisites of construction and restoration also mandates a tailored approach of project delivery method for project execution.

In this article, the aim is comprehensively exploring project delivery methods, examining their mechanics, advantages, and limitations. Among these methodologies, the traditional Design-Bid-Build (DBB) framework [19], Design-Build (DB) which integrates design and construction to overcome some of the hurdles [20] and one of the alternative delivery methods that is rapidly growing in popularity Construction Manager at Risk (CMAR) [21] will be focused. Additionally, as traditional project delivery systems used in the general construction sectors have many constraints [22], Integrated Project Delivery (IPD) which is an integrated delivery approach to the planning, design, and construction of civil engineering projects [23] and "an approach to enhance project implementation" [24], along with other innovative approaches.

Although Jackson [25] identifies three primary project delivery methods, design-bid-build, construction management, and design-build, which significantly differ in five key aspects namely the number of contracts the owner executes, the roles and relationships of these parties, the project stage at which the contractor becomes engaged, the potential for overlapping design and construction, and the entity responsible for ensuring the adequacy of plans and specifications, the study not only focused on those three project delivery methods, but also integrated project delivery (IPD) and some other methods such as CM Multi-Prime (CMMP) [26] and an innovative procurement technique job order contracting (JOC) [27] were also taken into consideration.

The core of this research revolves around the introduction of an approach tailored for restoration endeavours and adapted from the current project delivery methods, named as the Restoration manager delivery method. Recognizing the intricate and complex nuances in this realm, this method seeks to address the challenges and necessities associated with the restoration of architectural heritage.

The research commences with a review of the existing literature on project delivery methods. It subsequently delves into an evaluation of the inadequacies and limitations inherent in current delivery methods in the context of restoration projects. Following an analysis of survey results related to this topic, the study takes an approach that involves the adaptation of project delivery methods specifically tailored to the requirements of restoration projects.

The principal objective of this research is to enhance the effectiveness of restoration processes by addressing the limitations associated with traditional project delivery approaches in the context of architectural heritage restoration, ultimately improving project success rates. By establishing a tailored project delivery method, the study aims to augment the effectiveness of restoration processes, thereby contributing to the realization of successful outcomes. A successful restoration is a complex undertaking that involves a meticulous consideration of various criteria, i.e. historical authenticity is paramount, preservation of cultural value ensures that the restored heritage site not only maintains but enhances its cultural significance. Structural integrity is also fundamental, guaranteeing stability and safety for the structure's prolonged existence. Thorough documentation and research inform decision-making, while community engagement fosters a sense of ownership and aligns the project with community values. Sustainability is integral, promoting long-term economic, social and ecological balance. And compliance with standards ensures the restoration's quality and adherence to conservation guidelines. By meticulously addressing these criteria, a successful restoration goes beyond physical repairs, contributing to the holistic and sustainable conservation of cultural heritage.

2. Method

A two-phase approach was employed to conduct this research. The first phase encompassed a comprehensive literature review, while the second phase involved data collection through a questionnaire survey targeting professionals and researchers, followed by data analysis.

In the initial phase, the literature review focused on identifying relevant studies related to project delivery methods. The review entailed a thorough search of online databases, including Emerald Insight, Elsevier, ScienceDirect, EBSCO, Scopus, JStor, Taylor & Francis, Proquest, Wiley Online Library, TRDizin, and Semantic Scholar. The search was guided by specific keywords, such as project delivery methods, PDM, project delivery systems, construction, restoration, architectural heritage, built environment, Design-Bid-Build (DBB), Design-Build (DB), construction management, CM at risk (CMAR), CM multi-prime (CMMP), integrated project delivery (IPD), and job offer contracting (JOC). The scope of the search was limited to articles published from 1990 to the search date, and the findings indicated the critical significance of seven project delivery methods in successfully implementing organizational change.

The second phase involved data collection through a survey distributed to professionals and researchers working in the restoration of architectural heritage field. The survey was conducted as part of the doctoral research, titled "Development of a Sustainable Integrated Management System for the Conservation of Architectural Heritage," at Hacı Bayram Veli University. Its primary aim was to gain insight into the management landscape within the field of architectural heritage restoration. Respondents were selected from various backgrounds, including academics, government authorities, professionals from both the public and private sectors, and graduates of restoration programs. The survey was administered online via surveyhero.com, with the goal of broadening participation. The survey targeted individuals involved in various aspects of architectural heritage restoration, comprise a sample of 103 participants.

Employing a self-administered online survey as the framework, the questionnaire included five sections: introduction, explanation of survey content, participant information, questions, and conclusion. The survey, administered through a self-administered online link sent via email, was designed to be completed within 5 to 15 minutes. Launched on September 10, 2019, and accessible for three months. The survey employed in this study was structured into five sections, including an introduction, an explanation of the survey's content, participant information, a section containing questions, and a conclusion. The questions section comprised a total of 17 questions under five separate section headings, with some questions offering an "other" option to facilitate diverse responses. The survey underwent pretesting with 15 experts before launching. Feedback obtained during pretesting have guided final revisions under the supervision of the advisor. In summary, the survey framework, encompassing elements such as purpose, sample, structure, mode, time period, average time and pretesting, provides a foundational guide for comprehending the preferences and situation in the architectural heritage restoration field.

Since the survey was designed as part of a doctoral study titled "Development of a Sustainable Integrated Management System for the Conservation of Architectural Heritage," only the relatable survey data for this research has been incorporated into this study. Alongside the general information about the survey participants, the preferences for project delivery methods were assessed by posing the question, "In your opinion, which project delivery method is most suitable for the restoration of architectural heritage?". To ensure a common understanding among all respondents, the question was accompanied by concise explanations of the given options.

To ensure content validity, the survey questions were carefully constructed to avoid ambiguity, and the instrument underwent a pilot pretesting study to establish validity and reliability. Senior academics researching in the restoration of architectural heritage provided valuable feedback to enhance the instrument's face validity, relevance, and clarity. The data collection instrument deployed for the pilot study was administered prior to the main study to confirm the reliability of the data.

In the data analysis phase, responses from the survey were analysed using descriptive statistics in the form of percentages and tables. The analyses were conducted using Microsoft Excel as Microsoft Excel has been considered as one of the important tools for data analysis [28], thus it was employed for data processing in this study. Tables obtained from these data were used to enhance data evaluation.

This study adopted a quantitative approach, specifically a descriptive survey research design which aims to answer research questions about the current state of affairs, identify factors and relationships among them [29]. The design was chosen to collect information from respondents regarding their preferences for project delivery methods. The research falls into the categories of exploratory and descriptive research, with a primary focus on formulating a project delivery method tailored for restoration work practices, aligning it more appropriately with the exploratory study category [30-32]. Conformity with the relevant regulations for the ethical aspects of the research and data collection instruments used in the study is approved by Hacı Bayram Veli University Ethics Committee.

2.1. Literature review

Over the years, various project delivery methods have been developed to meet the unique needs of different construction projects. As the construction industry is constantly advancing, the project managers face the challenge of selecting the most appropriate project delivery method (PDM) for successful project completion. Although the progression of project delivery methods in the construction industry has been relatively slow compared to the industry's overall development [6], different project delivery methods have emerged over the years, each with its own set of characteristics with advantages and disadvantages.

The traditional Design-Bid-Build (DBB) method, where the design and construction phases are separate, has been widely used in the past, however, this method has limitations in terms of speed, price certainty, flexibility, and risk allocation [33]. As a result, alternative project delivery methods (APDM) such as Design-Build (DB), Construction Management at Risk (CMR) and Integrated Project Delivery (IPD) have gained popularity [34]. The term Alternative Project Delivery Methods (APDM) encompasses non-traditional construction contracting approaches. These approaches involve the contractor's involvement in design either as an advisor or fully responsible for it. Selection of the contractor depends on qualifications or best value which is a procurement strategy that considers a combination of factors, including cost, qualifications, expertise, and reputation, to select a contractor or service provider that offers the most advantageous overall value for a project. The range of APDMs comprises methods like Design-Build (DB), Construction Manager at Risk (CMAR), Integrated Project Delivery (IPD), and many others [21,22].

Design-Bid-Build (DBB) is the traditional project delivery method used in the construction industry. This method involves three separate phases: design, bidding, and construction [6]. In the design phase, the owner hires an architect or engineer to design the project. Once the design is complete, the owner puts the project out to bid, and contractors submit their bids. In the bidding phase, the owner solicits bids from contractors to construct the project. Finally, in the construction phase, the contractor with the lowest bid is awarded the contract and construction phase begins [35]. Design-Bid-Build involves a sequential process where the owner contracts with a designer/architect to develop the project's design, followed by a bidding process to select a contractor for construction [33]. DBB has been the dominant delivery method for many years, but it has certain limitations, such as limited collaboration and integration among project stakeholders [36].

The second project delivery method that is examined is Design-Build (DB). The DB method involves the integration of design and construction under a single contract, with a single entity responsible for both aspects. This method offers several advantages, including reduced project delivery time, cost savings, increased constructability, and innovation [33]. However, it may not be suitable for all types of construction projects, and careful consideration of key factors such as complexity, risk allocation, and quality standards are necessary [34]. DB promotes collaboration and integration among project stakeholders, leading to potential benefits such as improved project performance and reduced disputes [36]. Design-Build is a project delivery method that combines the design and construction phases into a single contract, and it can be summarized as a project delivery method that involves the owner hiring a single entity to design and construct the project [35].

Another PDM is Construction Management at Risk (CMAR) method. CMAR is a delivery method in which the construction manager is involved during the design phase of the project, assuming the responsibilities of both a project coordinator and a general contractor. This method emphasizes collaboration, trust, commitment, and co-learning. CMAR offers benefits such as early cost estimation, value engineering, and improved constructability [6]. However, it requires effective coordination and communication among project stakeholders to ensure successful project delivery. Construction Manager at Risk (CM at Risk) is a project delivery method that involves the owner hiring a construction manager during the design phase to provide input on constructability, cost, and schedule. The construction manager then provides a guaranteed maximum price (GMP) for the project and assumes the risk for delivering the project within that price [35]. This method is often used for large, complex projects, where the owner wants to reduce the risk of delays and cost overruns. Construction Management at Risk is also used for projects where the owner wants to have more control over the construction process [37]. The CM is responsible for managing the construction process, including scheduling, budgeting, and subcontracting. The CM also provides pre-construction services, such as constructability reviews, value engineering, and cost estimating. The CMAR method allows for early collaboration between the owner, designer, and contractor, which can result in a more efficient and cost-effective project delivery [38,39].

Integrated Project Delivery (IPD) is the last project delivery method examined in this study. Integrated Project Delivery (IPD) is a collaborative approach to construction project management that has gained popularity in recent years [40]. It is a method of project delivery that involves the owner, architect, contractor, and other stakeholders working together from the beginning of the project to the end [41]. The goal of IPD is to create a more efficient and effective construction process that results in a better end-product [42]. Integrated Project Delivery is often used for complex projects, where the owner wants to reduce the risk of delays and cost overruns or to have more control over the construction process. In this method, the team works together to develop a project plan that meets the owner's needs and budget. The team members are incentivized to work together to achieve the project goals, and any savings are shared among the team members [43]. Integrated Project Delivery (IPD) emphasizes collaboration, shared risk and reward, and a focus on project outcomes rather than individual interests [44]. This method has been shown to improve project performance, reduce conflicts, and enhance project outcomes. However, its successful implementation requires a high level of trust, open communication, and a shared vision among project participants [45].

The project delivery method, referred to as Construction Management Agent (CMA), involves the selection of an architect or engineer for project design, while concurrently choosing a construction manager to serve as the client's representative, offering administrative and management services. While the CMA assists in the design phase, it does not retain subcontracts or offer bonding for the project's construction. The selection of a CMA is based on their qualifications and prior experience, particularly their credentials and previous work as suggested by Gould [46].

Construction management multi-prime projects (CMMP), often referred to as multi-prime (MP) contracts, are characterized by the owner taking on the role of a general contractor. Under this contractual arrangement, the owner enters into contracts with each member of the design team and primary trade contractors, encompassing services ranging from general construction to earthwork, structural, mechanical, and electrical work. The owner assumes responsibility for the comprehensive management of both the project schedule and budget, as indicated by [26].

Job order contracting (JOC) represents an innovative procurement approach designed to enhance the efficiency of facility maintenance, repair, and minor construction activities. Its primary objective is to significantly reduce the time required for engineering and procurement by awarding a competitively bid, firm-fixed-price, indefinite-quantity, multitask contract to a single general contractor. This contract includes detailed task specifications. The utilization of a job order contract (JOC) eliminates the need for separate actions related to design, specification, and construction contracts. Pre-priced units of work are incorporated to streamline the process. The contracts are awarded through competitive procedures, and once awarded, the contractor receives individual task orders, also referred to as delivery orders, based on their continued high-performance levels [27].

Thus, the literature review highlights the importance of considering project-specific factors when selecting a project delivery method and provides an analysis of project delivery methods, highlighting their characteristics. Burjan mentions [47] that "there is more than one solution for almost every project", thus the adaptation of a project delivery method, which presents advantages compared to other existing project delivery approaches, may provide an enhanced solution for addressing restoration efforts concerning architectural heritage. Presently, the advantages and disadvantages of the project delivery methods need to be delineated to facilitate the determination of a more suitable approach for the restoration of architectural heritage.

Design-Bid-Build (DBB) is a traditional project delivery method where the owner contracts with separate entities for the design and construction phases of the project. The advantages of DBB include clear separation of responsibilities meaning the roles and responsibilities of each party are clearly defined. The architect/engineer is responsible for the design, and the contractor is responsible for construction. The competitive bidding for construction contracts and cost certainity is another advantage as the design is completed before bidding, the owner knows the project's cost upfront. DBB also have the ability to obtain multiple design options and as the design phase is separate from the construction phase, allowing for thorough design review and quality control [35,48].

However, DBB has some disadvantages, such as a lack of collaboration between the design and construction teams, potential delays due to the sequential nature of the process and longer project duration as the design phase must be completed before construction can begin, and limited flexibility for making changes during construction as changes during the construction phase can be costly and time-consuming because they require design modifications [35,49].

Design-Build (DB) is a project delivery method where the owner contracts with a single entity that is responsible for both the design and construction of the project. The advantages of DB include improved collaboration between the design and construction teams, faster project delivery, and the ability to make changes more easily during construction [49]. DB also allows for greater innovation and creativity in the design process [50]. DB also provides a single point of responsibility for the entire project, reducing the owner's administrative burden, time and cost savings as design and construction can overlap and risks are managed more effectively because the design-builder is responsible for managing all project risks [51]. However, DB may have some disadvantages, such as potential conflicts of interest between the design and construction teams, limited owner control over the design process, and the potential for cost overruns if changes are made during construction [48]. Also, there may be less owner control because the design-builder handles both design and construction, there may be a risk of design-builder to cut corners to reduce costs and limited competition because there may be fewer qualified firms that can bid for the project as the design and construction are bundled together.

Construction Management at Risk (CMAR) is a project delivery method where the owner contracts with a construction manager who is responsible for managing the project from design through construction. The advantages of CMAR include early involvement of the construction manager in the design process, improved coordination between the design and construction teams, and the ability to obtain cost and schedule guarantees from the construction manager [49]. CMAR also allows for greater flexibility in making changes during construction [52]. CMAR can also provide early cost input, cost input during the design phase, helping to keep the project within budget; better risk management as CMAR assumes the risk of construction at a guaranteed maximum price, protecting the owner and more quality control as it may provide constructability reviews during the design phase, improving the quality of the project [53]. However, it may have some disadvantages, such as potential conflicts of interest between the construction manager and subcontractors, potential delays if the construction manager is not involved early enough in the design process, cost uncertainty as the final cost is not known until the design is complete and the guaranteed maximum price is established. There will be also less competitive bidding because the selection of the CMAR is based on qualifications rather than low bid, which may result in higher costs. And lastly, there may be the potential for cost overruns if changes are made during construction [53-54].

As the Integrated Project Delivery (IPD) being a collaborative project delivery method where the owner, architect, and contractor work together as a team from the beginning of the project, the advantages of IPD include improved collaboration and communication between all project stakeholders, early involvement of the contractor in the design process, the efficiency on the use of resources, reducing waste and improving project performance and the ability to make informed decisions based on shared knowledge and expertise. IPD also allows for greater innovation and creativity in the design process and risks to be shared among all project participants, promoting a focus on project success rather than individual success [55-57]. However, IPD may have some disadvantages, such as potential conflicts of interest between project stakeholders, potential delays if the team does not work well together, and the need for a high level of trust and cooperation among all parties involved. IPD may also reflect disadvantages due to the complex contracts as IPD requires complex contracts that define the relationships and risk-sharing among all participants; a high level of trust and collaboration among all participants, which may be difficult to achieve and lastly, as IPD is a newer delivery method and is less proven than more traditional methods [57-58].

Job Order Contract (JOC) is a project delivery method that involves the use of pre-established unit prices for various construction tasks. It is often used for smaller projects or projects with a repetitive nature, such as maintenance and repair work. One of the main advantages of JOC is its flexibility and efficiency in handling multiple small-scale projects simultaneously [59]. JOC allows for quick project initiation and completion, as the unit prices and terms are already established, reducing the need for extensive negotiation and contract development. This method also promotes cost transparency and accountability, as the unit prices are predetermined and easily verifiable [59]. However, one of the disadvantages of JOC is the potential for cost overruns if the scope of work exceeds the estimated quantities or if unforeseen conditions arise during the project [59]. Additionally, JOC may not be suitable for complex or large-scale projects that require extensive coordination and management.

Construction Management Agent (CMA) is a project delivery method where a construction management firm acts as an agent on behalf of the owner. The construction manager provides expertise in project planning, coordination, and oversight, while the owner retains control over the design and construction process. One of the advantages of CMA is the early involvement of the construction manager, which allows for better coordination and integration of the project team [60]. The construction manager can provide valuable input during the design phase, helping to identify potential constructability issues and value engineering opportunities [60]. CMA also allows for greater flexibility in the selection of subcontractors and suppliers, as the owner has direct control over the procurement process [60]. However, one of the disadvantages of CMA is the potential for conflicts of interest, as the construction manager may have relationships with certain subcontractors or suppliers that could influence the selection process [60]. Additionally, CMA requires a high level of owner involvement and decision-making, which may not be suitable for all owners.

Construction Management Multi-Prime Projects (CMMP) is a project delivery method where the owner contracts directly with multiple prime contractors for different portions of the project. Each prime contractor is responsible for managing their own subcontractors and suppliers. CMMP allows for greater control and flexibility for the owner, as they have direct relationships with each prime contractor [61]. This method also promotes competition among the prime contractors, potentially leading to cost savings and improved quality [61]. CMMP can be particularly beneficial for complex projects that require specialized expertise, as the owner can select prime contractors based on their specific qualifications and experience [61]. However, one of the disadvantages of CMMP is the potential for coordination challenges and conflicts among the different prime contractors [61]. Effective communication and collaboration among the prime contractors are essential to ensure the successful completion of the project. Additionally, CMMP requires a high level of owner involvement and oversight to manage the multiple contracts and ensure that the project objectives are met [61].

In conclusion, each project delivery method has its own advantages and disadvantages. DBB provides clear separation of responsibilities but lacks collaboration, while DB allows for improved collaboration but may have conflicts of interest. CMAR offers early involvement of the construction manager but may have conflicts and potential delays. IPD promotes collaboration and innovation but requires a high level of trust and cooperation. JOC offers flexibility and efficiency for smaller projects but may not be suitable for complex or large-scale projects. CMA allows for early involvement of the construction manager and greater control over the procurement process but may have conflicts of interest and require high owner involvement. CMMP provides control and flexibility for the owner but requires effective coordination among multiple prime contractors and high owner oversight.

The selection of the most appropriate project delivery method should be based on the specific requirements and characteristics of the project. According to Mohd Noor et al. [8], the process of selecting a Project Delivery Method (PDM) typically entails the elimination of methods that are unrelated or unsuitable until a viable alternative delivery method remains. Nevertheless, as emphasized by Masterman [62], it is imperative to give due consideration to the principles of decision-making prior to evaluating and refining the framework for PDM selection.

2.2. Restoration manager project delivery method

The choice of a construction project's delivery system frequently relies on the project management team's past encounters. This pattern can result in a problematic cycle where recurring challenges like cost and schedule overruns persist across successive projects. From the perspective of Pöyhönen et al., there's a noticeable absence of comprehension about the development of a project delivery system to effectively address these recurring issues [63]. Within the realm of design and construction, property owners seek to recognize, manage, and alleviate project risks through the determination of timely and budget-conscious project delivery methods. The project delivery approach is an all-encompassing procedure involving designers, constructors, and diverse consultants who collectively offer design and construction services to bring forth a finished project for the proprietor [64].

Project delivery is a form of working relationship that defines roles and responsibilities [65]. According to American Institute of Architects, delivery refers to the method for assigning responsibility for providing a service. The main criteria for measuring the success of any project delivery methods are cost, quality, time, safety and how the project ultimately meets its intended purpose [66].

According to Migliaccio et. al. [64], project delivery method is a comprehensive process by which designers, constructors, and various consultants provide services for design and construction to deliver a complete project to the owner. Project delivery process issues include organisational and contractual arrangements, compensation for services, management of project, risk, application of appropriate technology, and information, systems, and management, and control of resources [67]. with the increasing complexity and evolution of the construction projects, project managers realized that there was a need for a structured mechanism or tool to assist them in choosing the most suitable delivery method for a specific construction project [68] and determining a project delivery method that matches the characteristics of a construction project is a critical step that affects the success or failure of a project [69].

The suitability of the project delivery method selected for a project greatly influences the efficiency with which the project is executed and thus constitutes a critical success factor [2]. While there is not a single perfect delivery method for every project [65], the attributes are listed as project delivery method; owner's commitment; project team procurement; contractual conditions and level of integration in the delivery process for project success [70].

Subsequent to the literature survey, a comprehensive review revealed the identification of five principal aspects deemed critical for a successful project delivery method, encompassing the allocation of roles and responsibilities, the design phase associated with the restoration process, aspects related to the selection of contractors, the level of collaboration among project stakeholders and the effective management of changes and issues during the restoration process. The criteria that were chosen to define a successful project delivery method included early assignment of roles and responsibilities, the early engagement of stakeholders during the design phase, the facilitation of contractor selection with a focus on the constraints such as cost, time and quality and increasing the competitiveness during the restoration process, a high degree of collaboration and communication among stakeholders, and the effective management of changes and issues during the restoration process.

In seeking balance between the advantages and disadvantages associated with existing project delivery methods, an adapted delivery approach was selected among them and tailored for restoration of architectural heritage. This approach, known as the restoration manager project delivery method, was devised to harness the strengths while minimizing the shortcomings. It is crucial, at this juncture, to establish a comprehensive definition of the restoration manager project delivery method.

The Restoration manager (RM) project delivery method assumes responsibility for the restoration of architectural heritage, primarily focusing on strategic restoration goals and objectives such as to preserve and transfer the cultural heritage with its original values to today's humanity and future generations. This role guarantees successful restoration implementation, management, monitoring, and control throughout the restoration management processes. The restoration manager oversees the preparation and approval of the initiation document after the pre-project/initiation phase, ensuring a smooth transition to the implementation phase post-planning stage following the guidelines of the restoration handbook which is a unifying and integrative document that includes all other management plans, describing how the restoration process will be implemented, monitored, controlled, and finalized. The restoration manager makes restoration decisions within constraints and tolerances, resolves conflicts, approves crucial project documents, and plays a pivotal role in achieving project success. This role encompasses resource management, conflict resolution, approvals of informational documents, responsibility for restoration outputs like projects, designs, and procurement, periodic progress updates to the owner, and maintaining effective communication.

In accordance with the restoration project validated and approved by the decision makers, the restoration manager proposes and executes restoration plans, coordinates the daily activities and resource allocation within their team, takes appropriate measures when challenges arise, manages stakeholder expectations, and conducts comprehensive risk management in the realm of restoration. In essence, the Restoration manager plays a central role in decision-making and acts as a linchpin for project success, ensuring that restoration activities adhere to their intended objectives while efficiently managing resources, risks, and communication.

The restoration manager approach is structured around the distinct life cycle phases encompassing the entire restoration process. Contracts between the owner and the restoration manager, the planning and design team, contractors, sub-contractors, and other essential stakeholders or groups required for executing the restoration process are kept separate. This separation minimizes unnecessary interactions but reinforces focusing solely on necessary engagement and data sharing.

During the initiation phase, roles and responsibilities for the restoration process are determined in accordance with the restoration project validated and approved by the decision makers. Information is initially collected and synthesized within a Restoration Initiation Request Document, where vital topics are deliberated between the owner and stakeholders, leading to decision-making and endorsement of key matters. This initial overview of the whole restoration project evaluates both the restoration management system and approach, detailing the organizational structure and foundational elements of the management system. Consequently, the restoration pre-project/initiation phase unveils the project's objectives, expected outcomes, and key results. The Restoration Initiation Request Document formalizes the restoration project, followed by the decision to procure or internally assign a restoration manager. The employment of the restoration manager is contingent upon owner approval of the document. During the pre-project/initiation phase, the restoration manager identifies constraints, tolerances, and defines restoration goals, recognizing that poorly selected aims can result in data gaps and increased risks. This phase plays a pivotal role in eliminating complexities from the restoration process, underscoring the importance of active engagement by the restoration manager and other stakeholders. Toward the phase's culmination, the restoration manager compiles the restoration initiation document, which, upon owner approval, marks the official commencement of the restoration process. This document encompasses an executive summary, the project's purpose or rationale, a general description, stipulated requirements, project objectives, associated success criteria, constraints, assumptions, and risks, restoration outputs, main milestones, budget summary, stakeholder list, information about the restoration manager, the restoration manager's roles and responsibilities, and an owner's approval section.

Upon completing these tasks, the planning and design phase initiates. Guided by the counsel of the restoration manager, the restoration support unit, slated to serve as designers during the restoration journey, is selected through a competitive bidding process or procurement. Following the engagement of the restoration support unit, a meeting convenes involving the owner, restoration manager, and restoration support unit to set the stage for the preparation of the restoration handbook. The Restoration Handbook serves dual purposes: firstly, it acts as a regular communication reference for stakeholders, updated periodically to reflect ongoing developments throughout the restoration process; secondly, it standardizes various reports and documents, fostering consensus on restoration outputs and procedures among all stakeholders. This comprehensive document amalgamates all management plans that detail the execution, monitoring, control, and culmination of the restoration process.

Upon completing these requisite procedures and securing the restoration handbook, inclusive of management plans and relevant outputs, the phase of contractor selection and mobilization ensues. In brief, the tender was advertised for potential bidders or invitations sent for the shortlisted ones after the design phase was finalized. The ultimate choice of contractor often hinged on the total construction cost, favouring the selection of the lowest bid contractor for project execution during this phase. Historically, a conspicuous lack of integration between designers and contractors prevailed. Designers were prohibited from engaging in construction methods, while contractors were exempt from design responsibilities. This dearth of interaction stemmed from the traditional, sequential construction process characterized by compartmentalized entities throughout the design and construction phases, ultimately culminating in recurring claims, disputes among project stakeholders, and instances of cost and time overruns.

However, the intervention of the restoration manager reshapes this landscape. The restoration manager effectively integrates the owner, restoration support unit, related stakeholders, and contractors. This integration entails the restoration support unit's active involvement in restoration decision-making processes and ensures the contractor's alignment with design responsibilities. Amplified stakeholder interaction yields diminished recurrence of claims, disputes, and constraint issues.

This method facilitates robust team integration, with the restoration manager fostering collaboration between the restoration support unit, related stakeholders, and contractors in the early planning and design stage. Drawing on the restoration manager's expertise, valuable input enhances the precision of cost estimation, scheduling, and document preparation for the owner and restoration support unit, ultimately contributing to well-informed execution of the restoration process. Moreover, the method cultivates a more favourable relationship between the contractor and the restoration manager in a consultant role, with this rapport taking root prior to the execution phase—similar to the integrated relationship forged between the restoration manager and the restoration support unit before the planning and design phase. To ensure a harmonious contractor-restoration support unit alliance, the restoration manager should integrate both parties as early as the mobilization phase.

The process of monitoring and control ensures proactive or remedial measures are enacted based on restoration management plans. This involves establishing priorities to discern between tasks encountering issues during preservation and those proceeding smoothly, then allocating resources and efforts accordingly. The restoration manager undertakes vigilant oversight, tracking process shifts and overall performance while attending to project constraints. This entails data processing and report generation for dissemination among stakeholders.

In the closing phase, the restoration manager compiles a comprehensive report encompassing various aspects. This report must incorporate elements such as the evaluation of process efficiency, organizational structure, all restoration management plans, acceptance logs, an assessment of the restoration support unit, contractors, subcontractors, lessons learned, and recommendations for the post-restoration period.

In summary, the restoration manager project delivery method embodies the advantages of existing methods while mitigating their weaknesses. This is achieved through the clear definition of roles and responsibilities early in the process, early engagement of stakeholders in the design phase, increased emphasis on and competitiveness in contractor selection, enhanced collaboration achieved by mitigating conflicts and promoting stakeholder interests, as well as facilitating better communication among them. Furthermore, it entails the augmentation of flexibility during the execution of the restoration project while effectively managing changes and issues.

The restoration manager is a highly collaborative project delivery method that focuses on quality and project success. The stakeholders like the owner, restoration support unit, related stakeholders, contractors and subcontractors, all work together in collaboration, aligning their goals and incentives for a better restoration outcome.

Restoration manager's strong focus on collaboration, early involvement, and shared risk/reward align well with the goals of achieving the highest quality in heritage restoration projects. By addressing the challenges through improvements in promoting a collaborative culture, clear contracts, effective communication, project management tools, and quality assurance protocols, restoration manager project delivery method can offer a more comprehensive approach to ensuring the successful restoration process.

These characteristics make restoration manager project delivery method also ideal for complex and challenging projects such as the restoration of architectural heritage works.

3. Results

The online survey conducted for the first author's doctoral study titled "Development of a Sustainable Integrated Management System for the Conservation of Architectural Heritage" at Ankara Hacı Bayram Veli University, Department of Conservation of Cultural Property, was answered by the participants.

The questionnaire used in this study is consisting of five sections and includes of introduction, explanation of the survey content, survey participant information, questions section and conclusion section. The questions section has seventeen questions under five separate chapters. Some questions included an option as “other” so that reflecting different views was allowed. The first questions were demographics questions. Then the question reflecting the preference of the project delivery methods in the survey is “Which project delivery method do you think is more suitable for the restoration of architectural heritage?” and the answers given were examined statistically.

47 of participants (45.63%) had a master's degree, 34 of participants (33.01%) had a bachelor’s degree, 13 of the participants (12.62%) had a doctorate or higher degree, and 9 of the participants had an associate degree (% 8.74) (Table 1).

Table 1. Graduation status of the participants.

Graduation status	N	%
Master’s Degree	47	45.63
Bachelor’s Degree	34	33.01
PhD and above	13	12.62
Associate’s Degree	9	8.74
Total	103	100.00

51 of participants (49.51%) are architecture graduates, 22 of participants are engineering graduates (21.36%), 10 of participants are graduates of vocational high school (9.71%), 9 of participants are fine arts graduates (8%, 74), 6 of participants are graduated from social sciences (5.83%), and 5 of participants (4.85%) are graduated from other departments (Table 2).

Table 2. Departments from which the participants graduated.

Departments	N	%
Architecture	51	49.51
Engineering	22	21.36
Vocational School	10	9.71
Fine Arts	9	8.74
Social Sciences	6	5.83
Other	5	4.85
Total	103	100.00

46 of the participants were from the private sector (44.66%), 36 of them were from the public sector (34.95%), 16 of them were academicians (15.53%), and 5 of them were other (4.85%) (Table 3).

Table 3. The professions of the participants.

Professions	N	%
Private Sector	46	44.66%
Public Sector	36	34.95%
Academics	16	15.53%
Other	5	4.85%
Total	103	100.00%

While 33 of the participants have more than 15 years of experience (32.04%), 29 of them have 1 to 5 years of experience (28.16%), 26 of them have 6 to 10 years of experience (25.24%) and 15 of them stated that they have 11 to 15 years of experience (14.56%) in restoration of architectural heritage field (Table 4).

Table 4. Experience of the participants in restoration of architectural heritage field.

Experience	N	%
More than 15 Years	33	32.04
1-5 Years	29	28.16
6-10 Years	26	25.24
11-15 Years	15	14.56
Total	103	100.00

The answers given to the question of "Which project delivery method do you think is more suitable for the restoration of architectural heritage?" are given in Table 5.

Table 5. The preferences of the participants about project delivery methods.

Preferences	N	%
Restoration Manager	43	41.75
Design-Bid-Build	23	22.33
Design-Build	22	21.36
Other	9	8.74
No Answer	6	5.83
Total	103	100.00

When the preferences of the participants about project delivery methods for the restoration of architectural heritage are examined, 43 of the participants think restoration manager method (41.75%) is more suitable for restoration of architectural heritage, 23 of them preferred design-bid-build (22.33%), 22 of them preferred design-build (21%, 36), 9 (8.74%) preferred other methods and 6 of the participants (5.83%) did not prefer to answer the question.

It is seen that the Restoration Manager Method is the first choice among all the participants, while the Design-Bid-Build and Design-Build methods are less preferred.

14 of participants who are associate and bachelor's degree think both the Restoration Manager and the Design-Build method are suitable for restoration of architectural heritage equally. On the other hand, 29 of participants with a master's degree or higher think that the Restoration Manager method is suitable for restoration of architectural heritage (Table 6).

Table 6. Project delivery method preferences of the participants according to their graduation status.

Contract Preferences	Associate and Bachelor's (%)	Master's and Above (%)
Restoration Manager	14 (13.59)	29 (28.16)
Design-Bid-Build	10 (9.71)	13 (12.62)
Design-Build	14 (13.59)	8 (7.77)
Other	6 (5.83)	3 (2.91)
No Answer	1 (0.97)	5 (4.85)

It can be observed that the preference percentage of the Restoration Manager method preferred by those having a master's degree or higher is more than the sum of the two options preferred by those having associate and bachelor's degrees. Also, the Restoration Manager method was preferred twice as much as the other closest preferences of the participants having a master's degree or higher.

24 of the architecture graduates (23.30%) and 13 of the graduates from other departments (12.62%) preferred the Restoration Manager method, 9 of the engineering graduates (8.74%) think that the Design-Bid-Build method is more suitable for restoration of architectural heritage (Table 7).

Table 7. Project delivery method preferences of the participants according to their graduation schools.

Project Delivery	Architecture (%)	Engineering (%)	Other (%)
Restoration Manager	24 (23,30)	6 (5.83)	13 (12.62)
Design – Bid - Build	8 (7.77)	9 (8.74)	6 (5.83)
Design-Build	12 (11.65)	5 (4.85)	5 (4.85)
Other	6 (5.83)	1 (0.97)	2 (1.94)
No answer	1 (0.97)	1 (0.97)	4 (3.88)

Restoration Manager, which is the method preferred by the majority of graduates of architecture and other departments, was preferred more than 4 times (35.92% vs. 8.74%) of the majority of engineering graduates.

9 of the academicians (8.74%) and 21 of the private sector employees (20.39%) think that the Restoration Manager method is suitable for restoration of architectural heritage. On the other side, 14 of the participants from the public sector (13.59%) prefer the Design-Bid-Build method (Table 8).

Table 8. Project delivery method preferences of the participants according to their professions.

Project Delivery	Academician (%)	Public (%)	Private sector (%)	Other (%)
Restoration Manager	9 (8.74)	11 (10,68)	21 (20.39)	2 (1.94)
Design-Bid-Build	2 (1.94)	14 (13.59)	7 (6.80)	0 (0.00)
Design-Build	4 (3.88)	6 (5.83)	11 (10,68)	1 (0.97)
Other	1 (0.97)	2 (1.94)	4 (3.88)	2 (1.94)
No Answer	0 (0.00)	3 (2.91)	3 (2.91)	0 (0.00)

It is observed that 20 of the 36 participants working in the public sector are engineering graduates. The Restoration Manager, which is preferred by the majority of academicians and those working in the private sector, was chosen more than twice the majority of the public sector participants (29.13% vs. 13.59%).

12 of the participants with 1-5 years of experience (8.74%), 14 of the participants with 6-10 years of experience (13.59%), 6 of the participants with 11-15 years of experience (5.83%) and 11 of the participants with more than 15 years of experience (10.68%) prefer the Restoration Manager delivery method (Table 9).

It is observed that all participating groups preferred the Restoration Manager method. The 41.38% of participants with 1-5 years of experience, 53.85% of the participants with experience between 6 to 10 years, 40% of the participants with 11-15 years of experience and

33,33% of the participants having 15 years or over experience have chosen this approach as a more suitable delivery method for restoration of architectural heritage.

Table 9. Project delivery method preferences of the participants according to their experience.

Project Delivery	1-5 years (%)	6-10 years (%)	11-15 years (%)	over 15 years (%)
Restoration Manager	12 (11.65)	14 (13.59)	6 (5.83)	11 (10.68)
Design-Bid-Build	4 (3,88)	7 (6.80)	6 (5.83)	6 (5.83)
Design-Build	10 (9.71)	5 (4.85)	1 (0.97)	6 (5.83)
Other	1 (0.97)	0 (0.00)	0 (0,00)	8 (7.77)
No Answer	2 (1.94)	0 (0.00)	2 (1.94)	2 (1.94)

4. Discussion

Upon a thorough examination and comparative analysis of the project delivery methods, the survey results have been presented. The online survey, conducted as part of the doctoral study on the development of a sustainable integrated management system for the conservation of architectural heritage, garnered responses from a diverse participant pool. The study's demographic insights revealed a mix of participants with different educational qualifications, ranging from bachelor's to doctoral degrees, representing various disciplines such as architecture, engineering, and fine arts. Moreover, respondents hailed from different sectors, including the private and public sectors, academia, and other domains. The stratification of participants based on their professional backgrounds provided a rich dataset for analysis.

One of the standout findings was the overwhelming preference for the Restoration Manager method among the participants. This discovery held true across educational categories, professional sectors, and experience levels. The breakdown of preferences based on educational attainment demonstrated intriguing patterns, with master's degree holders or higher exhibiting a notably stronger inclination toward the Restoration Manager method. Further dissection of preferences within professional sectors illuminated distinctive trends. Academicians and private sector employees predominantly favoured the Restoration Manager method, while a noteworthy proportion of public sector participants leaned toward the Design-Bid-Build method. This nuanced understanding suggests that contextual factors, such as the nature of work in different sectors, play a pivotal role in shaping preferences. The examination of preferences based on the participants' years of experience in the field added another layer of insight. The Restoration Manager method emerged as the preferred choice across all experience brackets, challenging assumptions about the influence of experience on project delivery method preferences.

As a result, the survey outcomes not only shed light on the prevalent preferences for project delivery methods in architectural heritage restoration but also provided a deeper understanding of how these preferences vary across educational, professional, and experiential dimensions. The findings offer valuable implications for both academia and practice, emphasizing the need for tailored project delivery approaches that align with the diverse needs and contexts of architectural heritage conservation.

Accordingly, the selection of characteristics and attributes has been conducted, emphasizing the capacity to enhance the restoration of architectural heritage. Subsequently, this section is dedicated to a comprehensive discussion of the study, with a particular focus on the potential implementation of the restoration manager project delivery method.

Design phase is a pivotal aspect throughout restoration works. In the Design-Bid-Build approach, design authority primarily lies with the owner and their selected architect. However, once the project is contracted to the contractor, making design alterations becomes less flexible and feasible. Conversely, the Design-Build method consolidates design control within the design-build entity, facilitating adaptability during the restoration works. While the owner maintains substantial design influence, the construction manager's input during the design phase is valuable in the CMAR method, where the construction manager bears the contractor responsibilities. Integrated project delivery embraces collaborative design decisions among key stakeholders, offering enhanced flexibility [35,71].

The Integrated Project Delivery (IPD) method is a project procurement approach that has been recognized for its ability to facilitate superior project performance [72]. It is a contractual agreement that establishes a common set of terms, expectations, and project goals among the project participants [73]. IPD has been positively linked with sustainability in design and construction [74]. One of the key benefits of IPD is its impact on design flexibility. By involving key stakeholders early in the project, IPD allows for greater collaboration and communication, which leads to more flexible design solutions [75].

In DBB, the designer is responsible for creating the design documents, and the contractor is responsible for executing the construction based on those documents. The roles and responsibilities are clearly defined, but there may be limited collaboration between the designer and the contractor. However, DB fosters collaboration and teamwork between the designers and contractors. The roles and responsibilities are more integrated, allowing for innovation and efficiency [76]. The construction manager acts as an advisor to the owner and coordinates the construction activities and the roles and responsibilities are shared between the owner, designer, and construction manager in CMAR [77]. In IDP, the roles and responsibilities are shared among all team members, promoting transparency and collaboration and this method emphasizes early involvement and integration of all stakeholders [78].

In IPD, the roles and responsibilities of the contractor are redefined. The contractor becomes an integral part of the project team, working closely with the owner and other stakeholders from the early stages of the project [79]. This increased involvement allows the contractor to contribute their expertise and insights, leading to more efficient and successful project delivery.

CMA, CMMP, and JOC are other project delivery methods in construction management, each with its own roles and responsibilities. CMA involves the construction manager acting as an advisor to the owner, CMMP involves the owner directly contracting with multiple prime contractors, and JOC involves a long-term contract with a construction contractor for smaller projects [80]. Comparing these methods, DBB and CMAR have more defined roles and responsibilities, but may lack collaboration and innovation, while DB and IDP promote collaboration and teamwork, leading to better project outcomes [81].

Zhang et al. [82] highlighted that the conventional DBB method does not support effective communication and collaboration among designers, builders, and owners, leading to project cost growth and delays. This suggests that DBB may have limitations in promoting collaboration and communication compared to other delivery methods. Furthermore, Hasanzadeh et al. [84] found that CMAR outperformed DBB in terms of design satisfaction and construction satisfaction, while DB projects had lower schedule growth compared to DBB projects. These results indicate that CMAR and DB may have advantages in facilitating collaboration and communication, leading to improved project performance.

Effective communication and collaboration constitute vital feature of successful restoration projects. Design-Bid-Build's communication between owner, designer, and contractor can be fragmented due to separate contracts. In the Design-Build approach, close collaboration between design and construction teams is innate due to their unified identity. CMAR's inclusion of the construction manager from early phases fosters collaboration, while Integrated project delivery embodies a pure collaborative model [45,57].

Collaboration and communication are essential components of IPD. The method encourages close collaboration among all project participants, including the owner, architect, contractor, and other key stakeholders [75]. This collaborative approach fosters a culture of trust and mutual benefit, leading to improved project outcomes [84]. Effective communication is crucial in IPD to ensure that all parties are aligned and working towards the same project goals [85].

A study by Suratkon et al. [49] compared the characteristics of procurement methods in Malaysia and found that the DB method fulfils almost all the characteristics under six categories, indicating its high level of flexibility. Similarly, Gabel et al. [86] found that changes related to unforeseen conditions had a greater impact on project cost, and such changes were more commonly experienced in DBB projects compared to DB or CMAR delivery methods. This implies that DB and CMAR may have better change management strategies and flexibility in dealing with unforeseen conditions. Overall, DB and CMAR methods may offer better flexibility and change management practices compared to DBB, however, further research is needed to explore the specific strategies and mechanisms to enhance flexibility and change management.

Considering risk allocation, Design-Bid-Build places substantial risks on the owner, whereas in the Design-Build approach, the design-build entity shoulders these risks. Construction managers assume execution risks in CMAR, whereas Integrated project delivery, characterized by contractual alignment among the owner, constructor, and designer, distributes risks across participants [67].

So, analyzing the restoration manager approach in terms of design control, its distinctive feature lies in the early integration of the restoration manager with the restoration support unit and contractors, enhancing the ease and flexibility of design control. Regarding communication and collaboration within the restoration manager method, it actively fosters engagement and cooperation among all stakeholders, recognizing their inclusion as a valuable asset. Analysing risk allocation and distribution, the restoration manager method exhibits characteristics parallel to a method integrated into a comprehensive restoration management system. Risks are allocated among stakeholders, including the owner as the decision-maker, the restoration manager as a consultant, the restoration support unit as the designer, and the contractor as the executor of restoration activities. Addressing quality of applications intended to safeguard the originality and integrity of the architectural heritage, the restoration manager method stands as effective. This is evidenced by the heightened project quality attributed to the early engagement of the restoration manager, an expert in architectural heritage restoration, who actively contributes to the design phase alongside the restoration support unit and to the execution phase alongside the contractor.

The restoration manager method proves to be an effective approach for restoration projects due to the enhanced design control, improved communication and collaboration, optimized risk allocation, expertise-driven decision-making and quality.

The early integration of the restoration manager with the restoration support unit and contractors facilitates design control and allows for necessary adjustments and refinements. Flexibility is thus offered as required. Heightened communication and collaboration among all stakeholders engaged in the restoration project is encouraged by the restoration manager method. This inclusive approach recognizes the value of input from various parties, contributing to comprehensive project development.

Within an integrated restoration management framework, the restoration manager method allocates risks among stakeholders, including the owner, restoration manager, restoration support unit, and contractor. This approach of collective responsibility contributes to a more balanced risk management strategy.

The involvement of a restoration manager, possessing expertise in architectural heritage restoration, enriches the decision-making process. Their consultative role, in conjunction with collaboration with the restoration support unit and the contractor, ensures well-informed choices that enhance project outcomes.

Commencing from the project's outset, the engagement of the restoration manager, coupled with their expertise on the restoration of architectural heritage, significantly amplifies the emphasis on project quality that restoration implementations increase in compliance with conservation principles. By assisting the restoration support unit during the design phase and the contractor during the execution phase, the restoration manager method contributes to upholding high standards in the final project.

5. Conclusion

In conclusion, project delivery methods hold significant importance in determining the success of construction projects. Although many options, ranging from traditional to integrated approaches, exists within the realm of PDMs, yet no single method can be universally deemed perfect due to the inherent uniqueness of each project. Within the specific context of restoration of architectural heritage, the imperative for developing a tailored project delivery method becomes evident, aimed at optimizing project success. The conceptualization and development of the restoration manager delivery method stemmed from a comprehensive assessment of existing conditions, facilitated by an in-depth literature review and an inclusive survey. This approach emerged as a result of examining the prevailing limitations and strengths of conventional methods. Through careful design and consideration, the restoration manager delivery method was constructed to address the specific demands of architectural heritage restoration projects.

In restoration manager project delivery method, design control is central, ensuring that restoration efforts are in line with strategic restoration goals. Communication and collaboration are key elements, as the restoration manager oversees the restoration processes executed by the contractor, effectively managing stakeholder expectations and resource allocation, all while conducting comprehensive risk and quality management. Roles and responsibilities are clearly defined during the initiation phase, enhancing the efficiency of the restoration process. Stakeholders come together to deliberate key issues, leading to informed decision-making. This phase sets the foundation for the entire restoration project, establishing objectives, expected outcomes, and key results. The restoration manager method emphasizes a separation of contracts to minimize unnecessary interactions and maintain a focus on essential engagement and data sharing. This approach significantly reduces potential complexities during the restoration process. In the planning and design phase, competitive bidding or procurement selects the restoration support unit. The Restoration Handbook becomes a vital document, serving as a communication reference and standardizing reports and documents. It fosters consensus among stakeholders regarding restoration outputs and procedures. The restoration manager, however, introduces integration, bringing designers and contractors together, reducing claims, disputes, and constraint issues. Expertise-driven decision-making and quality assurance are integral, with the restoration manager facilitating collaboration between all stakeholders. Early involvement ensures well-informed execution of the restoration process. The monitoring and control phase includes proactive and remedial measures based on restoration management plans. The restoration manager provides oversight, tracks process shifts, and generates reports for all stakeholders. The final phase involves comprehensive reporting, evaluating process efficiency, organizational structure, and lessons learned. The restoration manager project delivery method combines the strengths of existing methods while mitigating their weaknesses through early engagement, increased competitiveness in contractor selection, collaboration, clear communication, and quality control and assurance protocols. Thus the restoration manager project delivery method represents an innovative project delivery approach so that implementing this method increases the likelihood of achieving successful architectural heritage restoration.

The validation of the method was carried out by engaging professionals from diverse backgrounds, professions, and experiences within the restoration field with a survey. The response was encouraging, with participants consistently indicating a preference for the restoration manager method over alternatives. This endorsement underscores the method's viability and alignment with the unique demands of architectural heritage restoration.

The study of the Restoration Manager Project Delivery Method (RM) also has its limits and potential areas for further exploration.

Firstly, the study primarily focuses on the restoration manager method in the context of the restoration of architectural heritage works. While it demonstrates the method's effectiveness in this specific area, its applicability to other types of construction projects remains to be explored. The limits of its generalizability to diverse project types, scales, and geographical regions need further investigation. The restoration manager method's suitability in different cultural and regional contexts also remains a topic for further study. In addition, Cultural variations in project management practices, legal frameworks, and stakeholder dynamics may impact the method's effectiveness. Another limit and potential of the study is on long term outcomes. This study primarily focuses on the restoration manager method during the restoration process. However, a comprehensive assessment of its long-term outcomes on the preservation of architectural heritage, durability, and ongoing maintenance should be explored in future research. Adding to that, in-depth case studies across diverse restoration projects would provide a more comprehensive understanding of the method's limits and potential variations in its application.

The exploration of project delivery methods remains an ongoing pursuit, and this study's findings and methodologies are poised to contribute to further inquiries. By shedding light on the restoration manager method, this study aims to guide and inform fellow researchers and practitioners, empowering them to make informed decisions in selecting project delivery methods within the architectural heritage restoration.

The restoration manager method operates within specific legal and regulatory frameworks. An in-depth examination of how these frameworks influence the method's implementation and how they may vary across different regions is an opportunity for future research.

And lastly, the scalability of the method to large or complex restoration projects remains to be thoroughly assessed. Investigating the method's performance and adaptability in projects of varying scales and complexities is an essential area of research. While the study sheds light on the restoration manager method's potential, it serves as a foundation for further research that can delve into its broader applicability, effectiveness in different contexts, and long-term outcomes. Addressing these limits and exploring these areas will contribute to a more comprehensive understanding of the restoration manager method's potential and challenges.

The study of the restoration manager project delivery method (RM) not only enriches the understanding of an approach to architectural heritage restoration but also presents significant contributions to the academic field and professional practice. Academically, it lays the foundation for in-depth research on the broader applicability of the restoration manager across diverse projects and cultural contexts, fostering a more comprehensive understanding of project delivery methods. Additionally, it calls for future studies, opening paths for comparative analyses. Professionally, the restoration manager method introduces a collaborative culture, clearer contracts, effective communication and collaboration, and enhanced project management, helping to have improved restoration practices and successful project outcomes.

As this study concludes, it is an aspiration that this research serves as a foundational steppingstone for future investigations into the domain of project delivery methods. Further research in this area can explore the specific mechanisms and strategies employed within the restoration manager method, as well as its applicability and effectiveness in different restoration projects. Additionally, the method's potential for adaptation in various cultural and geographical contexts could be a valuable subject for future studies. Future studies can explore the perspectives of owners, contractors, restoration experts, and other project participants to gain a well-rounded view of the method's challenges and benefits.

Author contributions

Mehmet Emre Aktuna: Conceptualization, Methodology, Investigation, Writing-Original draft preparation. **Bekir Eskici:** Data curation, Validation, Reviewing and Editing

Conflicts of interest

The authors declare no conflicts of interest.

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Integration of blockchain and machine learning for safe and efficient autonomous car systems: A survey

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Abstract

The integration of blockchain and machine learning technologies has the potential to enable the development of more secure, reliable, and efficient autonomous car systems. Blockchain can be used to store, manage, and share the large amounts of data generated by autonomous vehicle various sensors and cameras, ensuring the integrity and security of these data. Machine learning algorithms can be used to analyze and fuse these data in real time, allowing the vehicle to make informed decisions about how to navigate its environment and respond to changing conditions. Thus, the combination of these technologies has the potential to improve the safety, performance, and scalability of autonomous car systems, making them a more applicable and attractive option for consumers and industry stakeholders. In this paper, all relevant technologies, such as machine learning, blockchain and autonomous cars, were explored. Various techniques of machine learning were investigated, including reinforcement learning strategies, the evolution of artificial neural networks and main deep learning algorithms. The main features of the blockchain technology, as well as its different types and consensus mechanisms, were discussed briefly. Autonomous cars, their different types of sensors, potential vulnerabilities, sensor data fusion techniques, and decision-making models were addressed, and main problem domains and trends were underlined. Furthermore, relevant research discussing blockchain for intelligent transportation systems and internet of vehicles was examined. Subsequently, papers related to the integration of blockchain with machine learning for autonomous cars and vehicles were compared and summarized. Finally, the main applications, challenges and future trends of this integration were highlighted.

1. Introduction

Blockchain and machine learning are two advanced technologies that researchers are exploring as possible ways to enhance the safety and effectiveness of self-driving cars and vehicles. Blockchain, a decentralized and distributed digital ledger, can provide secure and transparent tracking of data and transactions in autonomous vehicle networks. Machine Learning (ML) algorithms can enable autonomous vehicles to learn from and adapt to their environments in real time, equipping them with required Artificial Intelligence (AI) capabilities. Together, these technologies have the ability to make self-driving cars safer and more efficient so that can coordinate and communicate with other vehicles and infrastructure.

The blockchain technology can provide safe and open record-keeping, and it can maintain data across several distributed nodes using encryption to ensure its consistency. Due to its potential applications in several industries, such as banking, healthcare, transportation, and logistics, the blockchain technology has attracted a lot of interest nowadays. It can offer safe and effective solutions for data interchange and management and it is being investigated by the scientific research community. Because of its decentralized nature, blockchain enables the development of reliable systems that may be used to reduce the risk of data breaches, prevent fraud, and to simplify business operations. Several aspects of the blockchain technology, such as scalability, security, and privacy implications, are now being widely researched [1, 2].

On the other hand, the ways how we work, live, and interact with the environment are all being redefined by emerging machine learning algorithms and techniques. Moreover, machine learning has created a plenty of new opportunities in several industries, such as transportation, banking, healthcare, and cybersecurity. Machine learning and its various algorithms can learn efficiently from available data and then come to the best decision/solution for the addressed problem. The subfield within machine learning, called reinforcement learning, focuses on the decision-making process within an environment where an agent can receive rewards or penalties based on its taken actions. The most important objective for the agent is to enhance its performance over time by attaining knowledge from its experienced errors and maximizing the overall reward it receives. At present, intensive research has been carried out for reinforcement learning that has brought about the development of application fields, such as robotics, control systems, and games [3]. Moreover, the Neuro Evolution Augmenting Topology (NEAT) algorithm [4], one of the genetic algorithm variants designed to evolve neural networks both structures, i.e. the number of neurons in the layers and the number of connections, and the weights of individual connections. The NEAT algorithm and its extensions, like HyberNEAT [5], can be implemented for programming new autonomous cars with increased experiences along the way. This has the ability not only to develop complex neural networks, but also to compact and enhance their effective use, thereby minimizing the computational burdens and the training time of autonomous cars particularly.

To put it in other words, applications of blockchain and machine learning to vehicles can be a new, uprising field of research, resulting in innovative projects and solutions. The integration and adoption of machine-learning technology algorithms that allows learning from data as well the management of data information securely and transparently of the blockchain technology appear to be a potential disruptor in various scientific fields such as autonomous vehicles/cars. To sum up, the combination of blockchain and machine learning may create the technology of the future with regards to autonomous vehicles, and as the technology develops, we just might get to experience the benefits soon enough.

The main contributions of this survey include an overview of blockchain, machine learning, and autonomous cars technologies. It also summarizes relevant research papers that explore the integration of blockchain in intelligent transportation systems, internet of vehicles and autonomous cars. The paper highlights potential applications of this integration, such as secure data management, decision-making, and coordination among vehicles and infrastructure. Finally, the paper addresses and discusses the challenges associated with this integration and anticipates the future directions of this integration.

2. Overview of relevant technologies

2.1. Machine learning

Machine learning is the process of enabling machines/computers to learn and make decisions independently, eliminating the need for explicit programming. It constitutes a main subfield of the artificial intelligence and utilizes statistical models and techniques to assist computers in learning from data inputs, which in turn, facilitates predictions or decision-making. There is a lot of research in this domain, covering various topics and methodologies. Among the central types of machine learning are supervised learning, unsupervised learning, semi-supervised learning, reinforcement learning, and deep learning. In the process called supervised learning, a model articulated by an algorithm gets fitted using a dataset that has correct outputs or labels for every training sample. The target is to get sufficient estimation from the given data, and apply it on fresh, unseen data, for getting accurate predictions. Contrarily, in unsupervised learning, the algorithm doesn't have access to labeled training examples. Instead, it has to figure out the inherent structure of the data through methods such as clustering or dimensionality reduction. Semi-supervised learning bridges supervised and unsupervised learning, where the algorithm learns from a dataset that includes both labeled and unlabeled data. During the reinforcement learning [3], a machine is being trained to make sequence wise choices in a particular environment to get the highest possible reward. The training process takes place through a procedure of trial and error, in which rewards occur in case of correct actions, while penalties apply when the actions are wrongly performed. This method is extensively utilized in robotics and autonomous driving.

As a popular reinforcement learning algorithm, known as Q-learning [6], an agent will be ready to select the best action to resolve the Markov Decision Process (MDP) issue even before a model outlines the system dynamics. This is done by reinforcement learning which is discovering their action-value function, known as Q-function. It does by taking an action-value function, also known as a Q function, as an integral part of the machine. The function helps calculate the expected cumulative benefit of performing each action a in each state s under this perfect policy. The Q-function is represented as $Q(s, a)$ and can be updated using the Temporal Difference (TD) [6] learning rule (Equation 1):

$$\mathrm{TD}(a, s) = R(s, a) + \gamma \sum_{a'} P(s, a, s') \max_{a'} Q(s', a') - Q(s, a) \qquad (1)$$

Where $R(s, a)$ represents reward of applying action a on state s, $P(s, a, s')$ illustrates the to-from transition between a state s and an arising state s' after action a, and γ is the discount factor that belongs to [0,1] range. The equation represents how the environmental sectors are Q-value fair [6] which further gives insights of how and in what ways the environment may change over time. The updated Q(s,a) is then represented as follows (Equation 2):

$$Q_t(s, a) = Q_{t-1}(s, a) + \alpha \mathrm{TD}_t(a, s) \qquad (2)$$

The Learning rate, α in this expression, determines the time of adaptation the system requires to get informed about the inconstant changes that the environment imparts on it. The $Q_t(s, a)$ here stands for the Q-value at time t. The recorded Q-value if we replace $\mathrm{TD}_t(a, s)$ with its full-form Equation 2 [6], we should get (Equation 3):

$$Q_t(s, a) = Q_{t-1}(s, a) + \alpha(R(s, a) + \gamma \max_{a'} Q(s', a') - Q_{t-1}(s, a)) \qquad (3)$$

Additionally, Deep Q-Network (DQN) is a Q-learning extension that combines deep neural networks with the

Q-learning technique. The agent in DQN can manage high-dimensional state spaces and complicated situations because a deep neural network roughly approximates the Q-function, which is commonly used in autonomous cars. Furthermore, deep learning, a specialized area within machine learning, focuses on the training of artificial neural networks on extensive datasets. These algorithms have the capability to recognize various patterns and characteristics in provided data, resulting in their success across numerous applications and fields. This includes areas, such as image and speech recognition, natural language processing, and even in game-playing scenarios. There are many other topics and approaches within the field of machine learning, and new research is constantly being published [7]. Figure 1 highlights the intersections and differences among the various types and techniques of machine learning.

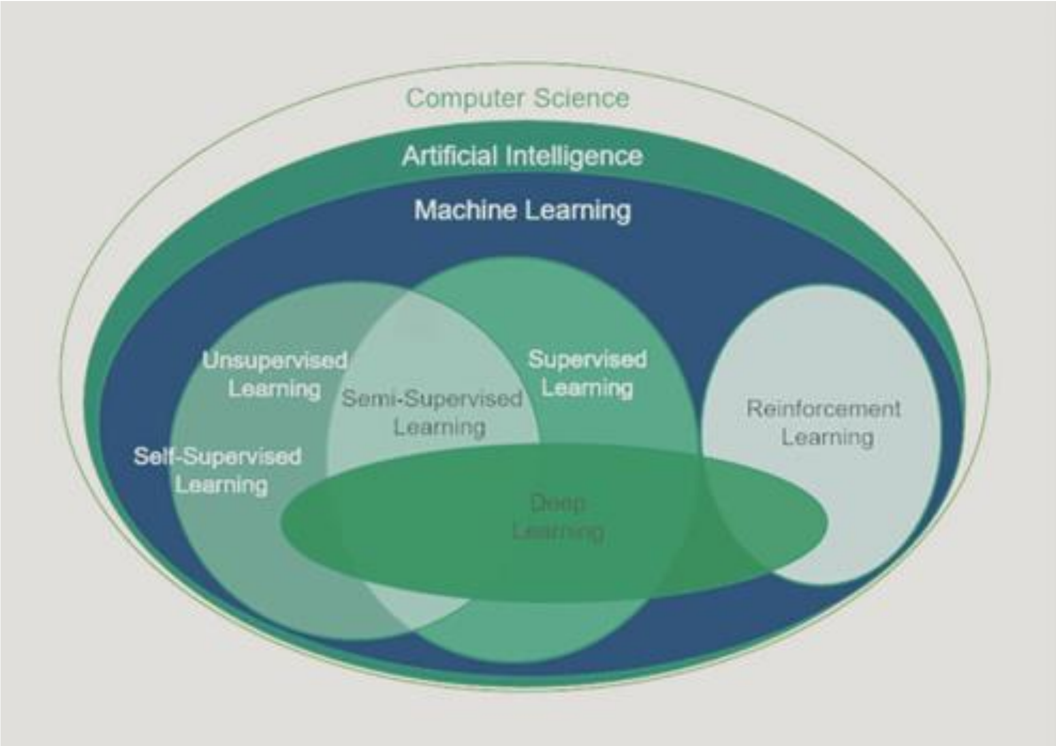

Figure 1. Different types of machine learning [8].

One of the basic algorithms of machine learning is the artificial neural network (ANN) [9], inspired by the structure and function of biological neural networks in the human brain. The ANN models consist of interconnected layers of nodes, artificial neurons, responsible for processing and transmitting information. The basic unit of an ANN is the artificial neuron, which receives input from other neurons or external sources, performs a mathematical computation on the input, and produces an output signal that is transmitted to other neurons or output nodes. The equation for the output of a single neuron in an ANN can be written as (Equation 4):

$$Y = F(\sum W_i * X_i) + b \tag{4}$$

Where Y is the output, F is the activation function applied to the neuron, e.g., ReLU, LeakyReLU, sigmoid, or tanh [10-12], Wi are the weights of the connections, Xi are the input values presented to the neuron, and b is the bias associated with the unit [9].

Furthermore, the neural networks are very accurate in many of the learning algorithms and the development of neural networks has been and is still a very important area of research in artificial intelligence and machine learning. One paper which has specialized on this field by Stanley and Miikkulainen [4] sheds light on the NEAT algorithm. In contradistinction to previous methods that only exploited weight tuning as an optimization tool, NEAT gives rise to both weight and structure optimization. This invention has given rise to neural networks, which unlike before can modify to respond to changes. Such networks can therefore be utilized in some tasks, including object detection, lane keeping, and decision-making. Along with NEAT, another remarkable paper that influenced the growth of large networks was by Stanley et al., [5]. They tackled the problem of matching neural networks for the high level of scalability by proposing a new variant called Hypercube-based NEAT (HyperNEAT). By means of this method, direct encoding is not used. Instead, the encoding exploits domain specific patterns leading evolution towards big neural networks having millions of connections able to display made up of modules, hierarchy, and regularity. Such tricks have opened an entirely new field of investigation into the fields of gentle learning methods and have become one of the leading applications in solving more and more complicated problems. They have motivated AI and ML researchers to explore new approaches for evolving neural networks and improving their structures.

However, some other machine learning techniques and approaches need to be taken into account while considering machine learning and its relevant technologies:

- Active learning: In this approach, the algorithm can request labels for specific examples to improve its performance. This can be more efficient than labeling the entire dataset in a supervised learning setting [13]. This type of learning is primarily associated with supervised learning.
- Online learning: Here, the algorithm receives a stream of data, and it should make predictions or updates on the same data, without the ability to go back and process old data [14]. It is associated with various types of learning, such as supervised learning, unsupervised learning, and reinforcement learning
- In multi-task learning model, a single model is taught how to perform multiple tasks that are interconnected and are at the same time using mathematical processing which is back propagation [15]. It might be associated with both supervised learning as well as unsupervised learning.
- Explainable artificial intelligence: This part of research aims at building machine learning models that bring out the explanations for their prediction or decisions thereby making transparent and humane the whole process [16]. To begin with, it is not deeply coupled to a particular learning kind; rather, it is an approach that is attuned to making AI decisions clearer and more comprehensible across learning paradigms.
- Federated learning: This is a distributed machine learning paradigm that helps parties to jointly train a machine learning model without such entities' direct access to their data [17]. It might refer to many kinds of learning, such as, but not limited to, supervised learning and unsupervised learning.
- Imitation learning: The purpose of such replication is to train a model to imitate the behavior of others, normally resulting in the identical actions or results as ones who are being imitated. It is mostly about supervised learning.
- Transfer learning: The point of this approach is that a model trained on the first task is repurposed and used as the model for a related task. The objective is that knowledge will transfer from the original task to the target task to the end that the model will perform better than if it was trained by scratch [18]. It relates to various ways of learning, such as supervised learning, unsupervised learning and reinforcement learning.

Moreover, familiarization with deep learning (DL) algorithms is becoming trending lately as it is already adopted in several fields of technology including the field of autonomous cars. In Table 1, the basic properties of the most employed deep learning algorithms are shown.

Table 1. Main deep learning algorithms.

Network Type	Features	Pros	Cons	Reference
Convolutional Neural Networks (CNNs)	Spatial hierarchies' recognition, Weight sharing, Feature extraction	Excellent for image and video analysis, Reduced parameters, Translation invariance	Computationally intensive, Limited sequential processing	[19]
Long Short-Term Memory Networks (LSTMs)	Sequential data modeling, Memory retention	Effective for timeseries data, Longterm dependencies capture	Training complexity, Computational demands	[20]
Recurrent Neural Networks (RNNs)	Sequential information processing	Suitable for sequential data modeling, Variable input lengths	Vanishing and exploding gradient problems, Training instability	[21]
Generative Adversarial Networks (GANs)	Generative modeling, Image synthesis	Produces realistic data, Creative content generation	Training instability, Mode collapse	[22]
Radial Basis Function Networks (RBFNs)	Nonlinear mapping, Pattern recognition	Fast training on fixed data sets, Good for radial symmetry	Limited generalization, Sensitivity to kernel selection	[23]
Multilayer Perceptrons (MLPs)	Universal function approximation	Versatile and widely applicable, Good for complex problems	Prone to overfitting, Sensitive to hyperparameters	[24]
Self-Organizing Maps (SOMs)	Unsupervised learning, Topological mapping	Dimensionality reduction, Clustering and visualization	Fixed structure and size, Limited to input topology	[25]
Deep Belief Networks (DBNs)	Layerwise unsupervised pretraining	Effective feature learning, Probabilistic inference	Computationally intensive, Training complexity	[26]
Restricted Boltzmann Machines (RBMs)	Stochastic, generative learning	Feature learning in unsupervised manner, Efficient pretraining	Training complexity, Sensitive to hyperparameters	[27]

2.2. Blockchain

Blockchain is a public database which can be adopted by several parties to record transaction activity on the distributed ledger. Record keeping for each entity is done through a cryptographic protocol. In each case, the transaction is recorded as a block, and then the chains of the blocks are connected to form an unbroken record of all the transactions on the blockchain. One of the crucial factors for blockchain is its distributed feature [1]. Instead of relying on a central authority to verify and validate transactions, a blockchain network relies on a peer-to-peer network of computers to reach consensus on the state of the digital ledger. This makes it difficult to manipulate the record.

Another important aspect of blockchain technology is its use of smart contracts, Figure 2. Smart contracts represent a key element of blockchain technology. They are autonomous contracts, with the terms of the agreement between the involved parties, such as a buyer and seller, encoded directly into the lines of code. This code, along with the enclosed agreements, is stored and duplicated within the blockchain network [28].

Among mathematical representations and equations widely used in smart contracts is cryptographic hash function [1] that takes an input and produces a fixed-size output. Mathematically, it can be represented as (Equation 5):

$$h = H(m) \tag{5}$$

Where h is the hash value, and m is the input message.

Furthermore, there are several different blockchain applications, such as the financial industry, supply chain management, and voting systems. Some of the key benefits of using blockchain technology include increased security, transparency, and efficiency. There has been a lot of research conducted on blockchain technology in recent years, with numerous papers being published on the subject. Some of the key areas of focus in these papers include the technical aspects of blockchain systems, their potential applications, and their economic and social impacts. Blocks and transactions are fundamental elements of blockchain technology, where blocks are digital containers of data, primarily consisting of transactions that document value exchanges across the network. Table 2 provides a comparison of the data elements included in blockchain blocks and transactions.

Figure 2. Smart contracts.

Table 2. Differences between blocks and transactions.

Feature	Blocks	Transactions
Definition	Collection of transactions bundled together and added to blockchain	Record of specific exchange or transfer of data or value on blockchain
Size	Larger than transactions	Smaller than blocks
Frequency of creation	Created less frequently than transactions	Created more frequently than blocks
Data stored	Hash of previous block, timestamp, transaction data	Data specific to transaction being recorded
Examples	Bitcoin block, Ethereum block	Bitcoin transaction, Ethereum transaction

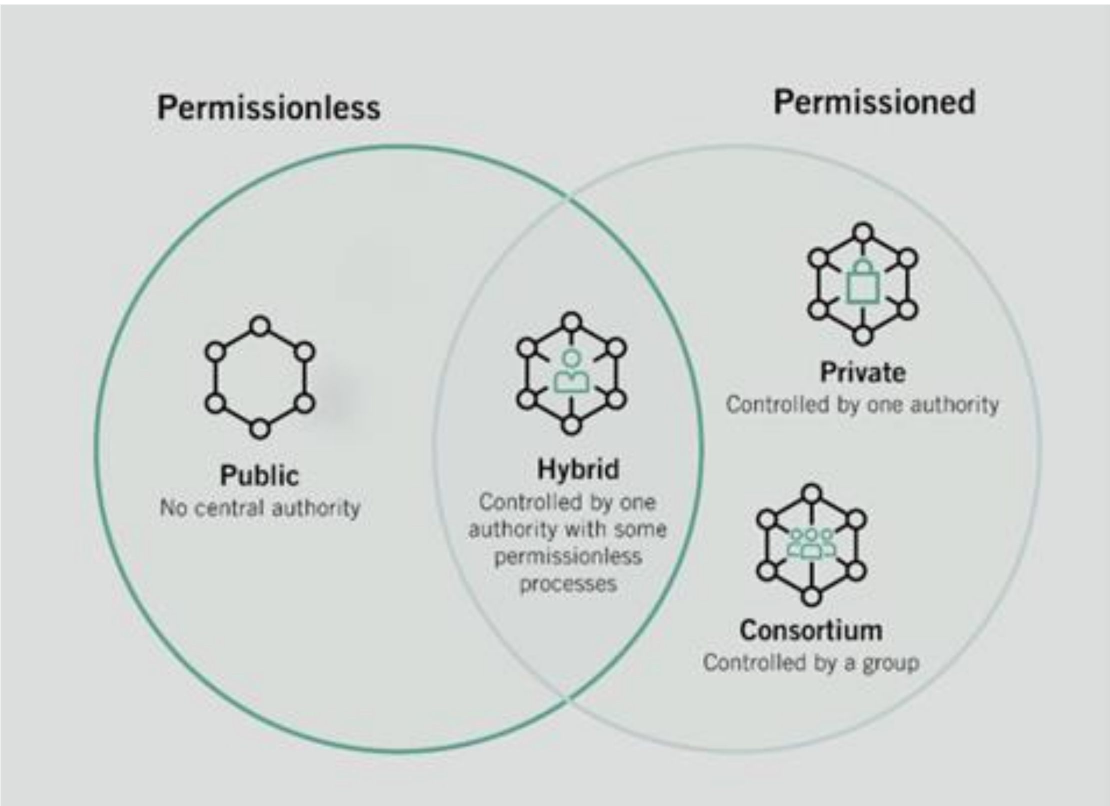

Figure 3. Different types of Blockchain [29].

Blockchains can be classified into four types, Figure 3, based on their accessibility and control:

- Public blockchains are open and decentralized, allowing anyone to participate and are secure.
- Private blockchains are for a specific group or organization and access is restricted to authorized members.
- Consortium blockchains are controlled by a pre-selected group of organizations.
- Hybrid blockchains combine the features of both public and private blockchains for a balance of security, privacy, and decentralization.

In a blockchain network, participants are typically referred to as nodes. Blockchain nodes vary as users, miners, validators, or other participant types. The specific blockchain and consensus algorithm determine the node types. A consensus algorithm ensures network agreement on the shared ledger state. All blockchain network nodes must agree on the current state. Having the same blockchain copy across nodes is crucial. Any new added blocks require most nodes' agreement. This maintains a tamper-proof, secure, and accurate transaction record. When adding a new block, the consensus algorithm determines the allowed node. It also ensures other nodes validate the block. The process may involve complex math problem-solving. A majority vote approach could be used. A combination of methods is also possible [30]. Once a block is added, the consensus algorithm ensures that all nodes in the blockchain network have the same blockchain copy and reach a consensus on its current state. This mechanism is, hence, crucial for ensuring the blockchain's overall authenticity and trustworthiness, irrespective of the individual node's particular intentions to modify the blockchain at will or introduce fake information. Table 3 presents a comparison of main blockchain consensus algorithms.

Table 3. Comparison of the main consensus algorithms.

Algorithm	Pros	Cons
Proof of Work (POW) [31]	Widely used and well-known	Energy-intensive
Proof of Stake (POS) [32]	Energy-efficient	Can be subject to "nothing at stake" issue
Delegated Proof of Stake (DPOS) [32]	Fast transaction speeds	Centralized decision-making
Byzantine Fault Tolerance [33]	Fast transaction speeds	Requires a relatively small and known group of nodes

2.3. Autonomous cars

An autonomous vehicle has sensors that allow its environment to be perceived without the need of a human operator. The array of sensors and complex machine learning algorithms that the autonomous car is equipped with helps in discerning the immediate surroundings and predicting the road ahead. Based on the perception, the machine then navigates the road accordingly. The efforts of developing self-driving cars have been driven by several goals, such as lowering traffic accidents, enhancing fuel efficiency, and offering transport to the people who cannot drive. Potential economic benefits exist with autonomous car usage. Car ownership needs could reduce. More efficient road space utilization may occur. Significant research and development efforts are underway in this field. Intelligent transportation systems are a focus area. Currently, multiple companies test self-driving vehicles on public roads. However, there are also several technical and organizational challenges that must be overcome before autonomous cars can be widely deployed. These challenges include the need to improve the reliability and safety of autonomous systems, develop standards for their operation, and address concerns about cybersecurity and data privacy. One of the key technologies that enables autonomous cars to navigate their environment is sensors. These sensors include lidar, radar, and cameras, which are used to create a high-resolution map of the car's surroundings [34]. Figure 4 provides a visual representation of the main tasks achieved by different sensors, while Table 4 summarizes the essential properties of the main sensors utilized in autonomous cars.

Table 4. Sensor types in autonomous cars.

Sensor	Pros	Cons	Distance	Reference
Camera	Wide field of view, high resolution, low cost	Sensitive to lighting conditions, easily fooled by camouflage and other visual illusions	Depends on camera resolution and zoom	[36]
Lidar	High resolution and accuracy	Relatively high cost, vulnerable to occlusion and interference from other lidar sources	100-200 m	[37]
Infrared Camera	Can operate in variety of lighting conditions, robust to visual illusions	Limited range, sensitive to temperature changes, vulnerable to occlusion	Depends on camera resolution	[38]
Ultrasound	Can operate in variety of lighting conditions, relatively low cost	Limited range, vulnerable to interference from other ultrasound sources	1-5 m	[39]
Radio Frequency (RF)	Wide range, relatively low cost	Limited accuracy and resolution, vulnerable to interference from other RF sources	Depends on antenna design	[40]
Dedicated Short-Range Communication (DSRC)	Wide range, high accuracy, robust to interference	Limited accuracy and resolution, vulnerable to interference from other RF sources	1,000 m	[41]

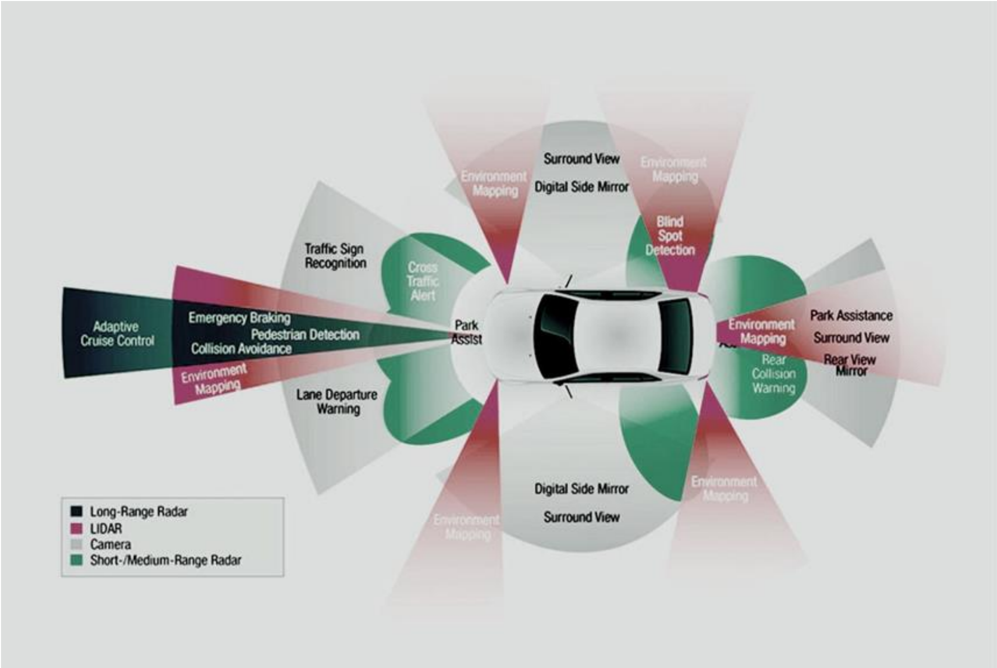

Figure 4. Different sensors used in autonomous cars [35].

Table 5. Sensor data fusion approaches for autonomous cars.

Method	Description	Cons	Pros	Reference
F-Cooper	Uses fully convolutional neural network (FCN) to extract features from both camera and lidar data. Features are then fused using cooperative learning framework	Not effective in complex environments	Handles high-dimensional data	[42]
V2VNet	Uses RNN to model temporal dependencies between frames of camera data. RNN is then augmented with vehicle-to-vehicle (V2V) module that learns to fuse information from neighboring vehicles	Computationally expensive	Improves object detection and tracking	[43]
AttFuse	Uses attention mechanisms to fuse features from camera, lidar, and radar data. The attention weights are learned in an end-to-end manner	Sensitive to noise in data	Improves object classification and localization	[44]
V2X-ViT	Uses ViT (Vision Transformer) encoder to extract features from camera data and FiT (Fusion Transformer) decoder to fuse features with information from V2X communication	Can be difficult to train.	Improves situational awareness	[45]
CoBEVT	Uses contrastive learning framework to learn representation of camera data that is invariant to ego-motion. Learned representation is then used for object detection and tracking	Requires large amount of training data	Improves robustness to ego-motion	[46]
No Fusion	Simply concatenates features from camera, lidar, and radar data before feeding them into classifier or regressor	Less effective than other fusion methods	Simpler to implement.	[47]
Late Fusion	Fuses features from camera, lidar, and radar data after they have been processed by separate networks	More computationally expensive than early fusion.	Preserves more information from original data sources	[48]
Early Fusion	Fuses features from camera, lidar, and radar data at the raw data level before they are processed by any networks	Less effective than other fusion methods when data sources are noisy or unreliable	Less computationally expensive than late fusion	[49]
MACP	Uses multi-attention fusion network to fuse features from camera, lidar, and radar data. The network uses multiple attention mechanisms to capture different types of relationships among features	More complex to implement than other fusion methods	Improves performance of autonomous vehicles in complex environments	[50]

Another important aspect required for autonomous cars is machine learning. Extensive efforts have been made in developing datasets of real driving scenarios for autonomous driving training, such as Kitti [51], Waymo Open [52] and V2V4Real [47] datasets. Other datasets, such as V2X-Sim [53] and OPV2V [54], are built using CARLA simulator [55] for different autonomous driving scenarios. Also, machine learning algorithms allow the car to analyze and fuse data from its different sensors, and then make decisions accordingly. Table 5 shows some utilized approaches for sensor data fusion in autonomous cars. Machine learning and blockchain techniques can further contribute to countermeasures strategies against security vulnerabilities in autonomous cars and vehicles. These can be intra-vehicle threats associated with engine control, transmission units, temperature control, and various Electronic Control Units (ECUs), or Vehicle-to-everything (V2X) threats, which include a spectrum of cyber threats, including DoS attacks, black-hole attacks, replay attacks, Sybil attacks, malware infiltration, falsified-information attacks, timing attacks, and impersonation attacks in V2X communications. Recent surveys [56, 57] provide a detailed exploration of security vulnerabilities and their countermeasure strategies using blockchain and machine learning technologies in Connected Autonomous Vehicles (CAVs).

Furthermore, mathematical models play a crucial role in the decision-making processes of autonomous vehicles. There are several models employed in various aspects of decision-making, such as path planning, control, and prediction. Here are three prominent models used in autonomous vehicle decision-making:

1. Probabilistic Models [58]: Probabilistic models are used to represent and reason about uncertain information, such as sensor noise, localization errors, and prediction of other road users' behavior. Bayesian networks, Markov Decision Processes (MDPs), and Partially Observable Markov Decision Processes (POMDPs) are examples of probabilistic models employed in autonomous driving. For example, in an MDP, the decision-making problem is modeled as a tuple (S,A,P,R), where S is a set of states, A is a set of actions. P(s'|s,a) is the transition probability function, which represents the probability of reaching state s' from state s when taking action a. R(s,a) is the reward function, which assigns a numerical value to each state-action pair. The goal in an MDP is to find a policy (a mapping from states to actions) that maximizes the expected cumulative reward over time.

2. Optimization-based Models: Optimization-based models are used to find optimal trajectories and control actions that minimize a cost function while satisfying constraints, such as vehicle dynamics, road geometry, and traffic rules. Examples of optimization-based models include Model Predictive Control (MPC), convex optimization, and Mixed-Integer Linear Programming (MILP). For example, in an MPC framework, the decision-making problem can be formulated as an optimization problem as follows (Equation 6-9).

$$\text{Minimize } J(x, u) \tag{6}$$
$$\text{Subject to}$$
$$x' = f(x,u) \tag{7}$$
$$g(x,u) \leq 0 \tag{8}$$
$$h(x,u) = 0 \tag{9}$$

where x represents the state vector, u represents the control input vector, $J(x,u)$ is the cost function to be minimized, $f(x,u)$ represents the state dynamics equation that describes the evolution of the state vector over time, $g(x,u)$ represents constraints on the states and control inputs, ensuring they satisfy certain conditions, and $h(x,u)$ represents any additional problem-specific constraints that need to be satisfied. The optimization problem aims to find the values of x and u that minimize the cost function J while satisfying the given constraints. The specific form of the cost function, state dynamics equation, and constraints would depend on the optimization-based model being used.

3. Graph-based Models [59]: Graph-based models are employed in path planning and route selection tasks in autonomous vehicles. The road network, traffic, and vehicle states are represented as graphs, and graph search algorithms, such as Dijkstra's, A*, or RRT (Rapidly exploring Random Trees), are used to find optimal paths or routes.

Figure 5 provides a flowchart for high-level overview of the decision-making process used by an autonomous car. The process of autonomous driving involves several key steps, which can be broadly categorized into perception, prediction, planning, control, actuation, and monitoring. In the perception phase, data are collected from various sensors to identify and track objects in the environment. The motion of other road users and changes in traffic lights are estimated in the prediction phase. In the planning phase, the optimal route and path are determined, and the desired vehicle motion is calculated. In the control stage, control inputs are calculated to achieve the desired motion, and these inputs are applied to the vehicle's actuators in the actuation stage. Finally, the system is continuously monitored and updated in real-time based on sensor data, and errors or unexpected situations are detected and handled appropriately. Overall, the flowchart provides a valuable way for understanding how an autonomous car navigates the road and makes decisions that prioritize the safety of pedestrians and other drivers on the road. Moreover, such or similar decision-making process is utilized in most autonomous vehicles for different purposes, such as self-driving cars, small cleaner robots [60] or autonomous drones [61, 62].

Many studies have utilized different machine learning algorithms for autonomous cars and autonomous driving systems. In [63], the authors provide an in-depth discussion of various deep learning approaches such as Convolutional Neural Networks (CNNs), Long Short-Term Memory (LSTM) and Generative Adversarial Networks (GANs) and their application in self-driving cars through case studies. The paper provides a comprehensive overview of the considerations and challenges of developing self-driving car systems using deep learning techniques. However, this paper focuses specifically on the use of deep learning and does not provide a complete analysis of other technologies or approaches used in autonomous driving systems. Another paper [64] presents a system for real-time obstacle detection and tracking for autonomous driving. This paper also talked about the sensors and

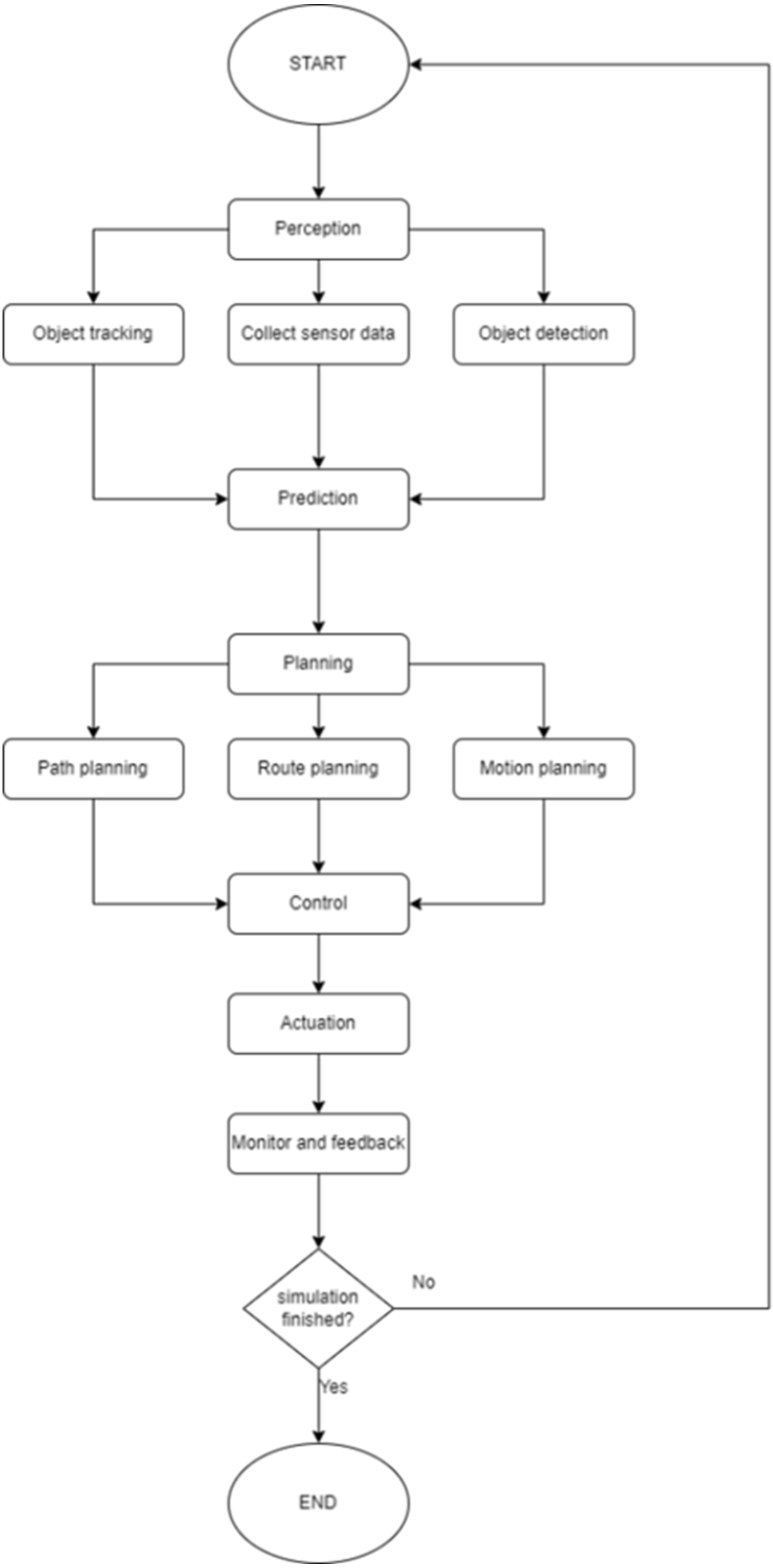

Figure 5. Flowchart of decision-making process in an autonomous car.

algorithms used. However, this paper focuses specifically on the problem of obstacle detection and tracking in autonomous driving and does not provide a comprehensive overview of other aspects of autonomous driving systems. When it comes to improving the autonomous driving systems, the bigger challenge is the amount of data required for learning. However, the authors in [65] discuss the problems such as overfitting and difficulty transferring models between different environments and to overcome these challenges, they provide an overview of several proposed solutions, including data augmentation, transfer learning, and active learning. Also, the authors suggest future directions of using deep learning techniques in autonomous driving by integrating other different technologies, such as edge computing and the internet of things.

To improve the efficiency of lane changing, the authors in [66] provide a machine learning-based approach for lane change intention awareness in assisted and automated driving. An autonomous vehicle learns to predict the lane change intentions of surrounding vehicles by analyzing their motion patterns and contextual information. Kendall et al. [67] present another example of machine learning-based approaches, where an autonomous vehicle learns to drive through interaction with the environment, receiving rewards or penalties. The paper is devoted to assessing the abilities of machine learning-based autonomous driving system using situations, such as like lane switching, lane merging and intersection moving. In [68], the authors investigate about the use of Deep RL (DRL) in the driverless vehicle systems. They provide various applications of DRL for autonomous driving systems, such as perception, decision making, controlling systems. Nevertheless, the employment of DRL in autonomous driving would require quite a big amount of data and computational capability which can result in systems that are more complicated and expensive. Similarly, Ni et al. [69] review the key applications of DRL in autonomous driving and the various evaluation metrics used to improve their performance.

However, all previous studies did not consider or benefit from blockchain technology for developing autonomous car systems or intelligent transportation systems.

3. Integration of blockchain in intelligent transportation systems

3.1. Blockchain and internet of vehicles

The incorporation of blockchain technology into the Internet of Vehicles (IoV) yields comprehensive solutions to security, privacy, and trust related problems, which are all vital to lessen IT intricacies in this domain. In [70], Chen et al suggested a hybrid approach for data trading in IoV that is based on both blockchain as well as edge computing. Blockchain is the basis for security and decentralization while edge computing allows for faster data processing. This technique prefers blockchain to keep track of data consistency and provide dynamic data exchange support among vehicles. In the same way, the authors from [71] propose a blockchain-based information sharing scheme for IoV with a data storage module, a data sharing module and a data access control module. Through the utilization of smart contracts, they were able to increase the smartness within their existing data sharing processes and implement various access control policies that regulate who can access to the shared data. Employing the blockchain for building trust management can help establish trust management among members in vehicular ecosystem by making transaction data transparent as well as immutable. Applications of blockchain in trust management and challenges with blockchain for vehicular networks were explored in [72], including the use of public, private and consortium blockchain. However, using blockchain for trust management may not be the best way or it still needs more studies. This is because of the implementation and maintenance costs and the need to secure trust data privacy, which is provided in more detail in [73]. The authors also explore decentralized decision-making algorithms and reputation systems for determining the trustworthiness of vehicles using blockchain-stored data. Additionally, the authors in [74] proposed a decentralized blockchain-based trust management framework for the IoV that uses smart contracts to automate the trust management process. In terms of communication, blockchain technology has been proposed for enabling secure and trusted communication among vehicles in the IoV.

While other work has elaborated the positive implications of blockchain technology for data sharing, Vattaparambil et al. [75] have also addressed the technical challenges and particularities of data sharing and trading among connected cars. The above paper discusses the improved connected car environment's new challenges, such as the data security and trust, which are vital for the whole system efficiency, and can be used for malicious attack purposes. Blockchain is a revolutionary technology that enables its application in the autonomous car's ecosystem, like the management of computing resources. Lin, et al. [76] introduced the application of a blockchain-based platform for the sharing of on-demand computing resources between each other in the case of smart cities. Among others is the application of smart contracts to regulate the resource management between the cars and other devices thereby, as well the use of distributed ledgers for the security and transparency of the resource trading process. Additionally, they discussed different challenges and the solution limitations, and they made a performance analysis demonstrating the effectiveness of their system.

To develop scalable, highly efficient, and highly safe blockchain-structured devices for IoV, it is imperative to develop the complete framework that allows the optimization of the blockchain use in IoV. The system utilizes a concept of technical optimization to solve issues of scalability, efficiency and the security, which typically crop up when we are designing the IoV blockchain. Being able to gain a perspective of the unique aspects that make the environment stand out like the need for scalability and interoperability and this framework can draw a solution that is specific to this application. Xu et al. [77] have applied edge servers to support the decentralized nature of blockchain-based communications in IoV to facilitate the local processing and help reduce the amount of data that needs to be transmitted. This improves the overall performance of the system and also enables the secure and reliable data exchange among vehicles and other participants. The paper provides the proposed system architecture and each of its components, such as the blockchain, edge server deployment algorithms, and the performance optimization issues.

Consequently, blockchain can also be leveraged for establishing systems that manage the charging stations for electric self-driving vehicles, as in [78]. The writers presented a framework of blockchain-powered software that would deliver charging electric cars in a secure way, and also allow sharing of charging resources among different vehicles. Smart contracts helped them to do the charging resources management in an automatic and direct manner. This reduces the need for manual intervention and improves the speed and accuracy of resource allocation. Also, the use of a consortium blockchain enables the system to scale to large numbers of charging stations and vehicles. It is worth noting that implementing a blockchain-based software system may require significant investment in terms of software development and infrastructure. There may also be regulatory or legal challenges associated with the utilization of blockchain in managing charging resources for electric self-driving cars.

However, very few surveys are recently available in the literature that discuss the application of blockchain in IoVs and Intelligent Transportation Systems (ITSs) [79,80]. Mollah et al. [79] conducted a survey on the latest advancements in blockchain for IoVs, highlighting different application scenarios and investigating key challenges where blockchain is applied in IoVs. They also discussed future opportunities and further research directions. The article emphasizes that the underlying platform of IoVs for information exchange needs to be transparent, secure, and immutable to achieve its required objectives. In [80], the authors systematically reviewed applications of blockchain in ITSs and identified several challenges in the realm of vehicular networks and suggested potential future research directions. Future research paths outlined by the authors encompass enhancing security against Distributed Denial of Service (DDoS) attacks, thorough analysis of the architectures, limitations and challenges of the IoVs as a pivotal facilitator of ITSs, and a focus on data management in smart cars. They foresaw that enhancing blockchain performance will be a significant area of interest in the future, particularly as Blockchain-based IoV (BIoV), with broader applications. They also explored blockchain role in vehicular network cybersecurity and assessed the cybersecurity threats in these networks. However, recent advancements in fifth Generation (5G) technology, big data analytics, and machine learning were not considered.

3.2. Integration of blockchain and machine learning for autonomous cars

The rise of autonomous cars and their intelligence capabilities has brought new challenges in data sharing and security. Blockchain, as decentralized and tamper-proof technology, can address these challenges in a secure and efficient way. In [81,82], the authors propose the utilization of blockchain technology to accelerate the training of autonomous cars. Blockchain technology by itself can be used as an infrastructure for securing the storage devices to store the bulk data requirement of the self-driven vehicles. Moreover, blockchain has opened up new ways of trusting and reconciling the authenticity and integrity of the underlying data.

In the context of supply chain management, the combination of reinforcement learning together with a heuristic search method was explored in [83]. Their purpose was improving the self-driving vehicles routing optimization in a supply chain management system, which would use blockchain technology. The paper has a different perspective which is the use of reinforcement learning and heuristic search for routing optimization of autonomous vehicles. The blockchain technology is going to be employed to create an infrastructure for the storage and sharing of data emanating from vehicles routing as well as for verification of their authenticity and integrity. In addition to this, Liu et al. [84] proposed a strategy based on blockchain technology and deep reinforcement learning to enhance the Industrial IoT (IIoT) systems in terms of data collection and sharing. An innovation with blockchain technology and deep reinforcement learning as a solution for data collection and sharing in industrial internet of things systems. Performance optimization of blockchain-integrated IIoT systems was the main concern of [85], which describes a DRL approach for improving the performance of blockchain-enabled IIoT systems. This paper focused on blockchain usage in IIoT rather than in vehicular networks. However, the use of deep reinforcement learning in such systems can be very useful to adjust the balance between decentralization and performance in IIoT systems.

Furthermore, blockchain technology in the context of federated learning for connected and autonomous vehicles was considered by He et al. [86]. That is, an autonomous car learning from the combined collective data of any given car while retaining the privacy of each individual vehicle data. The smart contracts technology was used behind the scenes to offer an automatic and transaction neutral exchange of data among cars. Moreover, smart contracts were implemented to guarantee the integrity of the data exchange. The paper showed a predictable architecture of federated learning for connected and autonomous vehicles, covering its advantages and disadvantages.

The authors in [87] examined the incorporation of Autonomous Vehicles (AVs) into our daily lives in numerous forms, such as autonomous drone delivery systems, driverless cars, automated vehicles in warehouses, autonomous home assistant devices, and Automated Eligibility Verification System (AEVS) for green energy solutions. The type, usage, and application of these vehicles largely depend on the level of their automation. The authors discussed the progression and feasibility of integrating advanced technologies like blockchain, Industry 4.0, AI, and IoT into these vehicles. They provided a comparative analysis of different types of autonomous vehicles and their various features, including private blockchain autonomous vehicles, public blockchain autonomous vehicles, and electric vehicles. The study also investigated the potential of integrating blockchain technology with networked groups of Unmanned Aerial Vehicles (UAVs) and the application of blockchain-based mutual-healing group key distribution schemes in UAV ad-hoc networks.

Overall, Table 6 summarizes the objectives, contributions, and important considerations of the relevant papers that propose blockchain-based techniques for solving privacy, trust and security issues in the internet of vehicles, vehicular networks, and autonomous car systems. The proposed solutions, as seen in Table 6, include secure and scalable communication protocols, trust management frameworks, data sharing schemes, and reinforcement learning-based optimization methods. Each paper in the table discusses important considerations, such as the trade-off between security and efficiency, the reliance on cloud computing, evaluation techniques, the scalability, and performance limitations of the blockchain technology.

Table 6. Relevant research papers summary.

Reference	Objective	Method	Important considerations
[75]	Secure and scalable vehicular communication protocol	Presents a protocol using blockchain to secure communication in vehicular networks and discusses its performance	Protocol evaluated through simulations. Results-protocol outperforms existing approaches in terms of security and scalability
[74]	Decentralized blockchain-based trust management	Uses decentralized blockchain network and trust evaluation model to enable secure and trusted communication among vehicles in IoV	Effectiveness of proposed framework evaluated through simulations
[71]	Efficient and secure blockchain-based data	Uses decentralized blockchain network to enable efficient and secure data sharing among vehicles in IoV	Efficiency and security of proposed scheme evaluated through simulations
[70]	Secure and scalable data sharing scheme for IoV	Uses blockchain-based trust model and cloud computing-based data storage and retrieval system	Reliance on cloud computing. Availability and reliability of cloud may impact overall performance
[81]	Blockchain-based system for training autonomous cars using AI	Uses blockchain to securely store and share data for training autonomous car AI model	Efficiency of AI model should be carefully evaluated. Scalability and security of blockchain-based data sharing system should also be considered
[82]	Blockchain-based system for training autonomous cars using ML	Proposes using blockchain to securely store and share data for training autonomous car ML model	Efficiency of ML model should be carefully evaluated. No real model was given
[83]	Reinforcement learning (RL)-based method for optimizing routes of self-driving vehicles	Uses RL to learn and adapt to changing conditions. Uses a heuristic search method to find optimal routes. Uses blockchain to store and share data in supply chain securely	Performance of RL should be carefully evaluated. Scalability and security of blockchain-based data sharing system should also be considered
[79]	Overview of current research on blockchain in Internet of Vehicles (IoV) and intelligent transportation systems (ITS)	Reviews various use cases, applications, architectures, challenges and future trends of blockchain in IoV and ITS	Underlying platform of IoV for information exchange needs to be transparent, secure, and immutable to achieve required objectives
[76]	Blockchain-based data sharing and resource trading model	Presents data sharing and trading model utilizes blockchain between connected cars and third parties. Model includes smart contract-based data trading	Potential benefits of model, including security, privacy, and data ownership. Challenges need to be addressed in practice
[72]	Comprehensive review of existing solutions for privacy, security and trust management issues	Presents overview of challenges and opportunities in application of blockchain in vehicular networks. Discusses various techniques for addressing these challenges	Further research in privacy-preserving blockchain design, and efficient and secure consensus mechanisms for vehicular networks needed. Does not consider scalability and performance limitations in large-scale vehicular networks
[80]	Systematic review for blockchain applications in ITSs	Uses private blockchain and deep RL for secure content caching in vehicular networks	Need for enhancing security against DDoS attacks, limitations and challenges of IoV, data management in smart cars, blockchain-based cybersecurity
[87]	Advances and trends of using blockchain in Autonomous Vehicles (AVs)	Comparative analysis of different types of autonomous vehicles, potential utilization of blockchain technology in networked AVs	Level of automation determining AV type, usage, and application of vehicles. Very wide spectrum of different AVs and application trends without focus on integration techniques

4. Challenges of integrating blockchain with autonomous cars

Along with the blockchain technology prospective benefits for self-driven vehicles, there are some challenges and issues to consider as well to fully leverage their impact. The challenge of scaling and performing stage is resulted from the growth of vehicles in networks that eventually enlarges the size of the blockchain and the computational power necessary to compute transactions. In this case, the transactions are run so slow and the latency highly increased that autonomous vehicles are inefficient and even dangerous. Autonomous vehicles have a challenge in reliability too, where they should run virtually error-free and with continuous availability. In case of failures or hacks, the blockchain network used for the cars would undermine platform safety as well as the operation functionality. Privacy and security are also among the major issues, because the central system of autonomous vehicles stores a lot of critical data, which may become available for unreliable or malicious users. Privacy is needed in autonomous vehicles, as they utilize anonymity and confidentiality to shield passengers' identity and location. The process of regulatory and legal compliance as well as maintaining the evolving standards and laws set in this integration is complex. This implies that those involved in the blockchain, and autonomous cars integration have to adhere to data protection laws and other cybersecurity regulations, among other road safety regulations.

Figure 6 provides the major challenges and considerations of blockchain, artificial intelligence and the convergence between them for intelligent transportation systems [88].

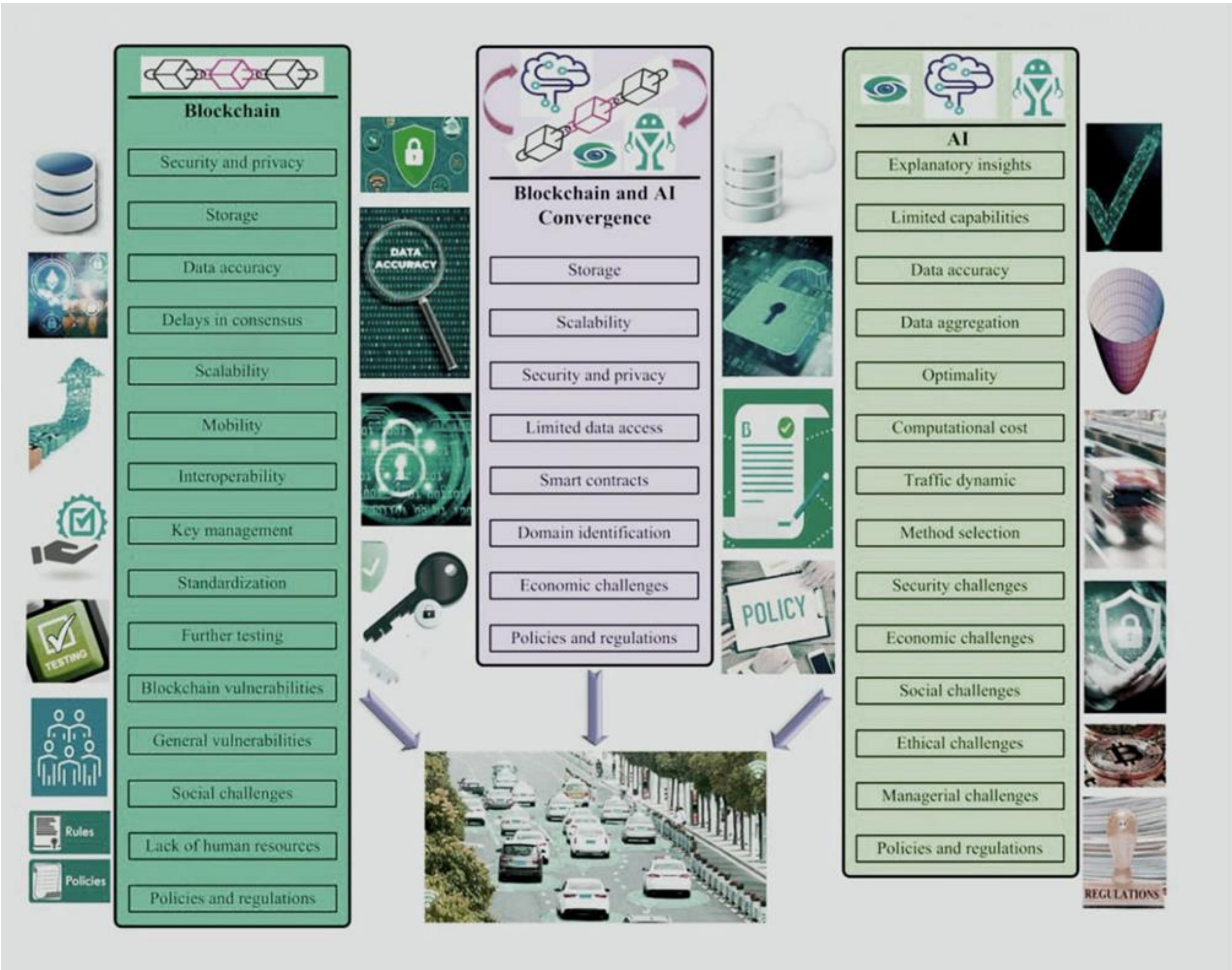

Figure 6. Main challenges in the applications of blockchain, AI, and their convergence for ITSs [88].

Factors that make blockchain challenging include security and privacy as well as data storage, throughput, data consistency, scalability, mobility, interoperability, key management, and standardization. On the AI side of the matter, the related questions involve giving explanatory insights to stakeholders, directing the abilities of AI, guaranteeing data integrity, coordinating data aggregation and, lastly, trying to achieve the highest possible optimality solutions. Other issues, such as bringing computational costs under control, opting for the right strategies to be used alongside the autonomous vehicles, issues of security are among the few obstacles. Their convergence is a double-edged sword affecting both opportunities and the formulation of new challenges and considerations. Such complexity is concerned with among others, ensuring security and privacy of data as well as limited data accessibility in the same process, storage problem, and smart contract system. Besides this, one must also examine the general implications in terms of the economy and policy and regulatory problems.

In this context, researches are working out different alternatives by which blockchain and autonomous vehicle technologies can work together. As such, blockchain could be deployed as an imperative trust management system for vehicle components, e.g. sensors, control systems and networks. It will also contribute in enhancing the security and reliability of autonomous cars. Additionally, reinforcement learning in conjunction with heuristic search methods can be employed to enhance the routes that autonomy vehicles will take within the supply chain management system. This helps in improving efficiencies and reducing the related costs. Blockchain-facilitated data collection and access can drive the improvement in the quality and reliability of the data used for autonomous vehicle learning process, which in turn increases the safety and excellence of their performance. Blockchain is not only used in data management and sharing models but also in trading models for connected cars. This technology can enable IoV-based smart city, on-demand computing resource trading and edge deployment schemes. The directions for the usage of blockchain technology have the possibility to stimulate the understanding of the intelligent transportation systems and autonomous vehicles however the challenges and limitations of the integration of the blockchain with these complex and safety-critical systems must be taken very cautiously into consideration.

5. Conclusion

Integration of blockchain and machine learning for autonomous cars is the uprising field with the capability to bring revolution in the field of self-driving vehicles with respect to safety, efficiency and security. So, this survey was built around three technologies: machine learning, blockchain and self-driving cars, studying how they work and interconnect. The covered literature also revealed that such integrations shall be applied in a multitude of ways in various fields, such as the training of self-driving vehicles and optimizing transportation routes in the supply chain management. The integration of the last-mentioned technologies with blockchain was presented as an innovative approach to address the challenges peculiar to autonomous cars, the internet of vehicles and intelligent transport systems. Additionally, the study ventured into federal learning, offering a secure approach on how connected cars can collaboratively enhance their models whilst still individual user's data privacy. Although the prospects were numerous, various challenges were encountered, such as operational challenges, technical issues, and the ideal balance between safety and efficiency. The blockchain technology has enabled transparency that raises privacy considerations for autonomous vehicles; they require anonymity and confidentiality for their operations. Besides the fact that legal space contributes to complexity, it is necessary to follow the changing rules and regulation in the field of data protection, cybersecurity, and road safety.The future research should be centered on creating scalable solutions that can be quickly replicated accordingly to fit the ever-increasing number of vehicles in the network. During the process, safety and efficiency should be taken into consideration for the sake of development of smart transport systems. Moreover, to ensure service stability, unconditional failure prevention and security protection mechanisms should be deployed. In addition to the privacy-preserving blockchain designs tailored for large-scale networks, further work on the vehicular network should be prioritized for the automobile industry. Alongside this is the need for cooperative efforts among researchers, industry representatives, and policymakers who can create awareness, and understanding of the broad aspects concerning the integration of technology, legality, and societal implications.

Author contributions

Hussam Alkashto: Writing-Original draft preparation, Visualization, Software, Data curation, Investigation. **Abdullah Elewi:** Conceptualization, Visualization, Validation, Supervision, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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An appraisal of statistical and probabilistic models in highway pavements

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Abstract

Accurate performance prediction is crucial for safe and efficient travel on highway pavements. Within pavement engineering, statistical models play a pivotal role in understanding pavement behavior and durability. This comprehensive study critically evaluates a spectrum of statistical models utilized in pavement engineering, encompassing mechanistic-empirical, Weibull distribution, Markov chain, regression, Bayesian networks, Monte Carlo simulation, artificial neural networks, support vector machines, random forest, decision tree, fuzzy logic, time series analysis, stochastic differential equations, copula, hidden semi-Markov, generalized linear, survival analysis, response surface methodology and extreme value theory models. The assessment meticulously examines equations, parameters, data prerequisites, advantages, limitations, and applicability of each model. Detailed discussions delve into the significance of equations and parameters, evaluating model performance in predicting pavement distress, performance assessment, design optimization, and life-cycle cost analysis. Key findings emphasize the critical aspects of accurate input parameters, calibration, validation, data availability, and model complexity. Strengths, limitations, and applicability across various pavement types, materials, and climate conditions are meticulously highlighted for each model. Recommendations are outlined to enhance the effectiveness of statistical models in pavement engineering. These suggestions encompass further research and development, standardized data collection, calibration and validation protocols, model integration, decision-making frameworks, collaborative efforts, and ongoing model evaluation. Implementing these recommendations is anticipated to enhance prediction accuracy and enable informed decision-making throughout highway pavement design, construction, maintenance, and management. This study is anticipated to serve as a valuable resource, providing guidance and insights for researchers, practitioners, and stakeholders engaged in asphalt engineering, facilitating the effective utilization of statistical models in real-world pavement projects.

1. Introduction

Highway pavements are crucial elements of transportation infrastructure, serving as the backbone for safe and efficient travel. These surfaces endure continuous strain from heavy loads, weather fluctuations, and environmental factors, often leading to degradation and diminished serviceability over time [1]. To confront these challenges, the field of highway pavement engineering increasingly relies on statistical and probabilistic models. These models serve as robust tools to comprehend pavement behavior and aid in strategic decision-making regarding design, construction, and maintenance approaches [2].

Statistical and probabilistic models offer a quantitative framework for predicting pavement performance, integrating uncertainties, and optimizing resource allocation [3]. They surpass conventional deterministic methods by accommodating variability in materials, construction techniques, and environmental conditions. This adaptability enables engineers and decision-makers to better evaluate the reliability, durability, and life-cycle costs of highway pavements [4].

Performance modeling and prediction stand out as primary applications of these models in highway pavement engineering. They facilitate the development of mathematical relationships between pavement performance indicators and influential factors like traffic volume, climate conditions, design specifics, and material properties. Leveraging historical data and statistical techniques, these models forecast future performance, pinpoint critical factors affecting pavement deterioration, and guide maintenance strategies to prolong pavement service life [5].

Reliability analysis constitutes another crucial area where statistical and probabilistic models make significant contributions. The principles of reliability-based design, integrating probabilistic models, empower engineers to design pavements meeting precise performance criteria with a desired level of certainty. By quantifying uncertainties related to input variables such as traffic loads, material attributes, and environmental circumstances, reliability analysis presents a more realistic evaluation of pavement performance, reducing the risk of premature failure [6].

Life-cycle cost analysis (LCCA) forms an integral part of pavement management, aiming to optimize long-term expenses while upholding desired performance levels. Statistical and probabilistic models enrich LCCA by considering input variations, encompassing construction costs, maintenance outlays, and pavement performance data [6,7]. Integrating these models into decision-making processes allows engineers to evaluate the cost-effectiveness of diverse pavement designs, materials, and maintenance strategies throughout the pavement's life cycle [7,8].

The criticality of uncertainty quantification and sensitivity analysis emerges in understanding the impact of input parameters and variability on pavement performance. Statistical methods serve as tools to gauge uncertainties and evaluate their effect on prediction reliability. Sensitivity analysis aids in pinpointing the most influential factors affecting pavement performance, enabling engineers to allocate resources strategically and focus on areas with the most potential for improvement [8-10].

Table 1. Comprehensive overview of models in highway pavement engineering: from mechanistic-Empirical to data-driven approaches.

Model Type	Application	Advantages	Contribution	Key Considerations	References
Mechanistic-Empirical Models	Rutting Prediction	Estimation of rut depth in pavements - - Calibration with field data	Equations for rutting prediction - - Regression coefficients	Dependence on accurate field data	[1-2]
Mechanistic-Empirical Models	Fatigue Cracking Prediction	Estimation of fatigue cracks in pavements	Mathematical relationship between factors - - Regression coefficients	Influence of traffic load, asphalt properties, temperature	[3-4]
Mechanistic-Empirical Models	Thermal Cracking Probability Prediction	Estimation of thermal cracking probability	Relationship involving asphalt binder properties, temperature gradient	Consideration of temperature differences	[5-6]
Statistical and Probabilistic Models	Performance Modeling and Prediction	Quantitative framework for predicting pavement performance - - Integration of uncertainties	Forecasting future performance - - Pinpointing critical factors	Adaptability to variable conditions	[7-8]
Statistical and Probabilistic Models	Reliability Analysis	Reliability-based design for pavement meeting performance criteria	Integration of probabilistic models - - Quantifying uncertainties	Reduction of risk of premature failure	[9-10]
Statistical and Probabilistic Models	Life-Cycle Cost Analysis	Optimization of long-term expenses in pavement management	Consideration of input variations - - Enrichment of LCCA	Evaluation of cost-effectiveness	[6, 11]
Statistical and Probabilistic Models	Sensitivity Analysis	Understanding impact of input parameters and variability	Gauging uncertainties - - Identifying influential factors	Strategic resource allocation	[8-10]
Data-Driven Approaches	Advanced Analytics	Fusion of statistical models with machine learning	Enhanced performance prediction and decision-making	Utilization of big data and analytics	[12]
Data-Driven Approaches	Machine Learning-Based Models	Insights from vast datasets - - Enhanced accuracy and efficiency	Improved pavement analysis - - Proactive and evidence-based pavement management	Integration with traditional models	[11-12]
Overall Study	Comprehensive Assessment	Examination of various models in pavement engineering	Scrutiny of equations, parameters, and applicability	Identification of factors impacting model performance	[13-14]
Recommendations	Actionable Guidance	Enhancing model efficacy	Informed decision-making for pavement design, construction, and management	Focus on precise input parameters, validation, and data availability	[15-16]

The emergence of big data and advanced analytics has propelled data-driven approaches in pavement engineering. Statistical and probabilistic models, in conjunction with machine learning techniques, facilitate insights from vast datasets, leading to enhanced performance prediction, condition assessment, and decision-making [11]. The fusion of data-driven approaches with traditional models enhances the accuracy and efficiency of pavement analysis, fostering proactive and evidence-based pavement management practices [12]. Table 1 provides a comprehensive overview of various pavement engineering models, categorizing them based on type, application, advantages, contribution, key considerations, and references, offering valuable insights for informed decision-making in pavement design, construction, and management.

2. Overview of statistical and probabilistic models

Mechanistic-Empirical (M-E) models in pavement engineering represent a pivotal integration of mechanistic principles and empirical data to forecast pavement performance [13]. These models rely on a series of equations that encapsulate the structural response of pavements to diverse factors such as traffic loads, climate variations, and material attributes [14]. A thorough assessment of M-E models involves scrutinizing equations, delineating parameters, evaluating performance, and considering the associated advantages, limitations, and applicability [15].

In Mechanistic-Empirical (M-E) models, a foundational equation addresses rutting prediction, estimating pavement segment rut depth. The equation is expressed as Rutting = $\beta 0 + \beta 1 \times$ Load + $\beta 2 \times$ Thickness + $\beta 3 \times$ Asphalt Properties + $\beta 4 \times$ Subgrade Strength + ϵ, where Load represents applied traffic load, Thickness indicates layer thickness, Asphalt Properties encompass asphalt mixture parameters, and Subgrade Strength denotes subgrade characteristics. The coefficients β0, β1, β2, β3, and β4 are derived through calibration processes using field data.

Another vital equation in M-E models deals with fatigue cracking prediction, estimating pavement fatigue crack count: Number of Cracks = $\beta 0 + \beta 1 \times$ Load + $\beta 2 \times$ Asphalt Properties + $\beta 3 \times$ Temperature + ϵ. In this equation, Load signifies traffic load, Asphalt Properties include asphalt material parameters, Temperature represents pavement temperature, and β0, β1, β2, and β3 are regression coefficients.

A third notable equation in M-E models focuses on predicting thermal cracking probability: Probability of Cracking = $\beta 0 + \beta 1 \times$ Asphalt Binder Properties + $\beta 2 \times$ Temperature Gradient + ϵ. Here, Asphalt Binder Properties denote asphalt binder attributes, Temperature Gradient signifies temperature differences across pavement layers, and β0, β1, and β2 are regression coefficients.

M-E models present advantages by capturing fundamental pavement behavior, enhancing accuracy compared to purely empirical models. Their adaptability allows calibration and customization for specific pavement types, materials, and climate conditions. These models facilitate design optimization by simulating diverse design alternatives and considering factors like material properties, layer thicknesses, and traffic loads. Additionally, they support the evaluation of existing pavements under varying conditions, aiding in asset management decisions and maintenance strategies. Furthermore, M-E models assist in life-cycle cost analysis by considering long-term performance and associated maintenance expenses [17].

However, M-E models entail certain limitations. The acquisition of accurate and representative input parameters, including traffic loads, material properties, and climate data, is vital for reliable predictions [18]. Calibration for these models can be intricate and time-consuming, demanding extensive field data, laboratory testing, and validation efforts. Detailed and specific data requirements may pose challenges, particularly for existing pavements with limited data availability. Sensitivity to assumptions concerning material behavior, layer interfaces, and boundary conditions represents another limitation, potentially affecting prediction accuracy. The complexity of M-E models may necessitate specialized expertise and computational resources for proper implementation and understanding [19].

The applicability of M-E models depends on factors such as pavement type, climate conditions, traffic characteristics, and the availability of reliable calibration datasets. Accurate material characterization and validation against field performance are essential for ensuring precise predictions. Incorporating M-E models within a comprehensive decision-making framework, considering engineering judgment, validation against field data, and local conditions, is crucial [19-20].

In conclusion, Mechanistic-Empirical (M-E) models stand as a transformative advancement in pavement engineering by amalgamating mechanistic principles with empirical data. The meticulous appraisal of these models involves dissecting equations, defining parameters, and evaluating performance. While offering advantages like realistic behavior, adaptability, design optimization, and life-cycle cost analysis, M-E models face challenges related to input parameter variability, calibration, data requirements, sensitivity to assumptions, and model complexity. Employing M-E models warrants a comprehensive approach within a broader decision-making framework [20-21]. Table 2 summarizes the advantages and limitations of various equations within Mechanistic-Empirical Pavement Models, highlighting their benefits and challenges, offering a concise reference for their utilization and potential pitfalls.

2.1. Weibull Distribution Models

The Weibull distribution is commonly used in pavement engineering to model the time-to-failure of pavement distresses such as cracking, rutting, and potholes [22]. The distribution provides a probabilistic framework for estimating the probability of failure at different times [23]. Critically appraising Weibull distribution models involves examining the equations, defining parameters, analyzing their performance, and

Table 2. Critical insights and considerations on advantages and limitations of mechanistic-Empirical pavement models.

Model Type	Application	Equation and Description	Advantages	Limitations	Applicability	References
Mechanistic-Empirical Models	Rutting Prediction	Rutting = β0 + β1 × Load + β2 × Thickness + β3 × Asphalt Properties + β4 × Subgrade Strength + ϵ	Estimation of rut depth in pavements	Dependence on accurate field data	Pavement types, materials, climate conditions	[13-15]
Mechanistic-Empirical Models	Fatigue Cracking Prediction	Number of Cracks = β0 + β1 × Load + β2 × Asphalt Properties + β3 × Temperature + ϵ	Estimation of fatigue cracks in pavements	Influence of traffic load, asphalt properties, temperature	Pavement types, materials, climate conditions, traffic characteristics	[13-15]
Mechanistic-Empirical Models	Thermal Cracking Probability Prediction	Probability of Cracking = β0 + β1 × Asphalt Binder Properties + β2 × Temperature Gradient + ϵ	Estimation of thermal cracking probability	- Consideration of asphalt binder properties, temperature gradient	Pavement types, asphalt binder properties, temperature differences across layers	[13-15]
Mechanistic-Empirical Models	Advantages	Captures fundamental pavement behavior - Enhances accuracy compared to purely empirical models	Adaptability for specific pavement types, materials, climate conditions	Acquisition of accurate input parameters, calibration complexity, data requirements	Design optimization, simulation of diverse alternatives, evaluation of existing pavements	[17-19]
Mechanistic-Empirical Models	Limitations	Input parameter variability - Calibration complexity and time-consuming efforts - Specific data requirements - Sensitivity to assumptions	Reliable predictions contingent on accurate and representative input parameters	Pavement types, climate conditions, traffic characteristics, reliable calibration datasets	-	[17-20]
Mechanistic-Empirical Models	Applicability Considerations	Dependence on accurate material characterization and validation against field performance - Comprehensive decision-making framework	- Comprehensive approach required, considering engineering judgment, validation, local conditions	Pavement type, climate conditions, traffic characteristics, reliable calibration datasets	-	[19-21]
Mechanistic-Empirical Models	Conclusion	Transformative advancement in pavement engineering - Amalgamates mechanistic principles with empirical data	Meticulous appraisal involving equation dissection, parameter definition, and performance evaluation	Challenges related to input parameter variability, calibration, data requirements, and model complexity	Comprehensive approach within a broader decision-making framework	[20-21]

evaluating their advantages, limitations, applicability, and other important factors.

The Weibull distribution function for pavement distresses can be expressed as (Equation 1):

$$F(t) = 1 - \exp(-(t/\beta)^{\alpha}) \quad (1)$$

In Equation 1, F(t) represents the cumulative probability of failure at time t, β is the scale parameter that determines the location of the distribution, and α is the shape parameter that influences the steepness of the distribution curve.

To estimate the parameters β and α, statistical techniques such as maximum likelihood estimation or least squares fitting can be employed. Once the parameters are determined, the Weibull distribution model can be used to estimate the probability of failure at specific time intervals.

Advantages of using Weibull distribution models in pavement engineering include their flexibility and ability to capture a wide range of failure behaviors [24]. The shape parameter α allows for modeling both early-life failures ($\alpha < 1$) and wear-out failures ($\alpha > 1$), making it suitable for representing different types of distresses [25]. The scale parameter β provides a measure of the time scale at which failure occurs. Weibull distribution models also allow for probabilistic predictions, enabling engineers to assess the probability of pavement distresses occurring within a given time frame [26].

Additionally, Weibull distribution models can be beneficial for analyzing the performance of pavement sections and making informed decisions regarding maintenance and rehabilitation strategies [27]. By estimating the probability of failure over time, engineers can prioritize repairs based on the expected life remaining for different distresses [28]. This probabilistic approach helps optimize resource allocation and reduce the risk of premature or delayed repairs.

However, there are limitations to consider when using Weibull distribution models. One limitation is the assumption of statistical independence, which may not always hold true for pavement distresses. For instance, the occurrence of one distress, such as cracking, may influence the development of other distresses, such as rutting. Deviations from independence can impact the accuracy of predictions [29].

Another limitation is the requirement of a sufficient amount of failure data for accurate parameter estimation. Obtaining a comprehensive dataset of failure times can be challenging, especially for rare or extreme distresses. Limited data can lead to uncertainties in parameter estimation and affect the reliability of predictions [30].

Furthermore, Weibull distribution models assume that the failure process follows a specific pattern. However, actual pavement distresses may exhibit complex behavior influenced by various factors, such as traffic loads, climate conditions, and material properties. The simplicity of the Weibull distribution may not fully capture the intricacies of the failure process, and additional factors may need to be considered [30-31].

The applicability of Weibull distribution models in pavement engineering depends on the specific distress being analyzed, the availability of failure data, and the objectives of the analysis [32]. These models are particularly suitable for time-to-failure analysis and can provide valuable insights into the reliability and performance of pavement sections [33, 34].

Weibull distribution models offer a probabilistic framework for analyzing the time-to-failure of pavement distresses [35]. They provide flexibility, probabilistic predictions, and aid in decision-making regarding maintenance and rehabilitation strategies [36]. However, limitations related to independence assumptions, data availability, and the simplicity of the model should be considered [37]. Weibull distribution models are applicable in pavement engineering for time-to-failure analysis, but they should be used in conjunction with other tools and engineering judgment to obtain a comprehensive understanding of pavement performance [38,39].

2.2. Markov Chain Models

Markov chain models have been widely used in pavement engineering to analyze the deterioration process of pavement infrastructure [40]. These models provide a stochastic framework for understanding the transition of pavement condition states over time. Critically appraising Markov chain models involves examining the equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [41].

The fundamental equation in Markov chain models is the transition probability matrix, which represents the probabilities of transitioning from one pavement condition state to another. Let's consider a simplified example where we have three condition states: Good (G), Fair (F), and Poor (P). The transition probability matrix can be represented as (Equation 2):

$$P = |\ p(GG)\ p(GF)\ p(GP)\ |\ |\ p(FG)\ p(FF)\ p(FP)\ |\ |\ p(PG)\ p(PF)\ p(PP)\ | \tag{2}$$

In this matrix, p(GG) represents the probability of transitioning from a good condition to Good condition, p(GF) represents the probability of transitioning from Good to Fair, and so on. The sum of probabilities in each row of the matrix is equal to 1, ensuring that a transition will occur at each time step [42].

The transition probability matrix can be estimated using historical data, expert opinions, or statistical techniques. Once the matrix is determined, it can be used to simulate the deterioration process of pavements over time and estimate the probabilities of being in different condition states at specific time intervals [43].

Advantages of using Markov chain models in pavement engineering include their ability to capture the stochastic nature of pavement deterioration and provide insights into the evolution of condition states over time. These models can assist in long-term planning, budgeting, and decision-making related to pavement maintenance and rehabilitation strategies. Markov chain models also offer a systematic approach to analyzing and predicting the future condition of pavement networks, allowing engineers to allocate resources efficiently [44-45].

Moreover, Markov chain models can accommodate various factors that influence pavement deterioration, such as traffic loads, climate conditions, and maintenance activities. By incorporating these factors into the transition probabilities, the models can provide a more realistic representation of the deterioration process [45].

However, Markov chain models have limitations that should be considered. One limitation is the assumption of stationarity, which assumes that the transition probabilities remain constant over time [46]. In reality, the transition probabilities may change due to external factors or changes in pavement management practices. Deviations from stationarity can affect the accuracy of predictions.

Another limitation is the requirement of reliable and representative data for estimating the transition probabilities. Obtaining comprehensive data on pavement condition states and their transitions can be challenging, especially for large pavement networks. Insufficient or biased data can lead to uncertainties in the estimated transition probabilities and impact the reliability of model predictions [47].

Additionally, Markov chain models assume a discrete set of condition states, which may not fully capture the continuous nature of pavement deterioration. The discrete nature of the model may result in limited resolution when analyzing pavement condition changes [48-49].

The applicability of Markov chain models in pavement engineering depends on the availability of data, the desired level of analysis (e.g., network-level or project-level), and the specific objectives of the analysis. These models are particularly useful for long-term asset management and can provide valuable insights into the evolution of pavement condition states [49]. Table 3 presents an overview and critical analysis of Distribution Models, focusing on Weibull Distribution, and Markov Chain Models in the context of pavement engineering.

Table 3. Distribution Models and Markov Chain models in pavement engineering.

Models	Equations	Advantages	Limitations	Applicability	References
Weibull Distribution Models	F(t) = 1 - exp(-(t/β)^α)	Flexibility, Probabilistic predictions, Maintenance decisions based on expected life	Independence assumptions, Data availability, Simplistic pattern assumption	Time-to-failure analysis, Reliability insights	[22-34]
Markov Chain Models	P = | p(GG) p(GF) p(GP) | | p(FG) p(FF) p(FP) | | p(PG) p(PF) p(PP) |	Stochastic representation, Long-term planning, Resource allocation	Assumption of stationarity, Data requirement, Discrete states' limitation	Long-term asset management, Pavement condition evolution insights	[40-49]

2.3. Regression Models

Regression models are extensively used in pavement engineering to establish relationships between various input variables and pavement performance indicators [50]. These models allow for the prediction of pavement behavior based on observed data and provide valuable insights for design, analysis, and decision-making processes. Critically appraising regression models involves examining the equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [51].

A common form of regression equation used in pavement engineering is the multiple linear regression model, which relates a dependent variable (e.g., pavement distress or performance indicator) to multiple independent variables (e.g., traffic load, climate conditions, material properties). The equation can be represented as (Equation 3):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_p X_p + \varepsilon \qquad (3)$$

In Equation 3, Y represents the dependent variable, β_0 represents the intercept, β_1, β_2, ..., β_p are the coefficients corresponding to the independent variables X_1, X_2, ..., X_p, and ε represents the random error term.

To estimate the regression coefficients, statistical techniques such as ordinary least squares (OLS) estimation or maximum likelihood estimation are commonly employed. The coefficients reflect the magnitude and direction of the relationship between the independent variables and the dependent variable. By analyzing the coefficients, engineers can gain insights into the significance and contribution of each independent variable to the pavement performance [52].

Advantages of using regression models in pavement engineering include their simplicity, interpretability, and ability to incorporate various input variables. Regression models provide a quantitative framework for understanding the relationships between input variables and pavement performance [53]. They can help identify the most influential factors affecting pavement behavior and guide decision-making processes, such as selecting appropriate materials, optimizing design parameters, and estimating future performance.

Moreover, regression models can facilitate the development of empirical design guidelines and performance prediction models. By analyzing historical data and observing the relationship between independent variables and pavement performance, engineers can establish empirical equations that simplify the design process and improve the accuracy of performance predictions [54].

However, regression models have limitations that should be considered. One limitation is the assumption of linearity in the relationship between the dependent variable and independent variables. In reality, the relationships may be nonlinear, and the use of linear regression may not capture the full complexity of the underlying behavior. Nonlinear regression techniques or alternative modeling approaches may be required to address this limitation [55]. Another limitation is the reliance on available data for model development. Insufficient or biased data can lead to unreliable regression models and inaccurate predictions. Data quality, representativeness, and sample size are crucial factors that can affect the performance of the regression models [55].

Additionally, regression models assume that the relationship between the independent variables and the dependent variable remains constant over time and across different conditions. Changes in environmental factors, traffic patterns, or material properties may violate this assumption and impact the accuracy of model predictions [56]. The applicability of regression models in pavement engineering depends on the availability of relevant data, the suitability of the selected independent variables, and the objectives of the analysis [57]. These models are particularly useful for analyzing and predicting pavement performance based on observed data. However, caution should be exercised when extrapolating the results outside the range of observed data or when applying the models to significantly different conditions [58]. Table 4 provides an overview of regression models in pavement engineering.

Table 4. Overview of Regression Models in pavement engineering.

S/No	Aspect	Description	References
1	Introduction	Regression models in pavement engineering	[50-51]
2	Regression Equation	Multiple linear regression for pavement distress [51].	
3	Variables	Y, $0\beta0$, $\beta1$,$\beta2$,...,βp, εε	
4	Coefficient Estimation	Statistical techniques for coefficient estimation	[52]
5	Advantages	Simplicity, interpretability, and versatility	[53]
6	Empirical Design Guidelines	Facilitating design guidelines and predictions	[54]
7	Limitations	Linearity assumption, data reliance, and stability concerns	[55]
8	Applicability	Applicable based on data, variables, and analysis goals [57].	[57-58]

2.4. Bayesian Networks

Bayesian networks have emerged as a powerful modeling technique in pavement engineering, allowing for probabilistic reasoning and analysis of complex relationships between variables [59]. These networks provide a graphical representation of variables and their dependencies, incorporating both observed data and prior knowledge to make informed predictions and decisions. Critically appraising Bayesian networks involves examining the equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [60].

In a Bayesian network, variables are represented as nodes, and their relationships are depicted as directed edges or arcs between the nodes. The structure of the network captures the conditional dependencies among variables, while probability distributions represent the strength of these dependencies. The network is constructed based on prior knowledge, expert opinions, and available data. Once the network structure is established, Bayesian inference techniques can be used to update and refine the probabilities based on observed data [61].

The key equation in Bayesian networks is Bayes' theorem, which allows for the calculation of posterior probabilities given prior probabilities and observed evidence. In a simplified form, Bayes' theorem can be expressed as (Equation 4):

$$P(H \mid E) = P(H) \times P(E \mid H) / P(E) \tag{4}$$

In Equation 4, P(H | E) represents the posterior probability of hypothesis H given evidence E, P(H) is the prior probability of H, P (E | H) is the probability of observing evidence E given H, and P(E) is the probability of observing evidence E.

Bayesian networks offer several advantages in pavement engineering [62]. First, they allow for explicit representation of uncertainties and their propagation throughout the network. This enables engineers to make probabilistic predictions and assess the reliability of their estimates. Bayesian networks can also handle incomplete or uncertain data by incorporating prior knowledge, making them robust in situations where data availability is limited [63]. Table 5 presents Bayesian networks in pavement engineering.

Furthermore, Bayesian networks provide a framework for incorporating multiple sources of information, including both quantitative data and qualitative expert opinions. This integration of diverse knowledge sources enhances the decision-making process and improves the accuracy of predictions. Additionally, Bayesian networks enable sensitivity analysis, which allows engineers to assess the impact of changes in input variables on the output predictions. This sensitivity analysis aids in identifying the most influential factors and understanding their relative importance in pavement performance [64].

Despite their advantages, Bayesian networks have limitations that should be considered. One limitation is the complexity of model development, which requires expert knowledge in selecting appropriate variables, defining their dependencies, and estimating the necessary probabilities. Constructing and updating the network structure can be challenging, particularly for large and complex systems [65]. Another limitation is the requirement of sufficient and representative data to estimate the probabilities accurately. In situations where data scarcity exists, the network may rely heavily on prior knowledge, which can introduce uncertainties and biases into the model [66].

Moreover, Bayesian networks assume that the network structure and parameter values remain constant over time and across different conditions.

Changes in the system or underlying relationships may require updating the model, which can be labor-intensive and time-consuming [67].

The applicability of Bayesian networks in pavement engineering depends on the availability of data, the complexity of the problem, and the objectives of the analysis [68]. These models are particularly useful for decision support systems, risk assessment, and performance prediction under uncertainty [69]. Bayesian networks can provide valuable insights into pavement behavior and support informed decision-making by considering both quantitative and qualitative information [70].

Table 5. Bayesian Networks in pavement engineering: aspects and applicability.

S/No	Aspect	Description	References
1	Methodology	Bayesian networks offer probabilistic reasoning and complex relationship analysis in pavement engineering [59].	[59-60]
2	Structure	Graphical representation with nodes for variables and edges for dependencies; constructed based on prior knowledge and data [60].	[60-61]
3	Equation	Bayes' theorem for calculating posterior probabilities based on prior probabilities and observed evidence [61].	[61]
4	Uncertainty	Explicit representation of uncertainties, enabling probabilistic predictions and reliability assessment [62].	[62-63]
5	Data Handling	Robust handling of incomplete or uncertain data through incorporation of prior knowledge [63].	[63]
6	Knowledge Integration	Integration of quantitative data and qualitative expert opinions for improved decision-making and prediction accuracy [62].	[62]
7	Sensitivity Analysis	Enables sensitivity analysis to assess the impact of input variable changes on output predictions [64].	[64]
8	Model Complexity	Model development complexity due to the need for expert knowledge and challenges in constructing and updating large and complex systems [65].	[65]
9	Data Requirement	Requires sufficient and representative data for accurate probability estimation; reliance on prior knowledge in data-scarce situations [66].	[66]
10	Model Dynamics	Assumes constant network structure and parameter values, requiring model updates for changes in the system or underlying relationships [67].	[67]
11	Applicability	Useful in decision support, risk assessment, and performance prediction under uncertainty in pavement engineering [68].	[68-70]

2.5. Monte Carlo Simulation Models

Monte Carlo simulation models have become a popular technique in pavement engineering for analyzing the uncertainty and variability associated with pavement performance [71]. These models utilize random sampling and repeated simulations to estimate the range of possible outcomes and their probabilities. Critically appraising Monte Carlo simulation models involves examining the equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [72].

The fundamental principle behind Monte Carlo simulation is to generate random samples for input variables based on their probability distributions. These input variables can include traffic loads, material properties, climate conditions, and other parameters that influence pavement performance. The simulations are then performed repeatedly using the sampled input values, and the results are recorded for analysis [73].

Monte Carlo simulation models offer several advantages in pavement engineering. Firstly, they provide a comprehensive assessment of uncertainty by considering the entire range of possible outcomes instead of relying on single-point estimates [73-74]. This allows engineers to understand the probabilistic nature of pavement performance and make informed decisions considering the associated risks [75].

Additionally, Monte Carlo simulation models can handle complex systems and interactions between multiple variables. By incorporating various input distributions and their correlations, these models capture the interdependencies and provide a more realistic representation of pavement behavior [76].

Furthermore, Monte Carlo simulation models are flexible and adaptable to different scenarios. They can be used in various stages of the pavement life cycle, from design to maintenance and rehabilitation, to assess the potential risks and guide decision-making processes [77].

However, Monte Carlo simulation models also have limitations that should be considered. One limitation is the need for a sufficient number of simulations to obtain reliable results. As the number of simulations increases, the accuracy and precision of the estimates improve. However, this can be computationally expensive and time-consuming, particularly for complex pavement models [77].

Another limitation is the requirement for accurate probability distributions for the input variables. The quality of the simulations heavily relies on the accuracy and representativeness of the chosen distributions. In cases where limited data or expert judgment is available, there may be uncertainties associated with the input distributions, which can impact the reliability of the simulation results [78].

Moreover, Monte Carlo simulation models assume that the input variables are independent and that the underlying system is stationary [78]. These assumptions may not hold true in all pavement engineering scenarios, and deviations from these assumptions can affect the accuracy and validity of the results [79].

The applicability of Monte Carlo simulation models in pavement engineering is wide-ranging. They can be used for probabilistic design, risk assessment, sensitivity analysis, and optimization of pavement performance. These models provide insights into the variability and uncertainty associated with pavement behavior, supporting decision-making processes and aiding in the development of robust pavement designs [80].

Table 6 presents a summary of Monte Carlo simulation models in pavement engineering. In conclusion, Monte Carlo simulation models offer a powerful approach to analyze uncertainty and variability in pavement engineering [81-82]. They provide a probabilistic framework for estimating the range of possible outcomes and assessing risks. However, limitations related to the number of simulations, accuracy of input distributions, and assumptions should be considered [82-83]. Monte Carlo simulation models are applicable in various stages of pavement engineering and can provide valuable insights when combined with other modeling techniques and engineering judgment [83-84].

Table 6. Monte Carlo Simulation Models in pavement engineering.

S/No	Aspect	Description	References
1	Application	Analyzing uncertainty and variability in pavement performance	[71, 82]
2	Methodology	Utilizes random sampling and repeated simulations	[72, 81]
3	Advantages	Comprehensive assessment of uncertainty, handles complex systems	[73,74, 76]
4	Flexibility	Adaptable to different scenarios and stages of pavement life cycle	[77, 80]
5	Limitations	Requires sufficient simulations, accurate probability distributions	[77-79]
6	Assumptions	Assumes independence of input variables and stationary system	[78]
7	Applicability	Wide-ranging: probabilistic design, risk assessment, sensitivity analysis	[80, 83]
8	Conclusion	Powerful approach for uncertainty analysis in pavement engineering	[81-84]

2.6. Artificial Neural Networks (ANN)

Artificial Neural Networks (ANN) models have gained significant attention in pavement engineering for their ability to capture complex relationships and make predictions based on historical data [85]. These models mimic the structure and functioning of the human brain, allowing for non-linear modeling and learning from data. Critically appraising ANN models involves examining the equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [85].

The equations used in ANN models are based on the concept of neurons and their connections within a network. The basic equation for a neuron in an ANN is the weighted sum of inputs, followed by an activation function. It can be expressed as (Equation 5):

$$y = f\left(\sum (w * x) + b\right) \tag{5}$$

In Equation 5, y represents the output of the neuron, f is the activation function, w and x are the weights and inputs, respectively, and b is the bias term.

ANN models consist of an input layer, one or more hidden layers, and an output layer. The weights and biases in the network are adjusted during a training process, where the model iteratively learns from the input-output data pairs [86]. The training algorithm, such as backpropagation, adjusts the weights and biases to minimize the error between the predicted outputs and the actual outputs.

One advantage of ANN models in pavement engineering is their ability to capture complex non-linear relationships that may exist between pavement performance indicators and various input variables. ANN models can learn from large amounts of data and adapt to changing conditions, making them suitable for analyzing the behavior of complex pavement systems [87].

Furthermore, ANN models can handle missing or noisy data and are capable of generalizing patterns from the available data to make predictions for unseen situations. This flexibility allows for the integration of diverse input variables, such as traffic loads, material properties, and environmental factors, in predicting pavement performance [87,88].

Another advantage of ANN models is their ability to provide real-time predictions. Once trained, ANN models can quickly process input data and generate predictions, making them suitable for applications that require timely decision-making, such as real-time pavement monitoring or management systems [89].

However, there are limitations to consider when using ANN models in pavement engineering. One limitation is the "black box" nature of these models, meaning they lack interpretability. It can be challenging to understand the underlying reasons for the model's predictions or to extract explicit relationships between input variables and output predictions [90].

Additionally, ANN models require a significant amount of training data to accurately learn the underlying patterns and make reliable predictions. In situations where data availability is limited, the performance of the model may be compromised. Furthermore, ANN models are sensitive to the selection of model architecture, activation functions, and training algorithms. The performance of the model can vary based on these choices, and finding the optimal configuration can be a trial-and-error process [91]. The applicability of ANN models in pavement engineering is vast. They can be used for various applications, including pavement performance prediction, optimization of pavement design, and decision support systems. ANN models are particularly useful when there are complex interactions between input variables and when non-linear relationships need to be captured [92].

Table 7 provides a summary of artificial neural networks (ANN) in pavement engineering. In conclusion, Artificial Neural Networks (ANN) models offer a powerful approach in pavement engineering to capture complex relationships and make predictions based on historical data. They excel in handling non-linear relationships, adapting to changing conditions, and providing real-time predictions [93]. However, their "black box" nature, the need for extensive training data, and sensitivity to model configuration should be considered. ANN models are applicable in a wide range of pavement engineering tasks, but care should be taken in model development, interpretation of results, and consideration of domain-specific knowledge [94-95].

Table 7. A summary of Artificial Neural Networks (ANN) in pavement engineering.

S/No	Aspect	Description	References
1	Model Type	Artificial Neural Networks (ANN)	[85]
2	Equation	$y=f(\sum(w*x)+b)$	
3	Model Structure	Consists of an input layer, one or more hidden layers, and an output layer. Weights and biases are adjusted during a training process using algorithms like backpropagation	[86]
4	Advantages	- Captures complex non-linear relationships. - Learns from large datasets and adapts to changing conditions. - Handles missing or noisy data. - Provides real-time predictions	[87-89]
5	Limitations	- Lack of interpretability (black box nature). - Requires a significant amount of training data. - Sensitivity to model architecture, activation functions, and training algorithms	[90,91]
6	Applicability	Suitable for various applications, including pavement performance prediction, pavement design optimization, and decision support systems. Particularly useful in capturing complex interactions and non-linear relationships	[92-95]

2.7. Support Vector Machines (SVM)

Support Vector Machines (SVM) models have gained prominence in pavement engineering for their ability to handle complex classification and regression tasks. SVM models aim to find an optimal hyperplane that separates data points into different classes or predicts a continuous output based on input features. Critically appraising SVM models involves examining the equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [96].

The basic equation for an SVM model can be represented as follows (Equation 6):

$$f(x) = \text{sign}\left(\sum (\alpha_i * y_i * K(x_i, x) + b)\right) \quad (6)$$

In Equation 6, f(x) represents the predicted output, α_i is the Lagrange multiplier associated with each support vector, y_i is the corresponding class label (-1 or 1), $K(x_i, x)$ is the kernel function that measures the similarity between input vectors x_i and x, and b is the bias term.

SVM models aim to maximize the margin between the hyperplane and the nearest data points of different classes, known as support vectors. The choice of the kernel function, such as linear, polynomial, or radial basis function (RBF), determines the shape of the decision boundary and the ability to handle non-linear relationships [97].

One advantage of SVM models in pavement engineering is their ability to handle high-dimensional datasets and capture non-linear relationships between input variables and pavement performance indicators. By utilizing appropriate kernel functions, SVM models can effectively map input data into higher-dimensional feature spaces, where patterns and separability become more apparent [98].

Furthermore, SVM models have a solid theoretical foundation, characterized by the structural risk minimization principle. This principle allows SVM models to generalize well from the training data to unseen instances, thus reducing the risk of overfitting and improving prediction accuracy. SVM models also offer robustness against outliers and noise in the dataset. The optimization process aims to maximize the margin between classes, effectively ignoring data points that lie far from the decision boundary. This property makes SVM models particularly useful in pavement engineering, where outliers and noise can be present due to variability in material properties, traffic conditions, or environmental factors [99].

However, there are limitations to consider when using SVM models in pavement engineering. One limitation is the computational complexity, particularly when dealing with large datasets or complex kernel functions. Training an SVM model with a high number of data points and features can be time-consuming and memory-intensive [100].

Furthermore, SVM models can be sensitive to the choice of hyperparameters, such as the kernel function, regularization parameter (C), and kernel-specific parameters. Selecting appropriate values for these hyperparameters requires careful tuning and cross-validation to achieve optimal model performance [101].

The applicability of SVM models in pavement engineering is broad. They can be used for classification tasks, such as identifying different pavement distresses or pavement condition assessment, as well as regression tasks, including predicting performance indicators such as pavement roughness or fatigue life [102]. Table 9 provides an overview of support vector machines (SVM) in pavement engineering.

Table 9. Support Vector Machines (SVM) in pavement engineering.

S/No	Aspect	Description	References
1	Model Equation	$f(x)$=sign(∑($\alpha i y i K(x i,x)+b$))	[96]
2	Kernel Functions	Linear, Polynomial, Radial Basis Function (RBF)	[97]
3	Advantages	Effective in handling high-dimensional datasets and non-linear relationships. - Solid theoretical foundation based on structural risk minimization. - - Robust against outliers and noise.	[98, 99]
4	Limitations	Computational complexity, especially with large datasets or complex kernel functions. - - Sensitivity to hyperparameters, requiring careful tuning.	[100, 101]
5	Applicability	Classification tasks for identifying pavement distresses. - - Regression tasks for predicting performance indicators like pavement roughness or fatigue life.	[102]

2.8. Gaussian Process Regression (GPR)

Support Vector Machines (SVM) models have gained prominence in pavement engineering for their ability to handle complex classification and regression tasks. SVM models aim to find an optimal hyperplane that separates data points into different classes or predicts a continuous output based on input features. Critically appraising SVM models involves examining the equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors.

The basic equation for an SVM model can be represented as follows (Equation 7):

$$f(x) = \text{sign}\ (\textstyle\sum(\alpha_i * y_i * K(x_i, x) + b)) \tag{7}$$

In Equation 7, f(x) represents the predicted output, α_i is the Lagrange multiplier associated with each support vector, y_i is the corresponding class label (-1 or 1), $K(x_i, x)$ is the kernel function that measures the similarity between input vectors x_i and x, and b is the bias term.

SVM models aim to maximize the margin between the hyperplane and the nearest data points of different classes, known as support vectors. The choice of the kernel function, such as linear, polynomial, or radial basis function (RBF), determines the shape of the decision boundary and the ability to handle non-linear relationships [103].

One advantage of SVM models in pavement engineering is their ability to handle high-dimensional datasets and capture non-linear relationships between input variables and pavement performance indicators [104]. By utilizing appropriate kernel functions, SVM models can effectively map input data into higher-dimensional feature spaces, where patterns and separability become more apparent [105].

Furthermore, SVM models have a solid theoretical foundation, characterized by the structural risk minimization principle. This principle allows SVM models to generalize well from the training data to unseen instances, thus reducing the risk of overfitting and improving prediction accuracy [106].

SVM models also offer robustness against outliers and noise in the dataset. The optimization process aims to maximize the margin between classes, effectively ignoring data points that lie far from the decision boundary. This property makes SVM models particularly useful in pavement engineering, where outliers and noise can be present due to variability in material properties, traffic conditions, or environmental factors [107].

However, there are limitations to consider when using SVM models in pavement engineering. One limitation is the computational complexity, particularly when dealing with large datasets or complex kernel functions. Training an SVM model with a high number of data points and features can be time-consuming and memory-intensive [108].

Furthermore, SVM models can be sensitive to the choice of hyperparameters, such as the kernel function, regularization parameter (C), and kernel-specific parameters. Selecting appropriate values for these hyperparameters requires careful tuning and cross-validation to achieve optimal model performance [109].

The applicability of SVM models in pavement engineering is broad. They can be used for classification tasks, such as identifying different pavement distresses or pavement condition assessment, as well as regression tasks, including predicting performance indicators such as pavement roughness or fatigue life [110].

2.9. Random Forest Models

Random Forest models have gained popularity in pavement engineering as a powerful machine learning technique for classification and regression tasks. Random Forest models are an ensemble of decision trees that make predictions by averaging the outputs of multiple individual trees. Critically appraising Random Forest models involves examining their equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicabilities, and other important factors [111].

The basic equation for a Random Forest model can be summarized as follows (Equation 8):

$$\hat{y} = RF(x) \tag{8}$$

In Equation 8, $\hat{y}$ represents the predicted output, and RF(x) denotes the Random Forest model's prediction based on the input features x.

Random Forest models consist of multiple decision trees, each trained on different subsets of the data using a technique called bootstrap aggregating (or "bagging"). Bagging helps reduce the variance and overfitting commonly associated with individual decision trees. The predictions of the individual trees are combined using averaging (for regression) or voting (for classification) to obtain the final prediction.

One advantage of Random Forest models in pavement engineering is their ability to handle high-dimensional datasets with a large number of input features. These models can effectively capture complex relationships between pavement performance indicators and a variety of input variables, such as traffic characteristics, climate conditions, and material properties [112].

Random Forest models also offer robustness against overfitting and noise in the data. By aggregating predictions from multiple trees, Random Forest models can reduce the impact of outliers and the influence of individual noisy data points, leading to more reliable predictions.

Furthermore, Random Forest models provide a measure of variable importance, which can be valuable in pavement engineering for identifying the most influential factors affecting pavement performance. This information can aid engineers in prioritizing interventions and optimizing maintenance strategies [113].

However, Random Forest models are not without limitations. One limitation is the lack of interpretability compared to simpler models like linear regression. Random Forest models are often considered black-box models, making it challenging to understand the exact relationships and mechanisms underlying the predictions [114].

Another limitation is the potential for overfitting if not properly tuned. Although Random Forest models are designed to mitigate overfitting, they can still exhibit overfitting behavior if the number of trees in the ensemble is too large or if the individual trees are allowed to grow too deep. Applicability-wise, Random Forest models find widespread use in pavement engineering for various tasks, including pavement distress identification, condition assessment, and performance prediction. They are suitable for both classification tasks, such as identifying different types of distresses, and regression tasks, including predicting performance indicators like pavement roughness or cracking [115]. Table 10 provides a comprehensive overview of random forest models in pavement engineering.

Table 10. A Comprehensive overview of Random Forest Models in pavement engineering.

Model	Equation	Advantages	Limitations	Applicability in Pavement Engineering
Random Forest Models	$y\text{\^{}}=RF(x)$	Handles high-dimensional datasets	Lack of interpretability	Classification: Distress identification - Regression: Pavement condition assessment, performance prediction
Ensemble of Decision Trees	Multiple trees with bagging	Robust against overfitting and noise	Potential for overfitting if not tuned properly	
Variable Importance	Provides a measure of influential factors	Lack of interpretability compared to simpler models		

2.10. Decision Trees

Decision tree models have been widely used in pavement engineering for their ability to handle both classification and regression tasks. They provide a transparent and intuitive representation of decision rules based on input features [116]. Critically appraising decision tree models involves examining their equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors.

The basic equation for a decision tree model can be represented as follows (Equation 9):

$$\hat{y} = \mathrm{DT}(\mathrm{x}) \tag{9}$$

In Equation 9, ŷ represents the predicted output, and DT(x) denotes the decision tree model's prediction based on the input features x.

Decision trees partition the feature space into regions based on the values of input variables and their associated thresholds. Each internal node represents a decision based on a feature and its threshold, while each leaf node represents a prediction or class label. The decision process follows a series of binary splits, leading to a hierarchical tree structure [117].

One advantage of decision tree models in pavement engineering is their interpretability. The decision rules generated by decision trees can be easily understood and visualized, allowing engineers to gain insights into the factors that contribute to pavement performance. This transparency makes decision trees valuable in explaining the decision-making process and building trust with stakeholders [118].

Decision trees can handle both categorical and numerical input features and are capable of capturing non-linear relationships. They are relatively insensitive to outliers and can handle missing data by considering surrogate splits. Decision trees also have low computational complexity during both training and prediction phases [119].

However, decision trees have certain limitations. One limitation is their tendency to overfit the training data, leading to poor generalization on unseen data. Decision trees have high variance, which means they can be sensitive to small changes in the training set and produce different trees.

To address the overfitting issue, ensemble methods such as Random Forest and Gradient Boosting are often employed, which combine multiple decision trees to improve prediction accuracy and reduce variance [119].

Another limitation is their instability to small changes in the input data. Decision trees can create different splits or structures when trained on slightly perturbed versions of the same dataset. This instability can lead to different outcomes and limits the robustness of decision tree models. In pavement engineering, decision tree models find applicability in various tasks such as pavement distress identification, classification of pavement types, and predicting performance indicators like pavement condition or remaining life [120]. Table 11 below provides an overview of application of decision trees in pavements.

Table 11. Application of Decision Trees.

Model	Equation	Advantages	Limitations	Applicability	References
Decision Trees	ŷ = DT(x)	Interpretability. - Transparent decision rules. - Handles both categorical and numerical features. - Low computational complexity.	Tendency to overfit training data. - High variance. - Instability to small changes in input data.	Pavement distress identification. - Classification of pavement types. - Prediction of performance indicators (e.g., pavement condition).	[116, 118-120]

2.11. Fuzzy Logic Models

Fuzzy logic models have gained popularity in pavement engineering for their ability to handle uncertainty and imprecision in decision-making processes. Fuzzy logic extends traditional binary logic by allowing degrees of truth between 0 and 1, which is particularly useful in situations where crisp boundaries are difficult to define [121]. Critically appraising fuzzy logic models involves examining their equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors.

Fuzzy logic models utilize linguistic variables and fuzzy sets to represent and manipulate imprecise information. The basic equation for a fuzzy logic model can be represented as follows (Equation 10):

$$\hat{y} = F(x) \tag{10}$$

In Equation 10, $\hat{y}$ represents the output, and F(x) denotes the fuzzy logic model's mapping from the input variables x to the output.

Fuzzy logic models consist of three main components: fuzzyfication, fuzzy rule base, and defuzzyfication. Fuzzyfication converts crisp input variables into fuzzy sets by assigning membership degrees to different linguistic terms. The fuzzy rule base consists of a set of IF-THEN rules that define the relationship between input fuzzy sets and output fuzzy sets. Defuzzyfication combines the outputs of the fuzzy rules to produce a crisp output [122].

One advantage of fuzzy logic models in pavement engineering is their ability to handle imprecise and uncertain information. This is particularly useful when dealing with subjective criteria or expert knowledge that may not be easily quantifiable. Fuzzy logic models can capture complex relationships between input variables and output predictions, allowing for more flexible and adaptive decision-making [123].

Fuzzy logic models also provide interpretability by using linguistic terms to describe input and output variables. This makes the models more accessible and understandable to engineers and stakeholders, enhancing the trust and acceptance of the model's predictions. Fuzzy logic models find applicability in pavement engineering tasks such as pavement condition assessment, risk analysis, and decision support systems. They can incorporate multiple input variables and expert knowledge to generate meaningful and actionable recommendations. Fuzzy logic models are particularly useful in situations where precise mathematical relationships are difficult to establish or when dealing with limited or uncertain data [124].

However, fuzzy logic models also have limitations. The design and tuning of fuzzy logic models require expert knowledge to define linguistic terms, membership functions, and fuzzy rules. This expertise may be time-consuming and subjective, and the performance of the model can be sensitive to these choices. Additionally, fuzzy logic models can suffer from the "curse of dimensionality" when dealing with a large number of input variables, leading to increased computational complexity [125].

Furthermore, fuzzy logic models may not capture complex non-linear relationships as effectively as other machine learning techniques such as neural networks or support vector machines. The interpretability of fuzzy logic models can sometimes come at the expense of predictive accuracy, as the simplicity of the fuzzy rules may not capture all nuances and interactions within the data [126].

2.12. Time Series Analysis Models

Time series analysis models play a crucial role in pavement engineering for understanding and predicting the behavior of pavement performance over time. These models analyze historical data collected at regular intervals to identify patterns, trends, and seasonal variations in the data. Critically appraising time series analysis models involves examining their equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [127].

One of the commonly used time series analysis models is the autoregressive integrated moving average (ARIMA) model. The ARIMA model is represented by the Equation 11:

$$Y(t) = \mu + \phi_1 Y(t-1) + \phi_2 Y(t-2) + \ldots + \phi_p Y(t-p) + \varepsilon(t) + \theta_1 \varepsilon(t-1) + \theta_2 \varepsilon(t-2) + \ldots + \theta_e \varepsilon(t-q) \tag{11}$$

In this Equation 11, Y(t) represents the observed value at time t, μ is the mean, ϕ and θ are the autoregressive and moving average coefficients, p and q are the order of the autoregressive and moving average components, and ε(t) represents the random error term.

Time series analysis models offer several advantages in pavement engineering. They can capture long-term trends, seasonality, and cyclic patterns in the data, allowing for accurate predictions of pavement performance over time. These models can be used to forecast future pavement conditions and estimate the remaining service life, which is essential for effective asset management and maintenance planning [128].

Time series analysis models also provide insights into the effects of external factors on pavement performance. For example, they can help identify the impact of traffic patterns, weather conditions, and maintenance interventions on pavement deterioration. By understanding these relationships, engineers can make informed decisions regarding pavement design, materials selection, and maintenance strategies [129].

Furthermore, time series analysis models are particularly useful when historical data is available but information about specific influencing factors or mechanisms is limited. They can extract valuable information from the data and provide a basis for decision-making even in the absence of detailed knowledge about underlying physical processes [130].

However, time series analysis models have certain limitations. They assume that the observed data follows a specific pattern and may not perform well if the data deviates significantly from this pattern. The accuracy of the models depends on the quality and representativeness of the historical data, and any biases or outliers in the data can affect the model's predictions.

Additionally, time series analysis models may not capture complex interactions between different variables or account for structural changes over time. In pavement engineering, where multiple factors can influence pavement performance, other modeling techniques such as regression analysis or machine learning may be more appropriate for capturing these complex relationships. It is important to note that the selection and performance of time series analysis models depend on various factors, including the availability of historical data, the nature of the data patterns, and the specific objectives of the analysis. Careful consideration should be given to the appropriate model selection and parameter estimation to ensure accurate predictions and reliable decision-making in pavement engineering [131]. Table 13 shows a summary on application of time series analysis models in pavements while Table 14 presents an overview of methods and applications in modeling techniques in pavement engineering.

Table 13. A summary on Application of Time Series Analysis Models in pavements.

Model	Equation	Advantages	Limitations	Applicability
ARIMA	$Y(t)=\mu+\phi 1Y(t-1)+\phi 2$ $Y(t-2)+...+\phi pY(t-p)+\varepsilon(t)+\theta 1$ $\varepsilon(t-1)+\theta 2\varepsilon(t-2)+...+\theta e\varepsilon(t-q)$	- Captures long-term trends, seasonality, and cyclic patterns. - Useful for forecasting future pavement conditions and estimating remaining service life. - Provides insights into the effects of external factors on pavement performance.	- Assumes a specific pattern in the data. - Performance may be affected if data deviates significantly from the assumed pattern. - May not capture complex interactions between different variables or account for structural changes over time.	- Forecasting pavement conditions. - Estimating remaining service life. - Identifying the impact of external factors on pavement performance. - Limited detailed knowledge about underlying physical processes.

2.13. Stochastic Differential Equations (SDE)

Stochastic Differential Equations (SDEs) have gained attention in pavement engineering for modeling the behavior of pavement systems under uncertain and random conditions. SDEs combine ordinary differential equations with stochastic processes, allowing for the inclusion of random variables and capturing the probabilistic nature of pavement performance. Critically appraising SDEs involves examining their equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [132].

A general form of a stochastic differential equation used in pavement engineering can be expressed as (Equation 12):

$$dY(t) = a(t, Y(t))\,dt + b(t, Y(t))\,dW(t) \qquad (12)$$

In Equation 12, Y(t) represents the pavement response variable at time t, a(t, Y(t)) is the drift term that describes the deterministic part of the equation, b(t, Y(t)) is the diffusion term that accounts for the random component, dt is an infinitesimal time step, and dW(t) represents a Wiener process or Brownian motion.

SDEs offer several advantages in pavement engineering. Firstly, they can capture the inherent uncertainties and randomness associated with pavement behavior, such as variations in traffic loads, material properties, and environmental conditions [133]. By incorporating stochastic processes, SDEs provide a more realistic representation of the complex and dynamic nature of pavement performance.

Moreover, SDEs allow for the estimation of probabilistic distributions of pavement responses, enabling the quantification of uncertainties in pavement design, analysis, and decision-making processes. This probabilistic framework facilitates risk assessment, reliability analysis, and the development of robust pavement designs that consider the uncertainties involved [134].

Table 14. Overview of methods and applications in modeling techniques in pavement engineering.

Modelling Technique	Description	Advantages	Limitations	Applicability in Pavement Engineering	References
Regression Models	Relates input variables to pavement performance indicators for prediction.	Simplicity and interpretability	Linearity assumption, sensitivity to data quality	Analyzing pavement performance based on data.	[50-56]
Bayesian Networks	Graphical representation of variable dependencies, allowing probabilistic reasoning.	Handling uncertainty, integrating knowledge	Model complexity, data requirements	Decision support, risk assessment in pavement.	[59-65]
Monte Carlo Simulation	Analyzes uncertainty by generating random samples for inputs.	Comprehensive uncertainty assessment	Computationally expensive, dependent on data quality	Probabilistic design, risk assessment in pavement.	[71-77]
Artificial Neural Networks	Captures complex relationships in pavement data with adaptability.	Capturing non-linear relationships	Lack of interpretability, data dependency	Pavement performance prediction and optimization.	[85-91]
SVM	Finds optimal hyperplanes for classification or regression tasks.	Handling high-dimensional datasets	Computational complexity, hyperparameter sensitivity	Distress identification, pavement condition assessment.	[96-102]
GPR	Handles complex pavement relationships, accounting for uncertainties.	Flexibility in capturing patterns, uncertainties	Computational complexity, sensitivity to parameters	Classification and regression tasks in pavement.	[103-110]
Random Forest	Ensembles decision trees for high-dimensional data, robust against overfitting.	Robustness, variable importance	Lack of interpretability, potential overfitting	Pavement classification, performance prediction.	[111-115]
Decision Trees	Provides transparent decision rules based on input features.	Interpretability, handles various features	Tendency to overfitting, sensitivity to input changes	Pavement distress identification, condition prediction.	[116-120]
Fuzzy Logic Models	Handles imprecise data using linguistic variables, allowing adaptive decisions.	Handling uncertainty, linguistic representation	Expertise for tuning, "Curse of dimensionality"	Pavement condition assessment, risk analysis.	[121-126]
Time Series Analysis	Analyzes historical data for pavement trends and patterns.	Captures trends, external factors' insights	Assumption limitations, sensitivity to data quality	Forecasting pavement conditions, understanding trends.	[127-131]

Another advantage of SDEs is their ability to model time-varying and nonlinear pavement behavior. They can capture dynamic processes and nonlinearity in pavement response, which are often observed in real-world conditions. This makes SDEs suitable for analyzing the performance of pavements under changing traffic conditions, environmental factors, and deteriorating mechanisms [135].

However, SDEs also have certain limitations and challenges in pavement engineering. Firstly, the estimation and calibration of parameters in SDEs can be complex and computationally intensive. Accurate estimation of drift and diffusion coefficients from limited data can be challenging, and their values may vary with different pavement types, conditions, and materials.

Table 15 presents a summary of Stochastic Differential Equations (SDE) in pavements. Furthermore, SDEs typically require a large amount of data to accurately capture the random component and determine the underlying stochastic processes. Obtaining reliable and extensive data for parameter estimation can be expensive and time-consuming, particularly for long-term pavement performance analysis. Applicability of SDEs in pavement engineering depends on the specific problem being addressed. They are particularly useful in studying pavement deterioration, life-cycle analysis, and reliability-based design, where uncertainties play a significant role. SDEs can assist in evaluating the long-term performance and reliability of pavements, facilitating informed decision-making for maintenance, rehabilitation, and asset management strategies [136].

2.14. Copula Models

Copula models have gained prominence in pavement engineering for capturing the dependence structure between random variables and analyzing their joint behavior. These models provide a flexible and powerful framework for modeling multivariate distributions, allowing for the incorporation of complex dependence patterns that cannot be adequately captured by traditional statistical approaches. Critically appraising copula models involves examining their equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [137].

Table 15. A summary of Stochastic Differential Equations (SDE) in pavements.

Model	Equation	Advantages	Limitations	Applicability
SDE	$dY(t)=a(t,Y(t))dt+b(t,Y(t))dW(t)$	Captures inherent uncertainties and randomness in pavement behaviour. Provides a realistic representation of complex and dynamic pavement performance. Enables estimation of probabilistic distributions for risk assessment and reliability analysis. Models time-varying and nonlinear pavement behaviour.	Complex and computationally intensive parameter estimation and calibration. Requires a large amount of data for accurate capture of random components. Challenges in obtaining reliable and extensive data for long-term analysis.	Pavement deterioration studies. Life-cycle analysis. Reliability-based pavement design. Evaluation of long-term performance and reliability.

The general form of a copula model used in pavement engineering can be expressed as (Equation 13):

$$C(F_1(x_1), F_2(x_2), ..., F_n(x_n)) \tag{13}$$

In Equation 13, C represents the copula function, $F_1(x_1)$, $F_2(x_2)$, ..., $F_n(x_n)$ are the marginal distribution functions of the individual random variables x_1, x_2, ..., x_n, respectively. The copula function captures the dependence structure between the variables and allows for modeling both linear and non-linear relationships.

One commonly used copula model in pavement engineering is the Gaussian copula, which assumes a multivariate normal distribution for the marginals. The correlation structure is then modeled using the copula function, typically the Gaussian copula. The equations and parameters for the Gaussian copula are as follows (Equation 14):

$$C(u_1, u_2, ..., u_n; \rho) = \Phi_n(\Phi^{-1}(u_1), \Phi^{-1}(u_2), ..., \Phi^{-1}(u_n); \rho) \tag{14}$$

Here, u_1, u_2, ..., u_n are the standardized values of the variables, Φ_n represents the joint cumulative distribution function for the multivariate normal distribution, Φ^{-1} denotes the inverse of the standard normal cumulative distribution function, and ρ is the correlation parameter that determines the strength and direction of the dependence.

Copula models offer several advantages in pavement engineering [138]. Firstly, they allow for the modeling of complex dependence structures, including asymmetry, tail dependence, and non-linear relationships. This flexibility enables a more accurate representation of the joint behavior of pavement variables, such as load and temperature, which are crucial in understanding pavement performance.

Additionally, copula models enable the estimation of joint probabilities and quantiles, which are useful in risk assessment and reliability analysis. By capturing the dependence structure, copula models can provide insights into the likelihood of extreme events, such as simultaneous high loads and high temperatures, that can lead to critical pavement failures [139].

However, copula models also have limitations and considerations in pavement engineering. Firstly, they require appropriate choice and calibration of copula functions. The selection of an appropriate copula function depends on the characteristics of the data and the underlying dependence structure. Choosing an incorrect copula can lead to inaccurate modeling results and unreliable predictions. Another challenge is the estimation of copula parameters, especially when dealing with limited data. The estimation process may require large sample sizes to achieve reliable parameter estimates, and the estimation can be computationally intensive for high-dimensional problems [140].

Table 16 presents a summary of the Copula Models in pavement engineering. Applicability of copula models in pavement engineering depends on the specific problem and the availability of relevant data. They are particularly useful when modeling the joint behavior of multiple variables that affect pavement performance. Copula models can be applied in various areas of pavement engineering, such as reliability analysis, performance prediction, and optimization of pavement designs [141].

2.15. Hidden Semi-Markov Models (HSMM)

Hidden Semi-Markov Models (HSMM) have shown promise in pavement engineering as they can capture the temporal dynamics of pavement conditions and predict their future states. HSMMs extend the traditional Hidden Markov Models (HMM) by allowing variable duration in each state, which is particularly useful for modeling the duration of pavement distresses. Critically appraising HSMMs involves examining their equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [142].

Table 16. A summary of the Copula Models in pavement Engineering.

Model	Equation	Advantages	Limitations	Applicability	References
Copula Models	$C(F_1(x_1), F_2(x_2), ..., F_n(x_n))$	Captures complex dependence structures.	Requires appropriate choice and calibration of copula functions.	Risk assessment and reliability analysis. Modelling joint behaviour of multiple pavement variables. Optimization of pavement designs.	[137-141]

In an HSMM, the pavement condition is represented by a sequence of hidden states, and the observed data correspond to these states. The key equations in an HSMM include the state transition probabilities, the duration probabilities, and the emission probabilities. HSMMs offer several advantages in pavement engineering. Firstly, they can capture the varying durations of pavement distresses, which is crucial for accurately predicting their evolution over time. Traditional HMMs assume fixed state durations, which may not accurately represent the real-world behavior of pavement conditions. HSMMs provide a more flexible framework for modeling the time spent in each state, leading to more accurate predictions [143].

Secondly, HSMMs allow for modeling multiple distinct states and their transitions, enabling the representation of different pavement distresses and their interrelationships. This capability is particularly valuable in capturing the complex nature of pavement deterioration processes, where multiple distresses can coexist and influence each other [143-144].

Furthermore, HSMMs provide a probabilistic framework for uncertainty quantification. They can estimate the uncertainty associated with the predicted pavement conditions, allowing for risk assessment and informed decision-making in pavement management and maintenance strategies [145].

However, HSMMs also have limitations and considerations in pavement engineering. One challenge is the estimation of model parameters, including the transition probabilities, duration probabilities, and emission probabilities. Adequate data for parameter estimation is crucial, and the accuracy of the model predictions heavily relies on the quality and representativeness of the training data. Another limitation is the computational complexity associated with the analysis and prediction using HSMMs, especially for large-scale pavement systems. The computational demands may increase with the complexity of the model, the number of states, and the length of the time series data [146]. Table 17 presents a summary of Hidden Semi-Markov Models (HSMM).

Applicability of HSMMs in pavement engineering depends on the specific problem and the availability of relevant data. They can be applied in various areas, such as pavement deterioration modeling, remaining service life prediction, and maintenance decision-making. HSMMs are particularly suitable when there is a need to capture the temporal dynamics and varying durations of pavement distresses [147].

Table 17. Hidden Semi-Markov Models (HSMM).

Model	Equations	Advantages	Limitations	Applicability	References
Hidden Semi-Markov Models (HSMM)	- State transition probabilities - Duration probabilities - Emission probabilities	- Captures varying durations of pavement distresses. - Models multiple distinct states and their transitions. - Provides a probabilistic framework for uncertainty quantification.	- Estimation of model parameters require adequate data. - Computational complexity, especially for large-scale pavement systems.	- Pavement deterioration modeling. - Remaining service life prediction. - Maintenance decision-making. - Suitable for capturing temporal dynamics and varying durations of pavement distresses.	[142-147]

2.16. Generalized Linear Models (GLM)

Generalized Linear Models (GLM) have been widely used in pavement engineering to analyze the relationships between predictor variables and pavement response variables. GLMs extend the traditional linear regression models by allowing for non-normal response variables and incorporating link functions to model the relationship between the predictors and the response. Critically appraising GLMs involves examining their equations, defining parameters, analyzing their performance, and evaluating their advantages, limitations, applicability, and other important factors [148].

The equation of a GLM consists of three main components: the linear predictor, the link function, and the probability distribution function.

1. Linear Predictor: The linear predictor in a GLM is defined as the sum of the predictor variables multiplied by their corresponding coefficients. It represents the systematic part of the model that captures the relationship between the predictors and the response variable. The equation of the linear predictor in a GLM can be written as follows (Equation 15):

$$\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_p x_p \quad (15)$$

where η is the linear predictor, $\beta_0, \beta_1, \beta_2, \dots, \beta_p$ are the coefficients, and $x_1, x_2, \dots, x_p$ are the predictor variables.

2. Link Function: The link function in a GLM describes the relationship between the linear predictor and the expected value of the response variable. It transforms the linear predictor to ensure that the predicted values are within a valid range for the chosen probability distribution. Commonly used link functions include the identity, log, logit, and inverse functions.

3. Probability Distribution Function: The probability distribution function determines the probability distribution of the response variable given the linear predictor. The choice of the distribution depends on the nature of the response variable. Commonly used distributions in pavement engineering include the Gaussian (normal), Poisson, negative binomial, and gamma distributions.

GLMs offer several advantages in pavement engineering. Firstly, they can handle a wide range of response variables, including continuous, count, and binary variables. This flexibility allows for the analysis of various pavement performance indicators, such as roughness, cracking severity, and distress counts.

Secondly, GLMs provide a probabilistic framework that allows for the quantification of uncertainty in the model predictions. The probability distribution function provides information about the variability of the response variable, enabling the estimation of prediction intervals and confidence intervals [149].

Furthermore, GLMs can incorporate both categorical and continuous predictor variables, allowing for the inclusion of factors such as traffic volume, climate conditions, and material properties in the analysis. This capability enables the identification of significant factors influencing pavement performance and the estimation of their effects. However, GLMs also have limitations and considerations in pavement engineering. One limitation is the assumption of linearity between the predictor variables and the linear predictor. If the relationship is highly nonlinear, alternative modeling techniques such as generalized additive models (GAMs) may be more appropriate [150].

Another consideration is the choice of the link function and probability distribution. The selection should be based on the characteristics of the response variable and the assumptions made about its distribution. Mis-specifying these components can lead to biased or inefficient estimates. Applicability of GLMs in pavement engineering depends on the research question and the nature of the data. They can be used for various tasks, including predicting pavement performance, analyzing the effects of factors on pavement deterioration, and identifying significant variables for pavement design and maintenance [151].

Table 18 presents a summary of the generalized linear models (GLM) in pavements while Table 19 summarizes a comparison of key aspects of each modeling technique in pavement engineering, including their descriptions, advantages, limitations, and applicability, along with the corresponding references for further details.

Table 18. A summary of the Generalized Linear Models (GLM) in pavements.

Model	Equations	Advantages	Limitations	Applicability	References
Generalized Linear Models (GLM)	- Linear Predictor: $\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_p x_p$ - Link Function - Probability Distribution Function	- Handles various response variables (continuous, count, binary). - Probabilistic framework for uncertainty quantification. - Incorporates both categorical and continuous predictors. - Provides insights into significant factors influencing pavement performance.	- Assumes linearity between predictors and the linear predictor. - Choice of link function and distribution is critical.	- Predicting pavement performance. - Analyzing effects of factors on pavement deterioration. - Identifying significant variables for pavement design and maintenance.	[148-151]

2.17. Survival Analysis Models

Survival analysis models, also known as time-to-event analysis or reliability analysis, have been increasingly used in pavement engineering to analyze the time until the occurrence of specific events or failures, such as pavement distresses, rutting, or fatigue cracking. These models are particularly useful when dealing with censored data, where the event of interest may not have occurred for all observed samples [152].

The main equation used in survival analysis is the survival function, which represents the probability of an event not occurring before a certain time t. The survival function is typically estimated using nonparametric methods such as the Kaplan-Meier estimator or parametric models such as the exponential, Weibull, or log-logistic distributions. Here are the equations for the survival function in the exponential and Weibull models:

Table 19. A comparison of some Modeling Techniques in Pavement Engineering: Methods, Advantages, Limitations, and Applicability.

Modeling Technique	Description	Advantages	Limitations	Applicability	References
Stochastic Differential Equations (SDE)	Incorporates stochastic processes into ordinary differential equations, modeling pavement behavior under uncertainty.	Captures uncertainties in pavement behavior, enables probabilistic predictions, models non-linear pavement responses.	Complex parameter estimation, data-intensive, calibration challenges.	Long-term pavement performance analysis, risk assessment, reliability-based design.	[132-136]
Copula Models	Captures complex dependence structures between random variables, allowing for flexible multivariate modeling.	Models asymmetry, tail dependence, non-linear relationships, aids in risk assessment, provides joint probabilities and quantiles.	Challenges in copula selection, parameter estimation, and computational complexity.	Modeling joint behavior of multiple variables, reliability analysis, risk assessment.	[137-141]
Hidden Semi-Markov Models (HSMM)	Extends Hidden Markov Models to model variable state durations in pavement conditions.	Captures varying distress durations, represents multiple distresses, aids in uncertainty quantification.	Complex parameter estimation, computational complexity, dependency on quality data.	Pavement deterioration modeling, remaining service life prediction, maintenance decisions.	[142-147]
Generalized Linear Models (GLM)	Extends linear regression, handles various response types using link functions and diverse probability distributions.	Analyzes different response variables, provides probabilistic framework, handles categorical and continuous predictors.	Assumes linearity, choice dependency on link and distribution, might lack flexibility in highly non-linear relationships.	Pavement performance prediction, factors influencing deterioration, maintenance analysis.	[148-151]

1. Exponential Survival Function: The exponential survival function assumes a constant hazard rate, meaning that the probability of failure remains constant over time. The equation for the exponential survival function is given by (Equation 16):

$$S(t) = \exp(-\lambda t) \quad (16)$$

where S(t) is the survival probability at time t, λ is the hazard rate, and exp() is the exponential function.

2. Weibull Survival Function: The Weibull survival function allows for the hazard rate to change over time. It is defined as (Equation 17):

$$S(t) = \exp(-(t/\beta)^\wedge\alpha) \quad (17)$$

where S(t) is the survival probability at time t, β is the scale parameter, α is the shape parameter, and exp() is the exponential function.

Survival analysis models offer several advantages in pavement engineering. Firstly, they account for censored data, which is common in pavement performance studies. By considering the time until failure or distress, these models provide a more comprehensive analysis of pavement deterioration.

Secondly, survival analysis models allow for the estimation of key parameters such as the hazard rate, which represents the instantaneous probability of failure at a given time. This information is valuable for understanding the deterioration patterns and predicting the remaining useful life of pavements [153].

Table 19 presents a summary of the Survival Analysis Models. Furthermore, survival analysis models can incorporate covariates or predictors to analyze the effects of various factors on pavement survival. This enables the identification of significant variables influencing pavement performance and the estimation of their effects on the failure probability.

However, there are certain limitations and considerations to be aware of when using survival analysis models in pavement engineering. One limitation is the assumption of independent and identically distributed (IID) observations, which may not always hold true in practice. Correlation among observations due to spatial or temporal dependencies should be carefully addressed [154].

Another consideration is the choice of the appropriate parametric distribution for the survival function. The selection should be based on the characteristics of the data and the underlying assumptions about the hazard rate. Mis-specifying the distribution can lead to biased or inefficient estimates.

Applicability of survival analysis models in pavement engineering lies in their ability to analyze time-to-event data, predict failure probabilities, and identify significant factors affecting pavement deterioration. They can be used for assessing pavement performance, estimating remaining service life, and informing maintenance and rehabilitation decisions [155].

Table 19. A Summary of the Survival Analysis Models.

Model	Equations	Advantages	Limitations	Applicability	References
Survival Analysis Models	- Exponential Survival Function: $S(t)=\exp(-\lambda t)$	- Accounts for censored data. - Estimation of key parameters like hazard rate. - Incorporates covariates for analyzing the effects of various factors.	- Assumption of independent and identically distributed (IID) observations. - Choice of appropriate parametric distribution is critical.	- Assessing pavement performance. - Estimating remaining service life. - Informing maintenance and rehabilitation decisions.	[152-155]

2.18. Extreme Value Theory (EVT)

Extreme Value Theory (EVT) is a statistical approach that focuses on modeling the extreme values of a random variable. In the context of pavement engineering, EVT has been used to analyze extreme events such as peak traffic loads, extreme temperatures, or exceptional pavement distresses. Critically appraising EVT involves examining its equations, defining parameters, analyzing their performance, and evaluating the advantages, limitations, applicability, and other important factors.

The main equation used in EVT is the Generalized Extreme Value (GEV) distribution, which characterizes the distribution of extreme values. The GEV distribution is defined by three parameters: location (μ), scale (σ), and shape (ξ). The cumulative distribution function (CDF) of the GEV distribution is given by (Equation 18):

$$F(x) = \exp\{-[1 + \xi(x - \mu)/\sigma]^{-1/\xi}\} \tag{18}$$

where F(x) is the CDF at a given value x, exp() is the exponential function, and ξ is the shape parameter.

EVT offers several advantages in pavement engineering. Firstly, it provides a robust framework for analyzing extreme events and their probabilities, which is essential for designing pavements to withstand extreme conditions. By focusing on the tail behavior of the distribution, EVT enables engineers to assess the risks associated with rare events that have significant implications for pavement performance [156].

Secondly, EVT allows for the estimation of extreme quantiles, such as the design traffic load or design temperature, with associated return periods. This information helps in designing pavements to meet specified reliability or risk targets.

Furthermore, EVT provides a flexible modeling approach by accommodating different types of extreme value distributions, including the Gumbel, Fréchet, and Weibull distributions. This allows for tailoring the modeling to the specific characteristics of the data under consideration [157].

However, there are limitations and considerations when using EVT in pavement engineering. One limitation is the assumption of the underlying distribution of extreme values. The choice of the distribution should be guided by statistical techniques and domain knowledge, but selecting an inappropriate distribution can lead to unreliable results.

Another consideration is the limited availability of extreme data in pavement engineering. Extreme events are by definition rare, and reliable data on extreme values may be scarce. This can lead to challenges in parameter estimation and uncertainty quantification. Applicability of EVT in pavement engineering lies in its ability to analyze extreme events, estimate extreme quantiles, and assess the risks associated with rare events. It is particularly useful for designing pavements to withstand extreme conditions and ensuring their resilience and longevity [158]. Table 20 presents a summary of the Extreme Value Theory.

Table 20. A summary of the Extreme Value Theory.

Model	Equations	Advantages	Limitations	Applicabilities	References
Extreme Value Theory	Generalized Extreme Value (GEV) distribution: $F(x)=\exp\{-[1+\xi(x-\mu)/\sigma]-1/\xi\}$	- Provides a robust framework for analyzing extreme events. - Allows estimation of extreme quantiles and return periods. - Flexible modeling with different extreme value distributions.	- Assumes the underlying distribution of extreme values. - Limited availability of extreme data.	- Designing pavements to withstand extreme conditions. - Estimating extreme quantiles for design criteria. - Assessing risks associated with rare events.	[156-158]

3. Application of response surface methods (RSM) in pavement engineering

Response Surface Methods (RSM) serve as invaluable tools in pavement engineering, offering a systematic approach to model and optimize the intricate relationships between multiple factors influencing pavement performance [159]. These statistical techniques facilitate the exploration of optimal pavement materials mix design and provide insights into the complex interplay of variables [160]. The general equation for a response surface model is $Y=f(x1,x2,...,xk)+\varepsilon$, where Y is the response variable (e.g., pavement strength, durability),$x1,x2,...,xk$ are the independent variables (e.g., mix proportions, curing time), f is the response function, and ε is the error term. In quadratic response surface models, the equation becomes more specific, incorporating terms like βi, βii, and βij to represent linear, quadratic, and interaction effects.

RSM offers several advantages in pavement engineering. Firstly, it enables efficient optimization by identifying the optimal combination of factors that lead to desired pavement performance [161]. Secondly, RSM provides insights into the interactions between various factors, aiding engineers in making informed decisions. Lastly, it contributes to resource savings by reducing the need for extensive experimental trials through the development of predictive mathematical models [162]. However, RSM has limitations. It assumes linearity in relationships, which may not hold for highly nonlinear pavement behaviors. The method is also confined to polynomial models, potentially limiting its accuracy in capturing complex pavement material interactions. Additionally, the presence of outliers in the data can impact the precision of the response surface model [163].

RSM finds practical applications in pavement optimization and materials mix design. It plays a crucial role in optimizing aggregate gradation to enhance pavement mechanical properties, including stability and rut resistance [164]. Additionally, RSM aids in determining the optimal binder content, achieving the desired balance between pavement stiffness and flexibility. Moreover, RSM optimizes factors such as curing time and temperature for concrete pavements, contributing to improved compressive strength and durability [165]. In the realm of additives and fillers, RSM assists in optimizing types and quantities, enhancing overall pavement performance [166]. In conclusion, Response Surface Methods offer a systematic and efficient approach to pavement optimization and materials mix design. While acknowledging their limitations, their advantages make them indispensable for engineers seeking to achieve optimal pavement performance through informed decision-making and resource-efficient experimentation. The diverse types of response surface models provide flexibility in addressing specific challenges encountered in pavement engineering.

4. Research gap and contribution to knowledge

The study on statistical and probabilistic models in highway pavement engineering stands as a pivotal consolidation of diverse methodologies crucial for understanding pavement behavior and facilitating informed decision-making. Its comprehensive review encompasses an array of models, from mechanistic-empirical models to artificial neural networks, offering a detailed evaluation of each model's equations, parameters, strengths, limitations, and applicability. This meticulous analysis serves as a critical bridge between historical perspectives and modern advancements, anchoring the state-of-the-art discussion in a rich foundation of past research while highlighting the context of current developments.

Notably, the study's contribution extends beyond a mere enumeration of models; it undertakes a rigorous examination of their performance in predicting pavement distress, evaluating performance, optimizing design, and conducting life-cycle cost analysis. By acknowledging both strengths and limitations, this research provides invaluable insights into the necessity of accurate input parameters, calibration, validation procedures, and the impact of data availability and model complexity. It doesn't just stop at identification; it delves into actionable recommendations for enhancing the efficacy of these models in pavement engineering, guiding future research and practice towards overcoming these identified challenges.

What truly distinguishes this study is its anticipation of serving as a crucial resource for various stakeholders in asphalt engineering. By offering insights and guidance for the practical application of statistical models in real-world pavement projects, it directly benefits researchers, practitioners, and stakeholders involved in the design, construction, maintenance, and management of highway pavements. This anticipated impact underscores the study's significance in serving as a benchmark for understanding, evaluating, and improving the application of statistical and probabilistic models in the realm of highway pavement engineering, making it an invaluable contribution to the field.

5. Recommendations

Based on the appraisal of statistical models in pavement engineering, the following recommendations can be made:

1. Further Research and Development: Continued research and development efforts should focus on refining and enhancing the existing statistical models. This includes improving the accuracy of predictions, addressing limitations, and incorporating new advancements in the field of pavement engineering.
2. Data Collection and Standardization: Efforts should be made to collect comprehensive and standardized data for input parameters of statistical models. This includes traffic loads, material properties, climate data, and pavement performance data. Standardization of data will improve the accuracy and reliability of model predictions.
3. Calibration and Validation: Proper calibration and validation of statistical models are essential to ensure accurate representation of pavement behavior. More research should be conducted to develop standardized calibration and validation procedures

specific to each model, taking into account different pavement types, materials, and climate conditions.

4. Integration of Multiple Models: Instead of relying on a single statistical model, the integration of multiple models can provide a more comprehensive and robust approach to pavement engineering. The combination of different models, such as mechanistic-empirical models with machine learning techniques, can enhance the accuracy and reliability of predictions.

5. Decision-Making Framework: Statistical models should be used as part of a broader decision-making framework that considers engineering judgment, local conditions, and validation against field data. Pavement engineers should exercise caution in interpreting and applying model results, using them as a tool to inform decisions rather than relying solely on the model predictions.

6. Collaboration and Knowledge Sharing: Collaboration between researchers, practitioners, and stakeholders in the pavement engineering field is crucial for sharing knowledge, best practices, and data. This collaboration can lead to advancements in statistical modeling techniques and ensure their practical applicability in real-world pavement projects.

7. Continuous Model Evaluation: Statistical models should be continuously evaluated and updated based on new data and advancements in the field. Ongoing monitoring and evaluation of model performance will help identify areas for improvement and ensure the models remain relevant and accurate over time.

By implementing these recommendations, the field of pavement engineering can harness the full potential of statistical models, improving the design, maintenance, and management of highway pavements, and ultimately contributing to safer and more efficient transportation infrastructure.

6. Conclusion

In conclusion, this study critically appraised several statistical models commonly used in pavement engineering, including Mechanistic-Empirical (M-E) models, Weibull distribution models, Markov chain models, regression models, Bayesian networks, Monte Carlo simulation models, Artificial Neural Networks (ANN) models, Support Vector Machines (SVM) models, Random Forest models, Decision Trees models, Fuzzy Logic models, Time Series Analysis models, Stochastic Differential Equations (SDE), Copula models, Hidden Semi-Markov Models (HSMM), Generalized Linear Models (GLM), Survival Analysis models, and Extreme Value Theory (EVT).

Each of these models has its own set of equations, parameters, advantages, limitations, and applicabilities in the field of pavement engineering. The equations presented for each model demonstrated their mathematical foundations and how they capture the behavior of pavement structures, predict distresses, estimate performance, or model uncertainties.

The appraisal highlighted the advantages of these models, such as their ability to incorporate mechanistic understanding, reflect realistic behavior, adapt to specific conditions, optimize designs, evaluate performance, and conduct cost analysis. However, the limitations and challenges associated with these models were also identified, including the need for accurate input parameters, calibration efforts, data requirements, sensitivity to assumptions, model complexity, and the need for expert knowledge.

The applicability of these models varied depending on the specific pavement engineering context, including pavement type, climate conditions, traffic characteristics, available data, and the availability of calibration and validation datasets. It was emphasized that these models should be used as part of a broader decision-making framework that includes engineering judgment, validation against field data, and consideration of local conditions.

Overall, the critical appraisal of these statistical models in pavement engineering revealed their potential to enhance pavement design, evaluation, and decision-making processes. However, it is important to carefully consider their limitations and ensure their appropriate and accurate application. Further research and advancements in these models, as well as their integration with other approaches, can continue to improve the effectiveness and reliability of pavement engineering practices.

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Author contributions

Jonah Chukwuemeka Agunwamba: Conceptualization, Methodology, Study design, Result interpretation. **Michael Toryila Tiza:** Conceptualization, Writing-Original draft preparation, Methodology, Result interpretation **Fidelis Okafor:** Methodology, Result interpretation, insights into statistical and probabilistic models, enriching understanding in the field

Conflicts of interest

The authors declare no conflicts of interest.

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SWOT analysis of green building systems in real estate development

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Abstract

Sustainable and green facts are important for leaving a healthy environment for future generations. These facts are like sustainable development, sustainable city, green building, green economy, and so on. Green building is an innovative solution to sustainable urban planning problems. In this study, green building, sustainability, development processes are examined, and the opportunities and threats of green buildings with their strengths and weaknesses are determined by SWOT analysis. Besides, the construction cost and energy savings of a green building are compared to the traditional building. As a result of SWOT analysis, besides its significant strengths such as sustainability of green buildings, low energy consumption, and independence of energy consumption, high initial investment cost was determined as the most critical weakness. The increase in building values and the emergence of new business ventures are considered opportunities for green buildings, and the perception of green buildings as luxury is considered a threat. Ultimately, this study reveals the critical significance of transitioning towards sustainable construction practices, supported by compelling numerical evidence. Despite the initial higher investment costs, green buildings exhibit substantial long-term benefits, with the construction costs of the LEED gold-certified building calculated at 31,798,854.3 ₺ and the platinum-certified building at 32,390,841.0 ₺ in January 2024. Notably, energy savings of 47.7% and 61.6% were projected for the gold and platinum-certified buildings, respectively.

1. Introduction

The subject of real estate according to the Turkish Civil Code [1]; the land constitutes independent and permanent rights (construction, resource, and other easement rights) recorded on a separate page in the land registry and unit of the building registered in the property ownership register. In legal literature, if something cannot be transported or moved without harming its essence, it is called real estate [2].

The real estate contains both underground and above-ground extensions [3]. In the Turkish Civil Code [1], it is stated that the ownership on the land covers the air above it and the ground layers below it to the extent that it is beneficial to use. This includes plants, animals, and resources, without prejudice to legal restrictions. Real estate development is defined as the process of creating value by making concrete improvements on the property [4]. The real estate development process ranges from the construction, marketing, and management of land production and new building construction to the renovation of existing buildings. It is the process in which physical places lived and worked are conceptualized, designed, and built. The successful implementation of this process is very important as it affects our economy as well as our daily life. Real estate development projects; architects, engineers, planners, etc. It consists of a team that includes many disciplines and professions. The real estate developer is the one who oversees this process and coordinates the information generated by each project participant. The success of the real estate developer is ensured by establishing the communication between the employees in the team correctly and by creating and sharing the information efficiently. Subjects of real estate project development; It includes many businesses such as the renovation of the real estate, the lease of it, and the sale of non-parceled land by parceling. The development process to building from land is shown in Figure 1. The unimproved land is firstly divided up into plots (parceling) according to zoning plan. Then it is researched with feasibility study in order to construct buildings, which is most effective and efficient use. The building development process is completed with sale and management (Figure 1).

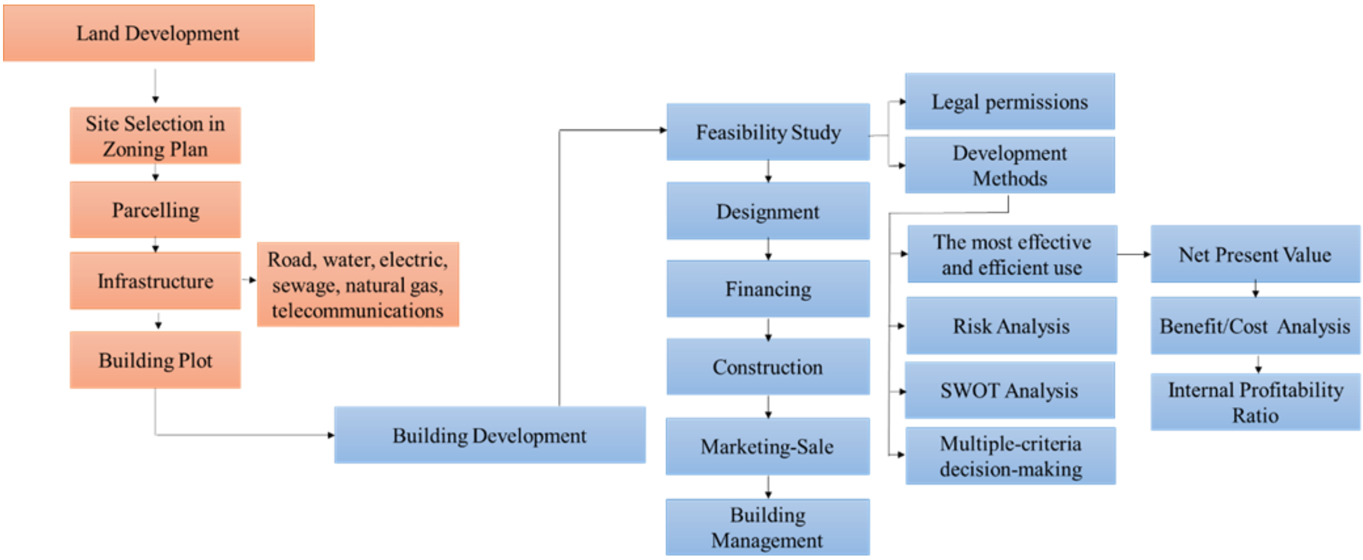

Figure 1. The development process to building from land.

Real estate development projects cover subjects such as land, residence, office, shopping center, hotel, factory. In addition to the development of some of these projects on-demand, some of them are mixed-use projects by bringing together many functions. Only new markets can be created with mixed-use projects and successful results can be obtained both economically and socially thanks to these projects. In this context, real estate development companies have a lot of work to do. Thanks to the advanced creativity of these companies, many different real estate development projects can be produced. For these projects to be realized, three important factors that can be defined as land, project idea, and capital need to be brought together. Gathering these three factors on one hand is the most practical solution for the realization of the planned project [3].

This study aim is to determine the differences between the construction of buildings consisting of 28 units of the building in Mezitli district of Mersin province as both green building and traditional building through SWOT analysis. In addition, the construction cost and energy savings of a green building, green building certification costs compare with traditional building.

Bruntland Report in 1987 with the term used today [5, 6]. According to the United Nations report in 1987, it is expressed as "developments that meet the needs of today without compromising the ability of future generations to meet their own needs" [7]. The sustainable development of contemporary cities is a highly critical task aimed at creating a beautiful, healthy, and ecological city that fully meets the needs of its inhabitants. People all over the country and city authorities must work together to ensure a better quality of life for people and the urban environment, and to balance the city with the natural environment. Concerns about climate change, clean air and water, renewable energy, and land use continue to highlight sustainability, particularly sustainable urban planning. Sustainable urban planning; includes many disciplines including architecture, engineering, biology, environmental science, materials science, law, transportation, accounting and finance, technology, economic development, and government. This type of planning also develops innovative and practical approaches to land use and its impact on natural resources.

New sustainable solutions for urban planning problems are green buildings and residences, mixed-use developments, green areas, and open spaces, alternative energy sources such as sun and wind, and transportation options. Good sustainable land use planning helps improve the well-being of people and communities by transforming urban areas and neighborhoods into healthier, more productive spaces.

Although the concept of sustainability is a new idea, sustainable cities have emerged as one of the leading issues of urbanism for more than thirty years. Sustainable cities cover a variety of sustainable urban form model topics, including eco-cities. An architect named Richard Register coined the idea of an eco-city in the late 1980s as a preferred solution to the challenges of sustainable development in sustainable development [8]. Eco-city has been defined as "an urban environmental system in which input (resources) and output (waste) are minimized" [9].

These three basic components, called social, economic, and ecological, are called "The Three Pillars of Sustainability". The ecological column is often the most noticeable. In recent years, companies operating around the world have focused on reducing their carbon footprint, packaging waste, water use, and overall environmental impact. The main reason for this is that companies have discovered that having a beneficial effect on the planet can also have a positive financial impact. For example, reducing the number of materials used in packaging generally reduces the total expenditure on these materials. The social column is another important pillar of sustainability. A sustainable business should have the support and approval of its employees, stakeholders, and the community in which it operates. The approaches to providing and maintaining this support are varied, but examples include treating employees fairly and benefiting well locally and globally. The economic pillar of sustainability is a place that most businesses consider to be on solid ground. To be sustainable, a business must be profitable. However, profit cannot overshadow the other two pillars. Profit at all costs is not the subject of the economic base. Activities that fit into the economic pillar, on the other hand, appear as compliance, appropriate management, and risk management. Sustainability will be achieved when these pillars are in harmony with each other [10].

As a result of the strategic combination of sustainability, smart cities and technology, sustainable development (energy efficiency, pollution, resources), citizen welfare (public security, education, health, social care), and economic development (investment, business, innovation) are provided [11]. Smart city and sustainable development policies and goals should be based on smart industries and services (smart energy, water, transportation, buildings, and government) and be supported by smart infrastructure (sensor networks, data analytics, smart devices, control systems, communication platforms, web). A smart city will be both a place to live and an economic space that ensures sustainable development through the systematic establishment of innovative technologies, materials, and services [12].

In the real estate development process, concepts that explain the nature of the real estate such as sustainable city, ecological city, green, environmentally friendly, and smart building have led to the creation of new concepts that enable the measurement of sustainability in structures such as advanced buildings program, business case study, LEED certification, and eco-label. Among these concepts, the concepts of ecological city and green building come to the foremost.

2. Material and method

2.1. Study area

In this study, a building located within the borders of the Mersin Province Mezitli District is considered. The district of Mezitli is located at latitude 36°.747536 and longitude 34°.518219 and has a height of 0-5 meters from the sea, fourteen floors, twenty-eight units of the building in the form of a reinforced concrete carcass II. A building in which a classroom was built is considered (Figure 2). Each unit of the building consists of 150 m^2 of living space, that is, flats. The construction cost of the building and natural gas, water, and electricity consumption were examined.

Figure 2. Study area.

2.2. Ecological city and green building

2.2.1. Ecological city

The concept of "eco-city" is one of the first organizations focusing on eco-city development, "Urban Ecology" founded by Richard Register in the USA in 1975. This organization has adopted the idea that cities and nature should be restructured in harmony [8, 13]. Founded in California, USA, this organization has made legislative proposals to encourage energy conservation and environmental policies required for the eco-city. These law proposals consist of many environmental activities, from planting trees to public transportation. Because eco-city is a phenomenon in which complex interactions between environmental, economic, political and socio-cultural factors based on healthy, human-oriented ecological principles are comprehensively addressed. In the future, living spaces such as cities, towns and villages should be designed to improve the health and quality of life of their inhabitants, and for the environment and people to live in harmony. The following items should be included in eco-city development [14, 15].

•Ecological security: disaster sheltered buildings, clean air, safe water and food

•Ecological health: ecological design and engineering to treat and recycle all waste cost effectively

•Ecological industrial metabolism: emphasizing the reuse of materials, sustainable energy use, efficient and green transport

•Eco-scape integrity: includes structures built to maximize biodiversity and maximize the city's accessibility for all citizens, open spaces such as parks and plazas, links such as streets and bridges, and natural features such as waterways

•Ecological awareness: helps people to understand their place in nature, their cultural identity, their responsibility to the environment and to increase their ability to change their consumption behavior and contribute to the preservation of high-quality urban ecosystems.

2.2.2. Green building

Green building emerges as a concept that aims to reduce the overall impact of cities on human health and the natural environment. Although this concept has been applied or defined differently in different countries, it generally covers three basic elements. These are: using energy, water, and other resources efficiently; protecting human health and the environment, to increase employee productivity; to reduce waste, pollution, and environmental degradation [15, 16].

The concept of green building, which developed at the end of the 20th century, includes concepts such as sustainable building, ecological building, and zero energy building. Green building in today's construction industry; India, Türkiye, Brazil, in the energy markets for developing countries like South Africa is of critical importance. In general terms, this concept includes parameters such as the use of the existing land, water efficiency, energy use, health and comfort conditions during the use process, selection of materials and resources used during the construction of the building, operation and maintenance activities, and innovation in this process, starting from the design process of the building.

Buildings have a certain impact on the environment during their life cycle. Harmful waste and carbon emissions arise through the use of energy, water, and other resources in the construction of buildings, their lifetime, renewal, and demolition. Sustainable building parameters, green building certificates, and rating systems have emerged to minimize these damages caused by buildings to the environment.

Green building systems developed indirectly with the concept of "Carbon Footprint" that emerged especially in the last years of the 20th century, and some certification systems in which certain common parameters are evaluated considering the differences in the geographical structures of the countries have emerged. The main goals of green buildings are as follows [17]:

• Flexible, long-lasting building designs that can adapt to changing conditions,

• Use of energy at maximum efficiency,

• Keeping the waste level to a minimum,

• Protection of water resources,

• Avoiding the use of non-environmentally friendly materials,

• Minimizing the effects that may threaten human health,

• Creating indoor air quality suitable for human health,

When the sustainability of green buildings is examined in terms of environmentally friendly design and the materials used, it is seen that they differ from other buildings. Comparing green buildings with traditional buildings, it is stated that green buildings have lower energy consumption, better indoor environmental quality, lower carbon emission emissions, and more efficient waste management, but costlier in terms of initial investment costs. Biological, ecological cement, green concrete, steel mesh, glass, etc. in the construction of green buildings materials are used, these materials are organic and mostly recyclable [18,19].

2.2.3. Green building certification systems

After the spread of the ecological, green, environmentally friendly, and sustainable building concept and the increase in its applications, there was a need for standardization in these types of buildings. It has come to the fore to establish a type of rating system that will objectively and concretely determine the effects of buildings on the environment and measure the sensitivity in the protection of natural resources. Thus, a standardization, evaluation, rating, and certification system has been established in green buildings. The certification system has enabled conceptual green buildings to become reality [20-22] (Table 1).

These systems are in chronological order in the world; BREEAM was developed in Great Britain in 1990, LEED USA in 1998, CASBEE in Japan in 2001, GREENSTAR in Australia in 2003, and DGNB in Germany in 2009.

The certificate systems designed according to the geographical characteristics of the countries spread to the developing countries with the development of the global energy economy and each country rearranged these certification systems according to their conditions [23,24].

Turkish Standards Institute in Türkiye (TSE) started to be implemented in 2013. "Safe Green Building Certificate" Environment and Urbanization prepared by the Ministry, in 2017 enacted Regulation "Green Certificates for the settlement with Buildings" will be internationally recognized national sustainable green building certification systems developed. Official institutions outside independent initiatives as Green Building Association (ÇEDBİK) in the building developed by the Ecological and Sustainable Design (B.E.S.T) manual were published in 2019 to date is the local certification system is being implemented in Türkiye and covers newly built homes.

B.E.S.T. Within the Housing Certificate System, it is planned to divide the newly built residences into 6 classes according to their square meters. For the evaluation of these houses, 9 main criteria were determined as "Integrated Green Project Management, Land Use, Water Use, Energy Use, Health and Comfort, Material and Resource Use, Living in Residence, Operation, and Maintenance, Innovation". These criteria are divided into two as construction and design, and the mandatory sections for each criterion are specified. Table 2 shows the points that the houses can receive according to B.E.S.T. Accordingly, it is evaluated as 45-64 approved, 65-79 good, 80-99 very good, 100-110 excellent [25]. Table 3 also shows the certification levels of housing evaluation systems applied in the world [21, 26].

Table 1. Green Building Certification Systems.

Criteria	BREEAM 1990 UK	LEED 1998 USA	Green Star 2003 Australia	CASBEE 2001 Japan	DGNB 2009 Germany	SB Tool 1998 Canada
Energy	✓	✓	✓	✓	✓	✓
CO_2	✓				✓	
Ecology	✓	✓	✓	✓	✓	✓
Economy					✓	
Health	✓		✓	✓	✓	
Indoor Environmental Quality	✓	✓	✓	✓	✓	✓
Innovation	✓	✓	✓			✓
Land Use	✓	✓	✓			✓
Management	✓		✓	✓		
Materials	✓		✓	✓	✓	
Environment pollution	✓	✓	✓	✓	✓	✓
Renewable technology	✓	✓	✓			✓
Transportation	✓	✓	✓		✓	✓
Waste	✓					
Water	✓	✓	✓	✓	✓	✓

Table 2. Certificate levels of green building certification systems in Türkiye [25].

B.E.S.T Criteria	Points
Integrated green project management	9
Land use	13
Water use	12
Energy use	26
Health and comfort	14
Material and resource use	14
Living in residence	14
Operation and maintenance	6
Innovation	2

Table 3. Certificate levels of green building certification systems in the world [26, 27].

Green building certification systems	Certificate levels
BREEAM	Moderate (1 Star) Good (2 Stars) Very Good (3 Stars) Excellent (4 Stars) Extraordinary (5 Stars)
LEED	Certificate (40-49 points) Silver (50-59 points) Gold (60-79 points) Platinum (80 points and above)
Green Star	4 Stars (45-59 points) 5 Stars (60-74 points) 6 Stars (75-100 points)
CASBEE	S,A,B+,B-,C
SBTool	-1 (Negative) 0 (Acceptable) 3 (Good) 5 (Best)

2.2.4. SWOT analysis

SWOT analysis was created for a detailed examination of the economy and marketing sector and is a strategic technique used to identify the strengths and weaknesses of the organization, technique, process, situation, or person involved in a project or a business venture, and to identify opportunities and threats arising from the internal and external environment. Later, it has been widely used in many research areas [28-32] including energy management [33].

A SWOT analysis consists of internal and external evaluations. Internal evaluation is done to show the strengths and weaknesses of an organization and strategic plan. External evaluation is applied to discover opportunities and threats [34]. Strengths represent available resources that can be used to improve performance. Weaknesses are flaws that can reduce competitive advantages, productivity, or financial resources. Opportunities are external changes that can contribute to further development, and threats are outside factors that can cause problems [35]. In the field of energy management, SWOT has typically been used to analyze the energy states of a single region or system. However, this study used SWOT analysis to examine sustainable green buildings [36, 37].

2.3. Ecologically sustainable real estate development

As understood in the name of ecological sustainable real estate development, it includes all of the real estate development processes and is sustainable in all of these processes. The first stage of green building projects is to determine sustainable technology and strategies after the project cost is determined within an appropriate range. The basic philosophy of green buildings aims at minimizing resource consumption and waste generation throughout the life cycle of the building. In order to achieve this goal, the stage in which many potential design alternatives are produced and evaluated during the design phase of green buildings is critical. Because the building shape and direction play an important role in the consumption of energy required for heating, cooling and lighting, it can reduce energy costs as high as 30-40% in green building construction [38]. In the green building development process, each issue should be considered separately and systematically evaluated.

Green building development projects are costlier than traditional building projects [39]. Because the various green technologies that should be used in green building development projects are in the development stage, causing them to be expensive. In order for the projects to be successful, it is necessary to make a feasibility analysis in a planned way, to make preparatory studies for project initiation and to make a detailed planning from the beginning to the end. It is critical that all stages, such as design, construction, project completion and transfer, and property management, are meticulously carried out and the plan is strictly adhered to.

The primary purpose of the concept of real estate development in green buildings is environmental sustainability, energy and water efficiency, and studies on the reduction of greenhouse gas emissions are common in the literature [13]. Technologies to be used in green building design are one of the most important parameters for green ownership [40]. It creates opportunities for property owners to minimize the environmental impacts caused by traditional buildings with various technologies identified in extensive studies [41, 42]. These technologies, such as solar energy systems [43] and waste management technologies [44], both reduce operating costs and are environmentally friendly.

There are two designs, passive and active, used in green buildings [45]. Active designs can be explained as providing electrical energy by using photovoltaic panels, wind and wave energy. Passive designs are the use of thick walls in home design, high ceilings, fans, the use of landscape elements, the use of natural and recycled materials, etc. can be listed as. In addition, it is necessary to manage natural resources, recycle waste and protect the environment for sustainability [46]. The sustainable use of underground space for infrastructure supply also has an important place [47].

2.4. Real estate development process in green buildings

During the building development process, while the design team works alone in traditional buildings, it is of great importance that the engineering and design team work together in green buildings [22]. In green buildings, it aims to create added value to the economy by combining project development, land, capital, and project thinking, and the construction of the building and the development of the land. The most effective method of creating qualified, sustainable and efficient buildings in the real estate sector are the holistic project approach. In the development process, which starts with the emergence of the project in green buildings, unlike traditional buildings, there is a holistic project approach that will start from planning and design stages to operation and demolition stages. With this operation, it will be possible to prevent the waste of labor that will occur due to both construction time and cost by predicting the problems that will occur in the design and construction process. Unlike traditional projects, it is necessary to evaluate many points in the design, construction, and operation phases of green building projects together and the design team should take more responsibility and pay attention to the certification features. The work flow chart of the real estate development process of green buildings is depicted in Figure 3. This figure adapted from Zhang et al. [48]. For example, in the design of a LEED-certified project, energy expenditures should be modeled and the design should be carried out. These LEED certification system requirements, which are not present in traditional projects, are among the criteria that must be integrated into the design and construction process [49]. Basic understanding of green building projects; contrary to the process of solving problems within the process of traditional projects, it constitutes an integrated and integrated project delivery process in which the whole system is designed from the beginning of the project. In this way, it reduces the inefficiency in the project and provides more effective work in the design, construction, and operation phases of the project [48].

According to the report of the World Green Building Council published in 2013; According to the cost evaluation of green buildings; Researches conducted by public institutions and green building organizations of various countries show that green buildings should not bring additional costs. A building should be energy and water efficient; it should be an application that should be standardized rather than an extraordinary application. Apart from this, in addition to the building construction cost, the certification process increases the initial investment cost, and when the life span and operating cost of the building are calculated, it may remain within the budget [50].

Ugur and Leblebici's study that green buildings are done on the effects of investment costs and property values, LEED-certified in Türkiye 7.43% in the gold-certified building the additional cost of green building, platinum-certified that the rate of 9.43% in the building and annual energy and, respectively, the water goes It was found that 31% and 40% savings were achieved [51].

In a study conducted for the cost of the LEED certification system in the USA, it was determined that it would bring an additional cost of over 25% for traditional buildings, while it was found that the cost of certification only increased the construction cost by 4-11% over time [52].

In another study conducted in 2010 and accepted to reach the most reliable results in terms of green building costs, it was found that the average construction cost of green buildings increased by 1.4% as a result of the calculation of building costs in an area consisting of 170 green buildings. Besides, it has been determined that the average energy saving of green buildings compared to traditional buildings is 34%. It is stated that the initial investment cost will be recovered in a short time with energy savings, considering the value of energy savings only, except for the savings to be provided from operating costs [48].

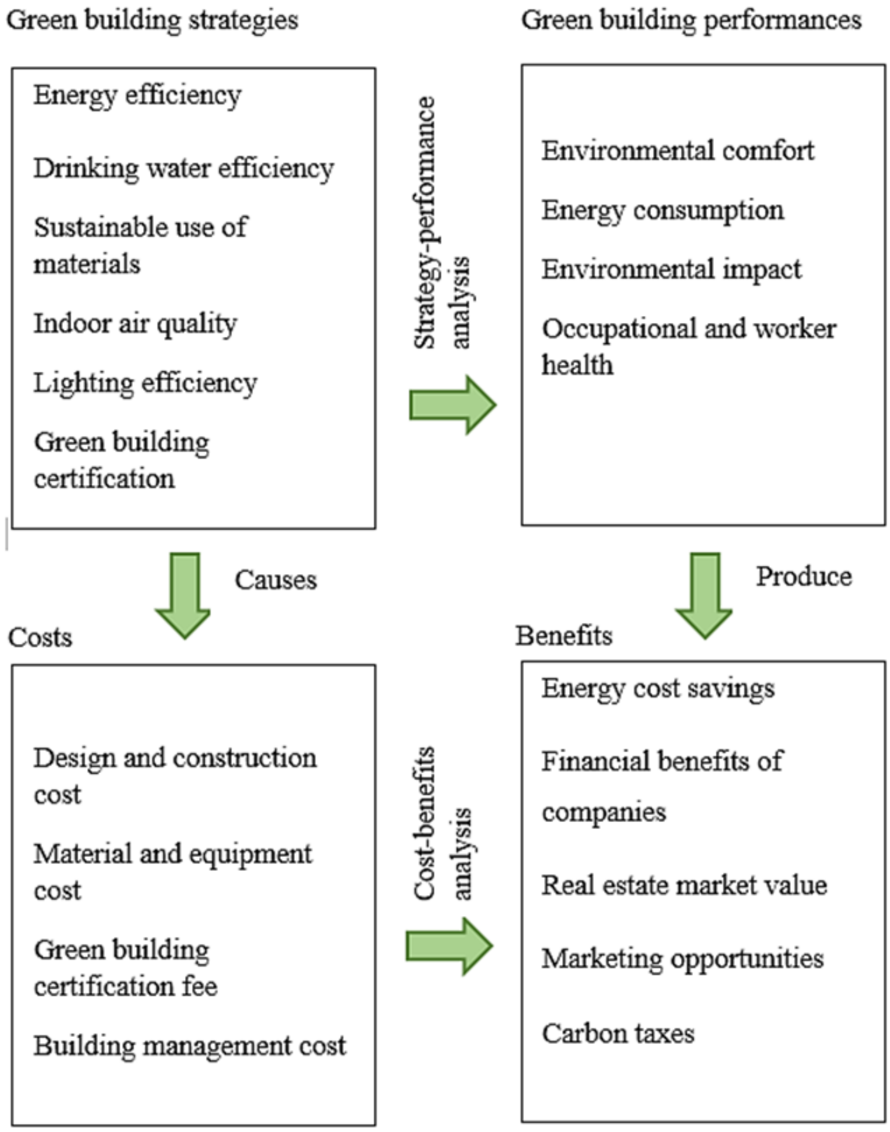

Figure 3. The work flow chart of the real estate development process of green buildings [48].

3. Results and discussion

3.1. Green Building SWOT Analysis

The SWOT analysis, in which the positive and negative aspects of green buildings are stated, are presented in Table 4 as strengths, weaknesses, opportunities, and threats. As a result of the SWOT analysis, although the initial investment cost is high and there is not enough infrastructure for some technologies in our country, the green buildings are sustainable, low energy consumption, reducing the greenhouse effect, and increasing the life quality of the society and people by living in a more environmentally friendly building, the positive aspects such as saving resources such as water and natural gas out of the monopoly of companies have been determined. Also, with the support of both states and international institutions for the construction of green buildings compared to traditional buildings, loan acquisition opportunities are facilitated to provide the necessary capital for the initial investment. In the SWOT analysis made, it is expected that green buildings will be preferred due to their advantages over traditional buildings and therefore their value will increase, the energy released in excess usage can be sold, and aesthetically, opportunities such as increasing the attractiveness of the region where green buildings are located and creating employment in different sectors are expected. As a threat, energy savings depend on consumers and misconceptions that green buildings are a luxury.

3.2. Comparison of green building cost and energy calculations with traditional buildings

In this section, the initial investment cost, annual natural gas, electricity, and water expenditures are calculated based on a 14-storey real estate with 28 units of the building with 150 m^2 flats (Table 5). The increase in the initial investment cost of the green building and the energy-saving rates were calculated by taking into account the studies of Uğur and Lebleci [51]. There is a 7.43% cost increase in the LEED gold-certified building and a 9.43% cost increase in the LEED platinum-certified building. Energy savings were calculated by assuming 31% in the gold-certified building and 40% in the platinum-certified building [51].

Construction cost and annual energy savings of traditional and green buildings are presented in Table 6. The closing time of the cost difference with energy savings is calculated as 14 years in the gold-certified building and 13 years and 10 months in the platinum-certified building. In January 2024, when it is examined the cost difference reflected in each unit of the building, it is determined as 78,544.8 ₺ in the gold-certified building and 99,687.2 ₺ in the platinum-certified building.

Table 4. SWOT analysis of green buildings.

Strengths	**Weaknesses**
• Sustainability • Low energy consumption • Low greenhouse effect • Utilizing solar energy • Independence of energy sources • Reduced heating and cooling costs • Availability of rainwater • Original structures • High rate of the loan	• Increase in initial investment cost • Low demand • Limited knowledge of sustainable technologies
Opportunities	**Threats**
• Increase in the value of the building • The ability to sell the excess produced energy • Providing new business ventures • Increasing sectoral employment • Increasing the attractiveness of the region where it is located	• Part of energy savings depends on the consumer • The perception that it is a luxury

Table 5. Annual energy consumption cost of the unit of the building in the real estate.

January 2024	150 m² unit of the building		28 units of the building	
	₺	$	₺	$
Natural Gas	3,510.71	112.10	98,299.88	3,138.60
Electricity	5,409.38	172.70	151,462.64	4,836.00
Water	2,801.19	89.40	78,433.32	2,504.30
Total	11,721.28	374.20	328,195.84	10,478.80

Table 6. Construction cost and annual energy savings of traditional and green building.

January 2024	Building (28 units of the building)		Gold-certified Building		Platinum-certified Building	
	₺	$	₺	$	₺	$
Construction cost	29,599,598.9	945,070.2	31,798,854.3	1,015,289.1	32,390,841.0	1,034,190.3
Annual energy savings	-		156,732.8	5004.2	202,235.9	6457.1
The traditional building cost difference	-		2,199,255.4	70218.9	2,791,242.1	89120.1
The closing time of cost difference with energy-saving			14 years 4 months		13 years 10 months	
Cost difference reflected in each unit of the building			78,544.8	2507.8	99,687.2	3182.8

4. Conclusion

One of the most important sectors that increase the consumption of natural resources is the construction sector. Traditional buildings built are the most effective factor that increases carbon emissions, which are harmful to the environment, together with fossil fuels used in cities. Therefore, it is necessary to develop the following items. To ensure that the consumption of natural resources is minimized by contributing to the sustainability of cities by those working in the field of real estate development, to make it cheaper and noticeable in order to increase use of renewable energy sources like wind, water, sun, biomass energy, etc. and developing new environmentally friendly materials and technology.

In these projects, very special solutions with reduced environmental negative effects should be produced and applications should be implemented. Also, a sustainable urbanization model should be performed by giving incentives to create adequate legislation and provide financial support for research on this subject.

In this study, by examining the concepts of ecological city and green building, housing ratings, and the processes in real estate development, a SWOT analysis was applied to green buildings and the cost calculations of green and traditional buildings were compared. As a result of the SWOT analysis, the most critical weakness of green buildings was the high initial investment cost, as well as the obvious strengths such as being sustainable, low energy consumption, and independent energy consumption. The increase in building values and the emergence of new business initiatives are considered opportunities for green buildings, and the perception of green buildings as luxury is considered a threat. The construction costs of the real estate consisting of 28 units of the building were calculated as 29,599,598.9 ₺, the construction costs of the LEED gold-certified building were 31,798,854.3 ₺, and the platinum-certified building was 32,390,841.0 ₺ in January 2024. In terms of energy savings, 47.7% less energy will be spent in the gold-certified building and 61.6% less in the platinum-certified building. Although the construction costs of platinum-certified buildings are higher, the annual energy savings are higher than the gold-certified buildings, so the cost difference will close in less time. In this study, a study has been conducted on how many years the construction costs will be closed by comparing the electricity, natural gas, and water consumption of traditional and green buildings. It turns out that green buildings are more beneficial than traditional buildings, even with energy and water savings, ignoring other benefits. Considering the benefits arising from other functional, environmental, social, and aesthetic performances, it is anticipated that the real market value of green buildings will be determined by the willingness to pay and market demand, and these predicted values may rise further.

Author contributions

Munevver Cagan: Conceptualization, methodology, design, drafting, analysis, writing-original draft preparation data collection. **Fatma Bunyan Unel:** Conceptualization, methodology, design, data curation, writing-original draft preparation, validation.

Conflicts of interest

The authors declare no conflicts of interest.

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Building integration of solar energy systems in Türkiye and world

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Abstract

Energy is one of the most important issues from the industrial revolution and in the globalizing world. Energy is also a big problem for the Republic of Türkiye, which has made a serious industrial breakthrough in the last 20 years. Because Türkiye, which does not have rich fossil fuels like the Middle Eastern States or Russia, is a foreign-dependent country for its energy needs. It is known that fossil fuels will be depleted in the near future and waste materials generated as a result of energy production pose great threats to the world ecosystem. Therefore, in recent years, developed and developing countries have been developing investment projects for alternative energy sources instead of fossil energy sources. The most efficient and harmless of alternative energy sources is Solar Energy. It should be noted that the use of solar energy, which is so efficient for our world and more attractive than other alternative energy sources in terms of the energy size it produces, requires a certain technical knowledge. Because Türkiye is geographically located in the middle belt and due to its special location, the number of sunny days is much higher than in other countries. In this article, the reality of solar energy in Türkiye and its potential, the solar energy systems used and how they are integrated into buildings, and the advantages and disadvantages of these integrated systems is reviewed. In addition, some examples from some countries of the world will be discussed. Furthermore, projects of integrated solar energy application systems in buildings in Türkiye are reviewed, in addition to some suggestions and recommendations in this field.

1. Introduction

Energy, which is the main agenda item of our world and will remain on the agenda for many years, is also a very important problem for Türkiye [1]. Türkiye is lucky compared to many countries in terms of its solar energy potential due to its geographical location [2]. In most European countries, buildings account for approximately 40% of the total energy use [1]. While nearly half of the energy used in buildings in Europe is produced by solar energy systems, in Türkiye, where the number of sunny days is much higher than in Europe , most of the energy used in buildings is obtained from fossil energy fuels, in addition to non-residential buildings [2].

As observed in Figure 1, Türkiye's sunshine duration is longer than that of many European countries. The developing technology and construction sector in Türkiye and the decrease in the lifespan of fossil fuels make it necessary to use the solar energy system, which is one of the alternative energy sources, in buildings. Most solar components are mounted on building roofs and they are frequently seen as a foreign element on the building structure [3]. This integration process is not accepted by many architects as it is against the design principles and spoils the appearance of the building. For these reasons, when using renewable energy systems (RES) in buildings, it is necessary to integrate the system correctly and not to spoil the form and aesthetic appearance of the building.

There is a lot of discussion by scientific committees about the advantages and disadvantages of RESs used in buildings. The advantages are:

1) Since the energy production is local, the transportation cost is minimized.
2) Since environmentally friendly energy is produced with RESs, very low levels of environmental pollution are obtained at the end of production.
3) Energy consumption expenditures of buildings are reduced.
4) It can be significant income for building owners. (for grid-connected systems)
5) The building can be of a higher class concerning energy performance certificate [3].

The disadvantages are:

1) Increases building construction costs.

2) Creation of RES models according to the design principles of the building.
3) RESs periodic maintenance and costs.
4) RESs disrupt building integrity.
5) The lack of sufficient technical infrastructure as solar energy systems in Türkiye are a new business line.

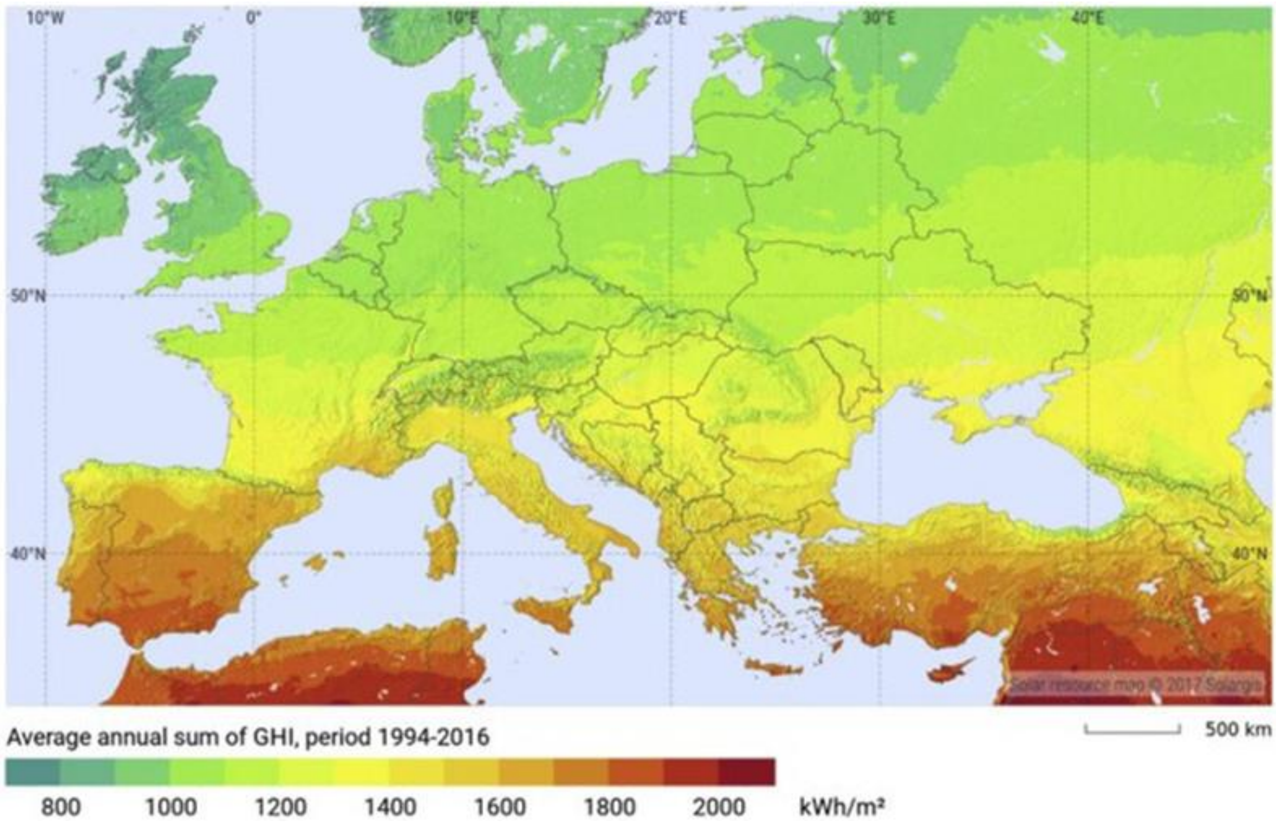


Figure 1. Annual Insolation Radiation in Europe [4].

2. Integration of solar res into buildings in Türkiye

2.1. History of solar energy system

The most important energy source in the world is the Sun. sunlight, earth and it is the main energy source possibility that affects the physical formations in the atmosphere order [5].

Socrates is the philosopher who first revealed the basic principles and principles of benefiting from this energy source [6]. Lavoisier developed a mechanism similar to a solar furnace that has a converging lens with a diameter of 1.30 meters directed to the center. With this mechanism, he achieved a temperature of 1750 °C, and inside the furnace he succeeded in melting the piece of iron that he placed [7]. The first use of solar energy, which has been used since ancient times, in its current sense it coincides with the 18th century [8]. The history of solar photovoltaic cells begins with Edmond Becquerel's discovery of the photovoltaic effect in 1839 [9].

Solar energy systems field activity in Türkiye started between 1980-1990 execution carried out; Establishing a heat pump system as a result of a practical application in the laboratory of Ege University and operating it with solar cells has been one of the first steps taken in this field [10]. Since 2000, the use of solar energy in Türkiye has been increased and the policies related to the use of solar energy have been given importance.

2.2. Solar energy potential in Türkiye

Due to its geographical location, Türkiye has many solar energy potential country is lucky [11]. The annual average solar radiation is 1303 kWh/m and the total annual sunshine duration is 2623 h. energy needed for heating applications sufficient to provide [12].

Although Türkiye is a rich country in terms of solar energy, can be noticed in Figure 2 that not every region or province has the same solar energy. In Türkiye, the smallest and largest values of annual average solar radiation occur in the Black Sea Region with 1120 kW/m^2 and in the Southeastern Anatolia Region with 1460 kW/m^2, respectively [13]. This difference is one of the most important factors in the integration of solar energy systems into buildings. For example, Şanliurfa is the province with the most sunshine duration in Türkiye, and Rize has the least sunshine duration. Solar energy systems to be integrated into buildings in these two provinces should not be designed and manufactured in the same way. Therefore, before a solar energy system is designed, the conditions of the region and even the province should be evaluated and solar energy systems should be produced as a result of these researches. Türkiye's sunshine duration by region is given in the Table 1.

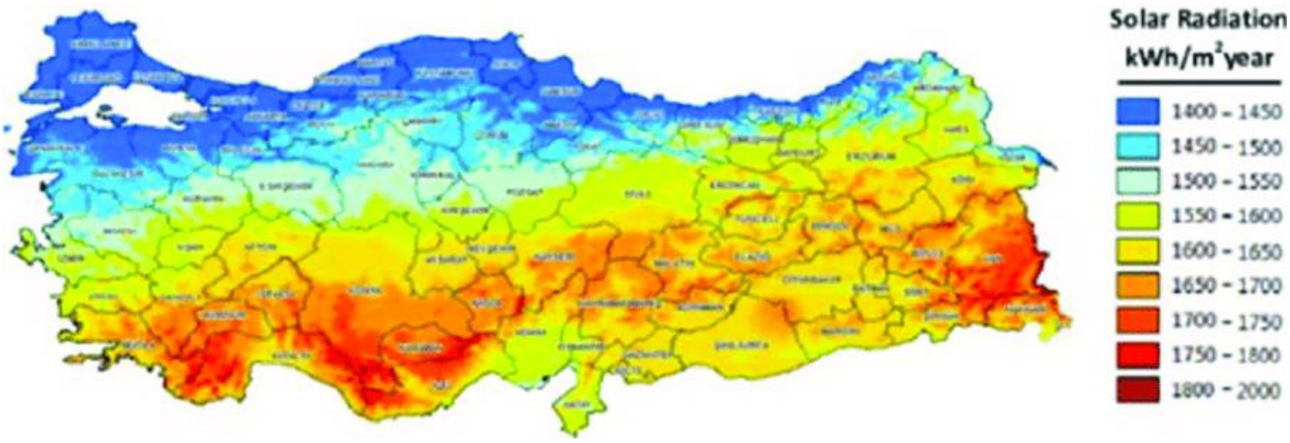


Figure 2. Average sunshine radiation of Türkiye [14].

Table 1. Distribution of solar energy and sunshine duration by regions in Türkiye.

Regions	Annual Total Solar Energy (KWh/m^2) year	Annual Total Sunbathing Time (Hours/year)
Southeast Anatolia Region	1 460	2 993
Mediterranean Regions	1 390	2 956
Aegean Region	1 304	2 738
Central Anatolia Region	1 314	2 628
Eastern Anatolia Region	1 365	2 664
Marmara Region	1 168	2 409
Black Sea Region	1 120	1 971
Türkiye Average	1 311	2 640

2.3. Types of solar energy systems used in buildings in Türkiye

Solar energy systems used in Türkiye are examined under two main headings:
1) Passive Systems
2) Active Systems

2.3.1. Passive systems

Between 470 and 399 BC The house of Megaron, belonging to Socrates, is a house that shows the beginning of passive systems [15]. While designing this house, the relationship of the facades of the house with the sun was taken into consideration. The windows of the rooms of the house were placed on the south facades and were designed according to the terrain conditions. If periods close to the day are examined, in 1940 Architect George Fred Keck designed the provincial passive solar house (Figure 3).

The most important thing about passive systems should be added to the building in the same process as the design phase of the building. Passive systems are not added to the building afterward. Without the need for any mechanical-technical staff, the location of the building, and other architectural features such as location, form, and building envelope relative to buildings made systems.

Passive Systems are examined under two headings among themselves:

Figure 3. George Fred Keck First Modern Passive Solar House, Chicago [16].

2.3.1.1. Passive systems formed by the natural environment

If the factors influencing the negative systems formed by the natural environment are included:
a) Latitude and longitude degrees of the region where the building will be built,
b) The sea level of the area where the building will be built,
c)Air temperature
d)Physical environment
e) Climate, humidity and wind,
can be counted as.

According to these effects in order to make the place comfortable, high indoor air quality and low cost. It is important that the space operates passively with less energy [15].

2.3.1.2. Passive systems formed by artificial environment

The environment created by man, not naturally, is called "Artificial Environment". Natural heating of buildings without the aid of mechanical devices or consciously at the design stage for ventilation of the wind, solar. Planning according to such factors reveals passive systems. The point to be considered with the artificial environment is the absence of any mechanical accents that are subsequently integrated into the building. Therefore, it should not be confused with active systems.

2.3.2 Active systems

Systems that convert the energy carried by the sun's rays from the sun into heat, light or electrical energy with mechanical and technical materials are called active systems. These systems are divided into two according to the purpose for which they use solar energy. The first system, the collectors, uses the solar energy to heat the water. The second system, Photovoltaic (PV) systems, converts the solar energy to electrical energy (Figure 4). If these two systems are examined separately:

(a) (b)

Figure 4. Solar Collector (a) and Photovolatic System (b).

2.3.2.1. Photovoltaic Systems

There are various ways to install Photovoltaic (PV) systems in a building. Among them, the most preferred method in Türkiye is the method installed with brackets on a flat or sloping roof (Figure 5).

Figure 5. PV's brackets [17].

Integration of PV systems into the building can be examined and applied under 3 main headings:

(a) Integrating the panels into the building's exoskeleton. In this integration method, PV panels are installed in the empty space by removing the roof tiles and external walls (Figure 6). Although it is a new integration method in Türkiye, it is more advantageous than other methods that are frequently used. Its advantages can be listed as follows:
1) It does not destroy the integrity of the building by removing the add-ons afterwards.
2) It provides high energy efficiency.
3) Since it is compatible with the architectural aesthetics of the buildings, it does not cause architectural deformation.
4) Since it is made of solid materials, it has a longer life than other methods.

Besides its advantages, it also has some disadvantages. These are:

1) It is a very costly method.
2) When there is a new business line in Türkiye, the necessary equipment and technical team are insufficient.
3) Since it is used only in electricity generation, it should be used together with hot water and other methods for heating.

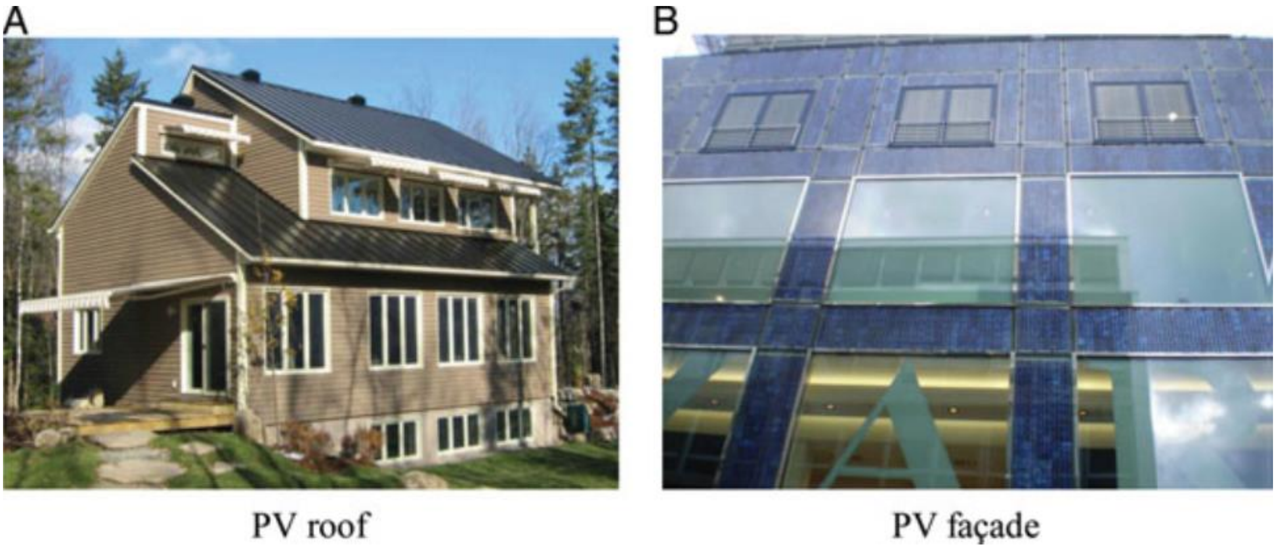


Figure 6. Building integration of PV. (a) PV roof. (b) PV facade [1].

(b) Use of heat collection functions in harmony with PV panels. PV panels typically convert from % 6 to 18 % of the incident solar energy to electrical energy, and the remaining solar energy is available to be captured as useful heat [1]. This heat is lost outdoors in normal applications. In this application, a cooling liquid (air or water) is circulated behind the panel. This liquid helps the panel to cool. This cooling increases the efficiency of the panel because if the temperature of the panel is lowered, the electricity generation life will be extended. This application can be configured in two different ways:

In one open-loop configuration, outdoor air is passed under PV panels and the recovered heat can be used for space heating, preheating of ventilation air or heating domestic hot water—either by direct means or through a heat pump [1]. Such systems produce both electricity and heat energy for the building and eliminate the extra application project load required for the heat in the first application.

It should be noted that in these two applications, PV systems are replaced by building elements. While these applications are economically beneficial, some problems also arise. These are the problems of rain penetration into buildings and heat insulation.

(c) Integrating light transmission functions into the PV panel – building integrated PV/light. In this application, special PV panels are used (translucent PV panels) that transmit some of the sun's rays into the building (Figure 7). In this application, some of the sun rays are absorbed by the panels, but a significant part is directed into the building to illuminate the building. One of the important difficulties of this application is to prevent the windows from overheating. Because this application can cause overheating of the rooms in the building and loss of comfort, since the panels act as windows in the building.

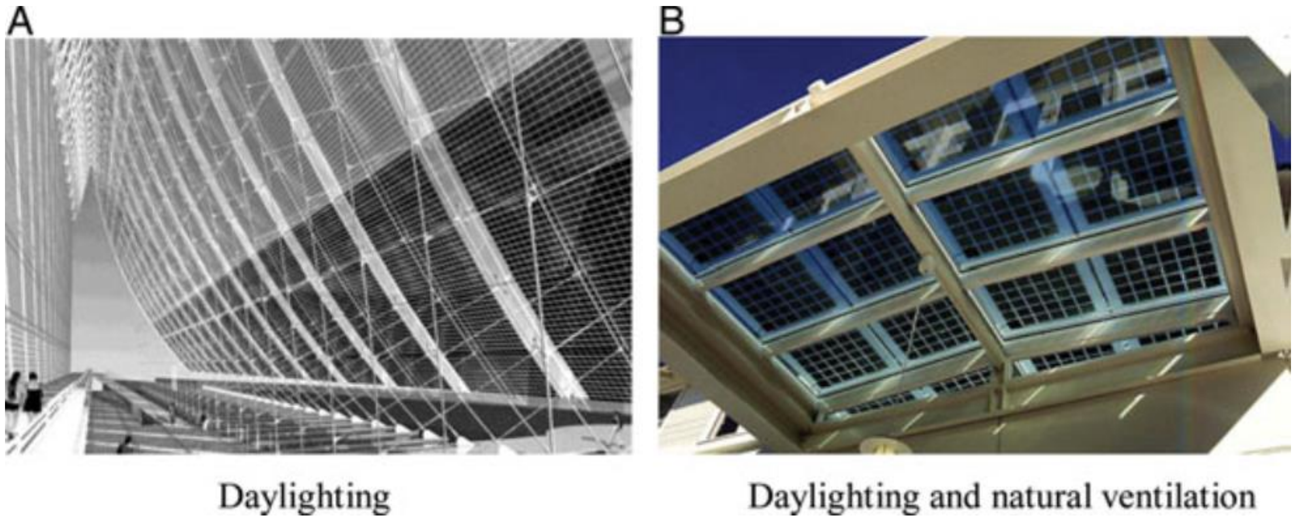


Figure 7. Combination of building integrated PV with daylighting and natural ventilation. (a) Daylighting (b) Daylighting and natural ventilation [1].

2.3.2.1.1. Considerations for the use of PV systems in Türkiye

Although the use of PV systems in Türkiye is a new business line, it can be said that it has progressed rapidly with the incentives made in recent years. There are some issues that need to be considered in the implementation of this developing business line in Türkiye. If these issues

are researched, it should be known that photovoltaic systems cannot be used in some areas. To exemplify these areas:
1) Since Türkiye has a rough terrain, PV systems cannot be used on lands with a slope of more than 3 degrees.
2) Large-scale PV systems are not used in residential areas.
3) PV systems are not used in areas within 100 m of highways and railways.
4) PV systems cannot be used in areas within 1 km of airports.
5) It cannot be used in areas within 500 m of environmental protection areas and nature parks.
6) PV systems cannot be used in lakes, dams and rivers.

2.3.2.1.2 Building integration applications of PV systems in Türkiye

In Türkiye, PV systems can be integrated into buildings in various ways. If these applications are checked:

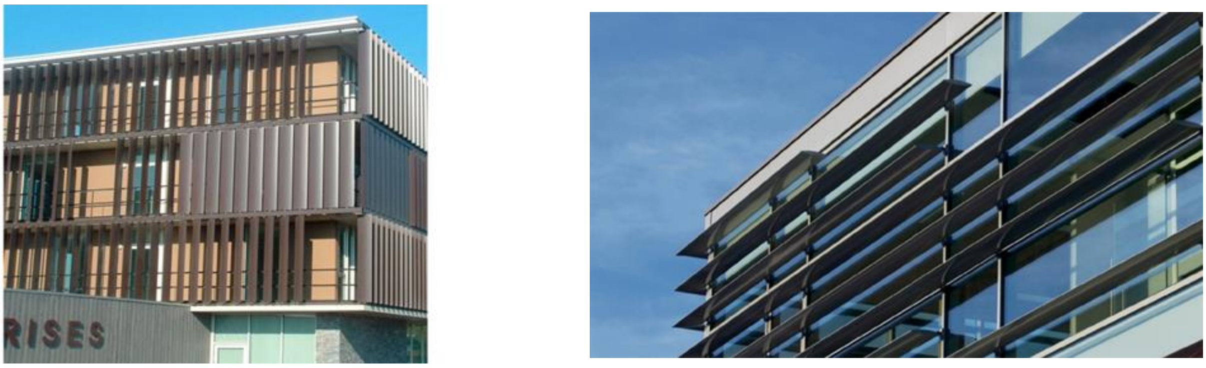
a) Using as a sunshade in buildings

This application, which is the most preferred application in Türkiye, is a useful application method to produce its own energy, to save energy and to protect the building from disturbing sunlight (Figure 8). The use of sunshades in Türkiye is not the same for every building facade. They are used horizontally on south facades. Because with this application, while the high-angle summer sun is prevented from entering the building, the low-angle winter sun is allowed to enter the building.

Vertical sunshades, on the other hand, are preferred on the west and east facades of the building, ensuring that the areas inside the building are protected from harmful sun rays in hot summer months.

b) Using as a coating facade in buildings

Another PV system application used in Türkiye is Coating Facade PV Systems. Facades are one of the most important structural elements in the aesthetic appearance of the building. For this reason, in the application of PV systems used on facades, the design phase of the building and the facade is more important than the installation of mechanical accents. While the coating facade PV systems are being designed, they should be designed together with the building and attention should be paid to the architectural harmony of the PV system and the building (Figure 9).



(a) (b)

Figure 8. Vertical PV sunshades (right photo) and horizontal PV sunshades (left photo) [18].

(a) (b)

Figure 9. Facade PV systems added to buildings later (b), Facade PV systems designed with the building (a) [19].

When examining the application forms in the two photos above, it can be seen that the photovoltaic system of facade cladding made with the building is more aesthetic.

c) Using as a glass in building

The method used as PV glass provides a significant amount of electrical energy to the building, as in other methods. It also contributes to the modern architectural movement by adding a different aesthetic appeal to the building (Figure 10). The most important thing that distinguishes this method from other methods is that thermal insulation elements can be used on glass. With this method, the building both produces its own energy and minimizes heat loss. Studies on this method, which has very little application area in Türkiye, should be intensified and the design and implementation teams should be informed about this method.

Figure 10. Example of Glass PV system used in buildings [18].

d) Use as roof covering in building

The PV system material used in this method is mounted on the roof. Contrary to other methods, in this method, the PV system is integrated into the existing building, not at the design stage of the building. The point to be considered in this application should be the choice of types and colors suitable for the aesthetic appearance of the building of the PV materials added later. These methods are embodied with pictures (Figure 11):

Figure 11. Integration of thin film PV system on roof [20].

The integration of the thin-film PV system on the roof is a method of adaptation to the existing building (Figure 12). The point to be considered in this method is that the aesthetic appearance of the building should not be impaired while the PV system is integrated into the building. This method is generally used in pitched roofs to maintain the existing slope of the roof.

In the framed PV system integration method, there is a frame construction, unlike the thin-film PV system. PV panels are not directly integrated into the roof. There are auxiliary structural elements (Figure 13). Just as thin film PV systems are used, framed PV systems are also used on pitched roofs. The difference from thin-film PV systems is higher energy efficiency. However, it is more costly than thin-film PV systems.

Another difference method of framed PV systems on roofs is their integration into flat roofs. Although the PV panel used is the same as the PV panel used in the other method, the additional construction used is different. In this integration method, since the roof is flat, it tends to better use the solar rays of the PV systems with an additional construction.

In the above titles, it has been explained what photovoltaic systems are, what methods they are used in and in which region of Türkiye. In next title, Solar collectors, which are the most widely used solar energy systems in Türkiye, will be included.

Figure 12. Integration of framed PV systems into the building [21,22].

Figure 13. Integration of framed PV systems on flat roofs [23].

2.3.2.2. Solar collectors

Solar collectors have a history dating back almost 120 years. Yet, benefiting new materials and innovative designs, they keep evolving to more effective systems satisfying the necessities of various applications [24]. Solar collectors convert solar energy into heat energy. They differ from PV systems because they convert solar energy into heat energy (PV systems convert solar energy into electrical energy).

Solar collectors consist of a double glass upper surface, the space left between the glass and the absorber layer, a metal or plastic absorber layer, a coating on the back and sides, and a casing that takes place inside all these parts (Figure 14) [15].

The sun's rays fall on the absorbing surface and heat this surface. It provides heating of the liquid inside the pipes connected to the heated surface.

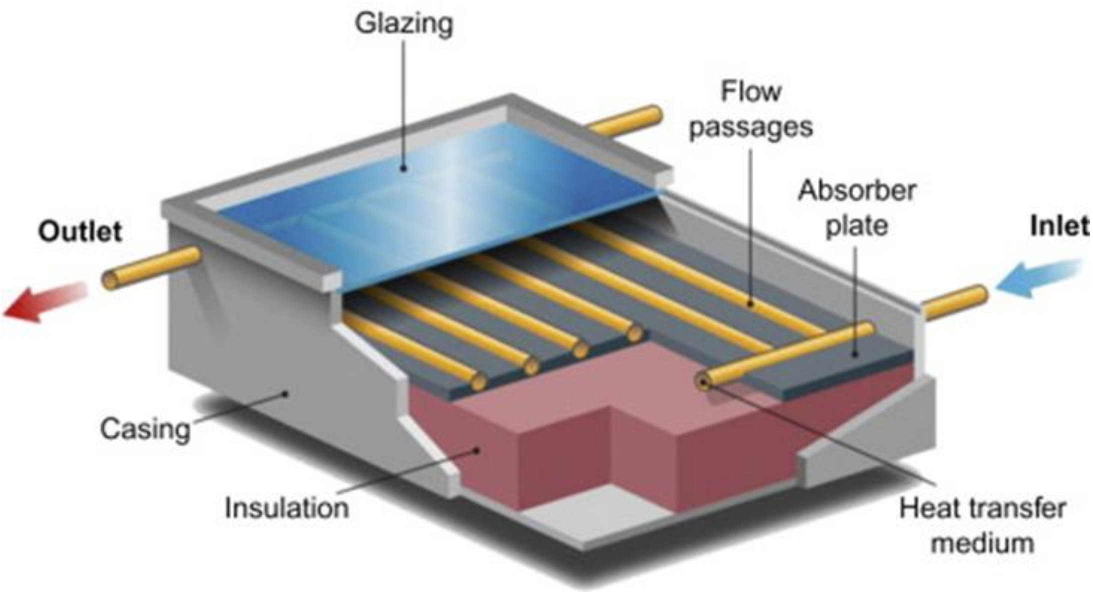


Figure 14. Elements that make up the collector [25].

Solar collectors (Solar Thermal Panel-STP); planar solar collector, vacuum tube solar collector classified as [26] In planar solar collectors (Figure 15), through the glass cover there may be heat losses by convection [26]. However, the vacuum tube solar collector heat losses by vacuuming between the transparent pipe and the black painted pipe inside is avoided [26].

The technical details of the types of solar energy systems and their integration into a building have been reviewed in the above headings. The next topic will review the application projects of solar energy systems to buildings in the world and in Türkiye.

(a) (b)

Figure 15. Planar solar collector (a) and vacuum tube solar collector (b) [25,27].

3.Application projects of solar energy systems in the world and Türkiye

Numerous projects in the world where building integrated active and passive solar energy systems are used exists [28]:

3.1. The world's largest solar energy office building shines in China

The world's largest solar building, exhibition halls, scientific research center, special for meetings and educational events, with a building area of 75,000 m^2 in the north-west of China it is a multifunctional project with areas and sections used as a hotel [28] (Figure 16). By encouraging the use of sustainable energy in building construction, solar energy was used instead of fossil fuels. A large number of solar panels are installed on the facade and roof of the building. Thanks to this design approach in the building, an average of 30% per year energy recovery was achieved [29].

Figure 16. World's largest solar Office building (China) [30].

3.2. Salavador Dali Museum

Yan Weymounth, the architect of the Salvador Dali Museum (Figure 17), which welcomes an average of 300 000 visitors a year, was based on the sustainable energy model during the design of the building. Thanks to the active and passive energy systems used on transparent and opaque surfaces, the heating-cooling, ventilation and electrical energy needs of this museum, which has a very intensive use, can be met to a large extent [16].

3.3. Novartis Building, Basel, Switzerland

This building (Figure 18), built in 2009, is perhaps one of the best examples in the world of the integration of solar energy systems into the building. The glass roof covering is equipped with semi-transparent PV panels and the panels are produced in a project-specific color [31]. With this integrated system, all the electrical energy needs of the building throughout the year are met.

3.4. Muğla University Türk Evi'' Student Cafeteria

It can be said that the planned integration of PV systems with the Muğla University student cafeteria is done (Figure 19). The roof of the building is covered with PV panels. With the building-integrated grid-connected system with an installed power of 25.6kWp over 35,000 kWh of electrical energy is produced annually and is connected to the grid is transferred [34].

Figure 17. Salvador Dali Museum [32].

Figure 18. Novartis Building, Basel, Switzerlan [33].

Figure 19. Muğla University Türk Evi'' Student Cafeteria [35].

3.5. Denizli government building

With the BIPV application (Building Integrated Photovoltaics) in the Denizli Government Building (Figure 20), all the energy needs of the building (75 kWp) are met from this system [31]. With the PV systems added to the roof, the building can produce the energy it needs. Since the system is connected to the grid, it can use the electrical energy it produces without storing it.

Figure 20. Denizli Government Building [36].

4. Conclusion and recommendations

Today, with the developing technology and rapidly increasing population, the desire of individuals to have better living standards has increased the energy used by humanity significantly [37]. Considering the future as well as the present, it is a necessity to design new buildings energy-efficiently, to make existing buildings energy-efficient, and not to create ecological environmental problems by choosing the energy needed by the building from renewable energy sources [38]. When examining the distribution of energy use in Türkiye according to sectors, the rate of energy used in buildings is not to be underestimated. In today's developing Türkiye, where fossil fuels seriously increase the foreign dependency of the country's economy, the use of alternative energy sources becomes even more important. At the beginning of these alternative energy sources, of course, is Solar Energy. Photovoltaic panels producing electricity in a country like Türkiye, which is extremely advantageous in terms of solar energy, it is possible to produce an estimated 40 billion kWh of electricity per year only by using it on the roofs of some houses, workplaces and especially in places such as factories with a large roof area [39]. In the light of the above information, studies should be carried out in order to benefit more from solar energy in Türkiye [29]. Here are some suggestions for the work that needs to be done:

4.1. Building legislation regulations:

Although there is the necessary legal infrastructure for legislative arrangements, it is known that there are important deficiencies in the administrative infrastructure. The joint efforts of the Ministry of Environment, Urbanization and Climate Change and the Ministry of Energy and Natural Resources should be increased and necessary arrangements should be made.

4.2. R&D and training studies:

R&D studies of solar energy systems should be made more comprehensive and these researches should be supported by the state and private sector. They should review the course content and make necessary educational reforms on the use of alternative energy sources and their integration into buildings in the Faculty of Architecture and Engineering.

4.3 Dissemination of architectural applications:

The state should build exemplary structures and provide comfortable working spaces for architects and engineers working in the private sector.

Author contributions

Ahmad Aboul Khail: Supervision, Visualization, Editing
Zeynel Polattaş: Methodology, Investigation, Writing, Original draft preparation

Conflicts of interest

The authors declare no conflicts of interest.

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Forensic examination of lipsticks as trace evidence under different environmental conditions

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Abstract

Trace evidence such as fingerprints, biological fluids, fibres, glass, hairs, soils, and cosmetics have been considered most of the important materials on the crime scene, which can be potentially transferred or exchanged between two surfaces when one makes contact to another. Cosmetic products are one of the valuable trace pieces of evidence on crime scene that are generally used for beautification, moisturize, reinforcement of the skin, nutritiveness, and improve the feeling or sensory aspects. In this study, different lip cosmetic products including wax lipstick, liquid lipstick, gloss and lip balm were investigated as forensic evidence. For this, 102 of lip cosmetic samples (20 of lipstick, 14 of lip gloss, 22 of lip balm and 46 of liquid lipstick) were analyzed by using Fourier-transform Infrared spectroscopy (FTIR). The differentiation between lip cosmetic products is detected. The effect of environmental conditions is studied. For this, lip cosmetic products are kept in various water medium such as simulated sea water, tap water, and distilled water in order to track the chemical stability by FTIR. Moreover, they are kept in different time of intervals from 1 day to 1 month to investigate the change over time. Staining of lip products to various substrates including fabric, glass and paper towel have been also explored. The effect of substrate type, lip cosmetic products, time and water sources have been systematically explored by FTIR and video spectral comparator (VSC). All the samples have been examined under different light sources such as visible light, UV-A (365 nm), infrared (695 nm) and spot (fluorescence) to observe the distinctive features of lip cosmetic samples on different substrates. The results have demonstrated that lip products including wax, liquids lipstick, gloss and lip balm have distinguishing character which is observed by FTIR and VSC8000. Moreover, the chemical stability of lip cosmetic products under different water sources could be characteristic tools for differentiating of lip cosmetic products. The outcomes show that cosmetic trace evidence found in water source could be critical evidence in crime scene investigation.

1. Introduction

Violence against women has become a big problem to be solved for many countries, which has been recognized as a global pandemic by United Nations Secretary [1]. In crime scene, it could be countered various evidence that helps to solve the cases. Detection, quantification, and characterization of the evidence play a critical role for solving the crime [2].

Forensic scientists follow up various evidence, namely classified as physical, chemical, and biological evidence. Cosmetics, one of the encountered pieces of evidence in the event of crime against woman, could be detected in different surfaces such as clothes, cigarette butts, drinking cups, mirror, facial cleanser cotton, and many others [3]. Cosmetics cover various commercial products including eyeliner, lipstick, vermilion, hand cream, nail polish, mascara, eye creams, and so on. Even cosmetic products give a valuable information as forensic evidence in crime scene investigation, some limitations including their abundance in different brands, containing wide variety of chemicals could make it non-utilizable evidence at crime scene. Therefore, characterization and differentiation of cosmetic products using destructive and non-destructive methods have gained immense attention in forensic science [2,4,5].

A variety of method have been extensively used to discriminate the cosmetic products. Cosmetic products can be classified into makeup products, hair care, skin care, intraoral product, nail care and perfumes [6]. In crime scene, numerous cosmetic products can be countered as trace evidence such as lipstick, eyeliner, vermilion, nail polish, kajal, toothpaste and so on. The identification of cosmetics has been part of forensic investigations since 1912, when Edmond Locard found that the pink powder under a murder suspect's fingernail was chemically identical to a makeup powder found in the victim's room [7]. The first studies that involved examining lip cosmetic stains as evidence and comparing their chemical composition in forensic analyzes appeared in the 1950s [8]. Lip cosmetics are one of the most used cosmetic products for beautification, moisturize, reinforcement of the skin, nutritiveness, and improve the feeling or sensory aspects which dates to Mesopotamian civilizations. In terms of forensic science, lipstick can be transferred to many objects including cigarette butts, fabrics, tissue papers, food and beverage products, pillows, and many other surfaces in the criminal events such as child abuse, sex assault, kidnapping, murder, rape etc. [8-11]. Moreover, evidence could be found in different places such as in soil, in lake or sea water. The stains on the evidence therefore can be structural change.

Recently, lip cosmetic products can be classified in different category including lipstick, lip balm, lip gloss, lip liner, liquid lipstick, lip tint and lip chalk according to the chemical compositions, physical structure, physical appearance, applying type, color, gloss and mattness etc. Up to now, various materials such as colored stones, ocher, lead, snake blood, insects, bromine mannite and iodine mixtures, vegetable oils and so on have been used to form lip cosmetic products [12]. With the increasing industrialization and globalization, various chemicals were used to fabricate different lip cosmetic products in high amounts. Although many manufacturers use different chemical for the fabrication of lip cosmetic products, there are 3 chemicals that almost all manufacturer uses including wax, oil and pigment. Wax is responsible for the consistency. hardness, and stability of the lipstick. It softens and smoothes the lips. The types of wax used can be classified as herbal (carnauba, candelilla), animal (beeswax), mineral (ozokerite, paraffin), and synthetic (polyethylene) [9,13].

While waxes maintain structural integrity, they cause the gloss of the lipstick to decrease and the product to become sticky. Oils are used to ensure the diminishing shine and reduce the stickiness of the lipstick. Oils also ensure that the pigments mix homogeneously and make the lips softer. Natural oils such as castor oil, jojoba oil, and lanolin are frequently used in these products [8,13]. Colorants that determine the color tones of lipsticks are synthetic (tartrazine, erythrosine, eosin, phloxine), natural (carmine), organic and inorganic dyes, especially iron (II) and (III) oxides, or titanium (IV) oxide, and mineral pigments (lead white, iron yellow) which adjusts the brightness, opacity, and concealment of the color [8]. Some manufacturers could add other chemicals such as filters, emulsifiers, colorants with different concentration depending on manufacturer [8,14,15].

Lip cosmetics can be found also different forms and types including solid or liquid. Also, they can be named as gloss, balm or lipstick. While wax lipstick consist of wax, liquid lipstick generally contains solvent (usually alcohol), which make them liquid. Wax is also added in some product as a thickening agent. In liquid lipstick forms, solvent is added which rapidly evaporate and leave a thin layer of paint on the skin. Isododecane is one of the most used solvents for liquid lipstick. Moreover, low-density siloxane polymers such as polydimethylsiloxane, trimethylsiloxysilicate, and cyclopentasiloxane have been extensively used to increase the permanence of products, provide creamy form, soften and increase film-forming properties [16,17].

Although lip balms are similar to lipstick in terms of structure, their wax and oil content are much higher than lipsticks. Since their primary purpose is not to provide color, they contain very little pigment [18]. To increase antioxidant properties synthetic antioxidants such as butyl hydroxytoluene (BHT), ascorbic acid, kojic acid, mercury, and hydroquinone etc. can be used. For the high sun protection factor (SPF), chemical sunscreens can be used such as octyl methoxycinnamate, octocrylene, octyl salicylate, benzophenone-3, etc. [13,19]. Aromas are generally used to suppress the bad taste of chemicals [13].

The purpose of lip glosses is to make the lips look brighter. Lip gloss formulations contain more oils and significantly lower amounts of waxes and colorants compared to lipsticks [20]. Like most lip products, lip glosses contain tocopherol (vitamin E) to protect the lips. They typically contain highly tacky film formers such as polybutene. These film formers provide a more transparent and fluid texture and have a high refractive index for shine. Although it is not possible to make a definitive identification of cosmetic stains at the crime scene due to reasons such as the lack of clarity of the complex ingredients of the products, the existence of secret formulas, and global mass production, this evidence helps establish a connection between the suspect, the victim, and the crime scene [21].

The discrimination of chemical composition of lip cosmetic products is critical parameter to solve criminal cases in forensic science. For this, various methods such as atomic absorption spectrometry (AAS), inductively coupled plasma mass spectrometry (ICP-MS), thin layer chromatography (TLC), gas chromatography- mass spectrometry (GC-MS), high performance liquid chromatography (HPLC), Fourier-transform infrared spectroscopy (FTIR) have been performed to differentiate the cosmetic evidence [22-24].

Gładysz et al. [25] have used attenuated total reflectance – Fourier transform infrared spectroscopy (ATR-FTIR) spectroscopy in combination with chemometric techniques to distinguish 38 lipstick samples. Chopi et al. [26] performed the distinguishing of 25 of lip cosmetic samples via cluster analysis and principal component analysis (PCA). However, these studies focused on restricted colors (usually red and tan). This highlights the lack of lipsticks in other shades and even other lip cosmetics in similar studies. Kaur et al. [3] stated that ATR-FTIR is an excellent technique for classifying lipstick samples of different colors and brands in their study with 47 brown, 57 pink and 55 red lipstick samples using ATR-FTIR spectroscopy and chemometric methods. Jasuja and Singh have investigated the liquid lipstick by using TLC method to discriminate various liquid lipstick samples [16]. Wong et al. have investigated the use of spectroscopic methods to examine the 40 of lipstick and liquid lipstick staines. They have used ultraviolet-visible spectroscopy (UV-Vis) and ATR-FTIR to distinguish between stains, each with a different color (red and nude shades). They also succeeded in distinguishing 40 lipsticks with red and nude shades using PCA and linear discriminant analysis (LDA) [17]. Gardner et al. [27] have used Raman spectroscopy to discriminate 34 lip glosses and 17 lip balms. it was reported that fluorescence was more common especially in products containing dyestuffs. However, it was stated that most of the dye-free samples did not contain fluorescence. Salahioglu et al. [28] examined lipstick stains on fabric, cigarette butts and tissue paper by Raman spectroscopy. It was reported that the aim of the study was to keep the stains for a long time and to show their time-dependent changes, but they did not find any significant changes over a two-year period. However, in some lipstick spectra, it was found that the intensity of the C=C band at 1655 cm^{-1} and the -CH band at 3011 cm^{-1} decreased and disappeared over time. It was aimed to determine the effect of environmental conditions on the samples as time passed, since the sample expired due to the waiting period in the forensic examination process and many cases were sent to forensic science laboratories. Kaur et al. [29] have studied lip gloss and used the thin layer chromatography (TLC) method for branded products. With this method, they aimed to develop a new solvent system for the separation of various components of lip glosses. However, it was stated that the results were not reproducible in the non-branded lip gloss sample. Sharma et al. [20] examined the time-dependent changes of the samples in TLC and FTIR study with 25 lip gloss samples. It was concluded that new and old lip gloss (with 1 month aged) stains can be analyzed by applying TLC and FTIR techniques. It was determined that the components could be distinguished for a period of 1 month, but the color intensity decreased as time passed. In a possible case, this will help the suspect to be associated with the crime scene in a temporal sense. Ka Khei et al. [30] have studied the effect of substrate type for discrimination of lipstick samples by using ATR-FTIR. They used various substrates such as wet tissue, nitrile gloves, white paper, and polyester with 10 brands of lipsticks.

It was demonstrated that among them, FTIR is non-destructive method spectroscopic method which is widely used for the analysis of various forensic evidence including soil, cosmetic products, hair, polymer etc. [31]. This technique allows rapid, robust, non-destructive, and reproducible results with minimal sample size and does not require any pre-treatment, solvent, standards for analyzing of samples. In a crime scene, lipstick-stained objects as physical evidence could be encountered in different environmental conditions such as buried, in forest, in different water such as lake, sea or dam. Therefore, the determination of structural change in these environmental conditions is gaining importance in the forensic field. Until now, most of studies have examined fresh lip cosmetic samples and only few studies investigated the effect of environmental conditions on the structural change of lip cosmetics as evidence [26]. Gładysz et al. [32] conducted a stability experiment with various lipstick products in their study. For this, they studied the effect of time, surface and lights to examine the structural change against the environmental conditions. It was found some structural change with time, but no consistent changes were observed. They also studied the effect of surface by glass, fabric, paper to examine the surface type, but they could not conclude about the effect of the surface on stability studies. It was also mentioned that fabric surface is found to be challenging substrate to work the lipstick on the surface.

The present study aims to differentiate the lip cosmetic products and also examines the effect of time, substrate type and environmental conditions. The structural analysis of samples is achieved by FTIR. The images of samples in different substrates are captured using Video spectral comparator (VSC) 8000. Also, various light sources including visible light, UV light (365 nm), infrared (695 nm) and spot (fluorescence) by VSC 8000 have been used to differentiate the lip cosmetic products groups. Lips samples are stained to various substrates such as document paper, fabric (cotton), and paper towel in order to examine the permanence of lip cosmetic stain marks under different environmental conditions. It is also aimed to investigate the stability of lip cosmetic stains on the different substrates against to the environmental conditions. For this, lip cosmetic staines in different substrates are dipped in various water sources such as tap water, simulated sea water, distilled water. The stained substrates are also kept at different time of intervals (from 1 day to 1 month) in order to examine the change over time. Even all lip cosmetic groups including lip gloss, lip balm, wax lipstick and liquid lipstick looks similar when viewed with naked eye, they can be discriminated by VSC under different light sources and FTIR which make them preferable method because of their non-destructive character. The outcomes show that FTIR is important technique for the discrimination of lip cosmetic samples in crime scene. The use of VSC8000 also is a valuable step to investigate the different type of evidence which can be utilized under different light of source including UV light, infrared, and spot (fluorescence).

2. Materials and method

2.1. Sample collection and preparation

This study groups all the lip cosmetic samples in 4 categories under lipstick, liquid lipstick, lip balm and lip gloss. For the study, 46 of wax lipstick, 22 of lip balm, 20 of liquid lipstick, and 14 of lip gloss have been used. All the samples are collected from various district bazaars and grocery chains in Turkey. The samples are named with different codes to avoid confusion at the classification stage. In this nomenclature, the first letter in the codes indicates the type of sample (lipstick, liquid lipstick, balm, gloss); the other two letters represent the brand of the sample. The numbers next to the codes represent different products of that brand. Letters representing the type of sample; the letter "**R**" for lipstick, the letter "**L**" for liquid lipstick, the letter "**N**" for lip balm and the letter "**P**" for gloss. While choosing the letters representing the brand, if the brand name consists of two or more words, the initials of the first two words, if it consists of a single word, the first two letters of the word are taken as basis. The details including sample code, sample type and brand are given in Table 1. Samples coded LMA-06 for liquid lipstick, RBE-02 for lipstick, NGA-02 for lip balm and PBC-01 for lip gloss were used and were never changed during the experiment. Since the color appears more intense, care was taken to choose red color, but pink color was preferred due to the higher color intensity in lip balm.

Table 1. Nomenclature of samples.

Sample	Type	Brand	Sample	Type	Brand
LAV-01	Liquid lipstick	Avon	NBE-02	Lip balm	Beaulis
LBA-01	Liquid lipstick	The Balm	NBE-03	Lip balm	Beaulis
LBE-01	Liquid lipstick	Beaulis	NBL-01	Lip balm	Blistex
LBE-02	Liquid lipstick	Beaulis	NBO-01	Lip balm	Bote
LBE-03	Liquid lipstick	Beaulis	NFL-01	Lip balm	Flormar
LBE-04	Liquid lipstick	Beaulis	NGA-01	Lip balm	Gabrini
LCR-01	Liquid lipstick	Crystal	NGA-02	Lip balm	Gabrini
LEL-01	Liquid lipstick	Estel'la	NGR-01	Lip balm	Golden Rose
LEL-02	Liquid lipstick	Estel'la	NHH-01	Lip balm	Himalaya Herbals
LEL-03	Liquid lipstick	Estel'la	NKI-01	Lip balm	Kiva
LEN-01	Liquid lipstick	Enigma	NMA-01	Lip balm	MonAmour
LEN-02	Liquid lipstick	Enigma	NMN-01	Lip balm	Maybelline New York
LFA-01	Liquid lipstick	Farmasi	NNI-01	Lip balm	Nivea
LFL-01	Liquid lipstick	Flormar	NPB-01	Lip balm	PrettyBeauty
LFL-02	Liquid lipstick	Flormar	NPB-02	Lip balm	PrettyBeauty
LFL-03	Liquid lipstick	Flormar	NUS-01	Lip balm	Ushas
LGO-01	Liquid lipstick	Gossamer	NVE-01	Lip balm	Vesslina
LGR-01	Liquid lipstick	Golden Rose	PAA-01	Lip gloss	Markasız
LGR-02	Liquid lipstick	Golden Rose	PBC-01	Lip gloss	BriConti
LGR-03	Liquid lipstick	Golden Rose	PBO-01	Lip gloss	Bonica
LGR-04	Liquid lipstick	Golden Rose	PBO-02	Lip gloss	Bonica
LGR-05	Liquid lipstick	Golden Rose	PBO-03	Lip gloss	Bonica
LLL-01	Liquid lipstick	Light of Life	PBO-04	Lip gloss	Bonica
LLP-01	Liquid lipstick	Loreal Paris	PBO-05	Lip gloss	Bonica
LMA-01	Liquid lipstick	MonAmour	PEN-01	Lip gloss	Enigma
LMA-02	Liquid lipstick	MonAmour	PES-01	Lip gloss	Essence
LMA-03	Liquid lipstick	MonAmour	PGR-01	Lip gloss	Golden Rose
LMA-04	Liquid lipstick	MonAmour	PIR-01	Lip gloss	Irshi
LMA-05	Liquid lipstick	MonAmour	PLP-01	Lip gloss	Lancome Paris
LMA-06	Liquid lipstick	MonAmour	PMA-01	Lip gloss	MonAmour
LMN-01	Liquid lipstick	Maybelline New York	PTI-01	Lip gloss	Tikatti
LMT-01	Liquid lipstick	Makeup Time	RAP-01	Lipstick	Afrodit Paris
LMT-02	Liquid lipstick	MakeupTime	RAV-01	Lipstick	Avon
LNW-01	Liquid lipstick	NewWell	RAV-02	Lipstick	Avon
LNW-02	Liquid lipstick	NewWell	RAV-03	Lipstick	Avon
LNW-03	Liquid lipstick	NewWell	RAV-04	Lipstick	Avon
LNW-04	Liquid lipstick	NewWell	RBE-01	Lipstick	Beaulis
LNW-05	Liquid lipstick	NewWell	RBE-02	Lipstick	Beaulis
LNW-06	Liquid lipstick	NewWell	RBE-03	Lipstick	Beaulis
LNW-07	Liquid lipstick	NewWell	RBE-04	Lipstick	Beaulis
LPA-01	Liquid lipstick	Pastel	RBE-05	Lipstick	Beaulis
LPA-02	Liquid lipstick	Pastel	RBE-06	Lipstick	Beaulis
LPA-03	Liquid lipstick	Pastel	RBE-07	Lipstick	Beaulis
LRS-01	Liquid lipstick	Rosie Style	RBE-08	Lipstick	Beaulis
LUS-01	Liquid lipstick	Ushas	RBE-09	Lipstick	Beaulis
LUS-02	Liquid lipstick	Ushas	RCH-01	Lipstick	Chanlanya
NAN-01	Lip balm	Antipodes	RES-01	Lipstick	Estel'la
NBB-01	Lip balm	BeeBeauty	RGR-01	Lipstick	Golden Rose
NBB-02	Lip balm	BeeBeauty	RMI-01	Lipstick	Miniso
NBB-03	Lip balm	BeeBeauty	RMN-01	Lipstick	Maybelline New York
NBE-01	Lip balm	Beaulis	RPA-01	Lipstick	Pastel

2.2. Instrumentation

The cosmetic samples are analyzed by the Agilent Cary 630 FTIR Spectrometer and the MicroLab FTIR software of the same company accredited with this device. Spectra were obtained between 4000 and 650 cm^{-1} with a spectral resolution of 4 cm^{-1}. The data were converted to the appropriate file format using the OMNIC program. Orange Data Mining for PCA analysis were used. Samples were taken from three different point and compared in order to obtain good reproducibility, which is presented in Figure 1. The reproducibility test was carried out for all lip cosmetic samples including lip stick, liquid lipstick, lip palm and lip gloss.

Video Spectral Comparator 8000 (VSC-8000) was used to visualize the samples and show their variations under different wavelengths of light. The lip cosmetic samples are stained on A4 paper and images are taken. All the images are taken by VSC8000 under visible light, UV light, infrared (695 nm) and fluorescence (645 nm).

2.3. Sample analysis

For the structural analysis of samples, all lip products are stained on the glass microscope slides and allowed to dry for 20 min. After drying, the samples were scraped from the glass with metal spatula and collected in sample container.

The collected samples then analyzed by FTIR. Before analysis, the crystal was cleaned with alcohol, a paper towel, and a lint-free cloth prior to each analysis in order to avoid any foreign impurities. In order to get reliable and reproducible results, samples were taken from 3 different areas of lip cosmetic products.

2.4. The effect of substrate

In order to examine the effect of substrate type, different materials such as fabric (100% cotton), glass and paper towel have been used. Lip cosmetic products are gently stained to substrates at once then kept for 20 min for drying.

2.5. The effect of water source

Various water sources have been used to examine the environmental conditions. For this, distilled water, tap water and simulated sea water (3.5% NaCI) are used. For the stability experiments, stained substrates are dipped in various water source and kept at room conditions. Moreover, all the samples are kept in water sources at different time of intervals (1 hour, 1 day, 1 week, 1month) to investigate the change over time.

2.6. Data analysis

The PCA method, one of the chemometric methods, was preferred so that the analyzes made in the data analysis could be calculated statistically and the difference from each other could be displayed. Orange Data Mining program was used during the processing of this method. At this stage, PC-1 and PC-2 values were considered.

3. Results and discussion

3.1. Visual comparison of lip cosmetic products

All samples are stained to white copy paper in order to observe under different light of sources. For this, the images under visible light, UV light, IR and fluorescence light by VSC 8000 are captured which is given in Figure 1.

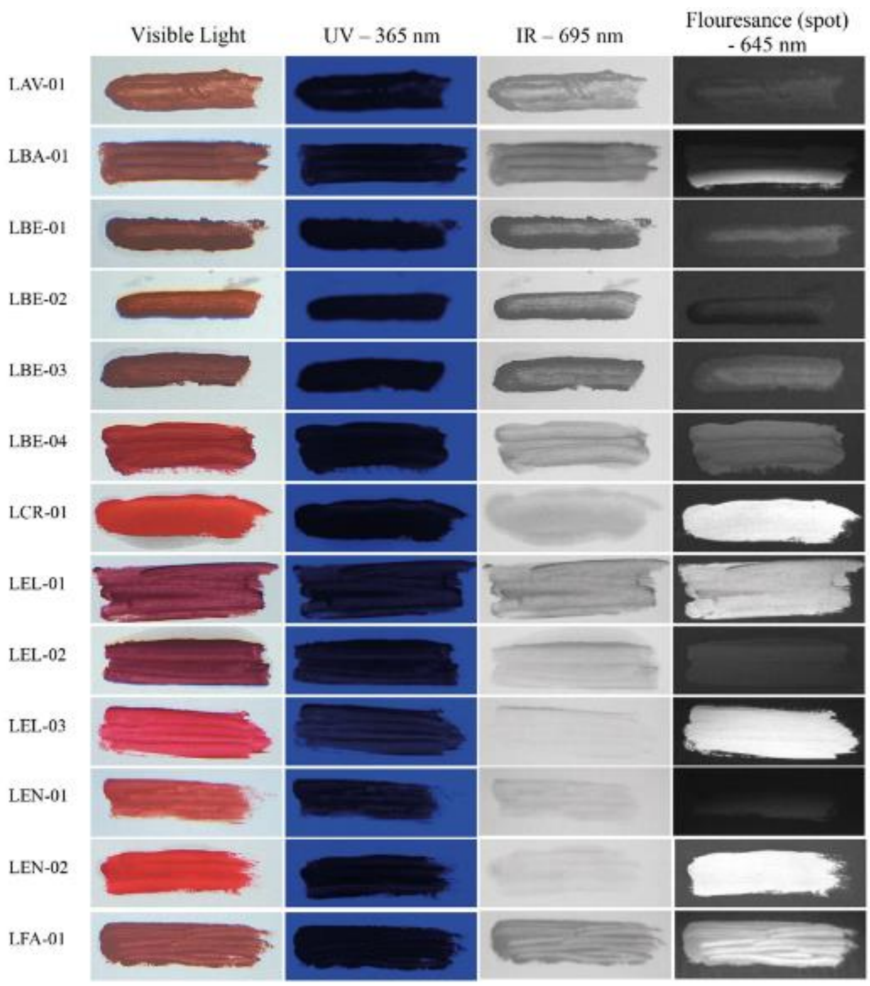

Figure 1. Liquid lipstick samples on VSC 8000 -1.

VSC 8000 have been used to differentiate the samples under various light sources. When the samples are examined with naked eye, it was observed that it was quite difficult to discriminate them in the same color group. However, they can be differentiated under IR and spot (fluorescence). For instance, LCR-01 and LMA-06 have similar images under visible light, but it can be differentiated in spot (fluorescence) which can be explained by the chemical ingredients. Manufacturers use various chemicals to produce lip samples. Moreover, use of UV light for differentiation of samples also provides efficient results. While all lipstick and liquid lipstick samples appear darker in UV light, most lip balm and lip gloss samples appear paler.

Although all the samples examined under fluorescent light show glows that cannot be included in a grouping, it has been seen that the lip gloss samples have different glows from the others. It is thought that the cause of the glows here is due to components with different fluorescence properties. Components with different fluorescence properties emit light at different wavelengths and intensities. It can cause different glitters under the same light.

The sparkle appearance of lip gloss samples is effective in showing its glittery structure. Lip gloss samples examined under fluorescence light are thought to be discriminated from others with this feature. The images of all other samples under different light sources were shown in Figure 1-9.

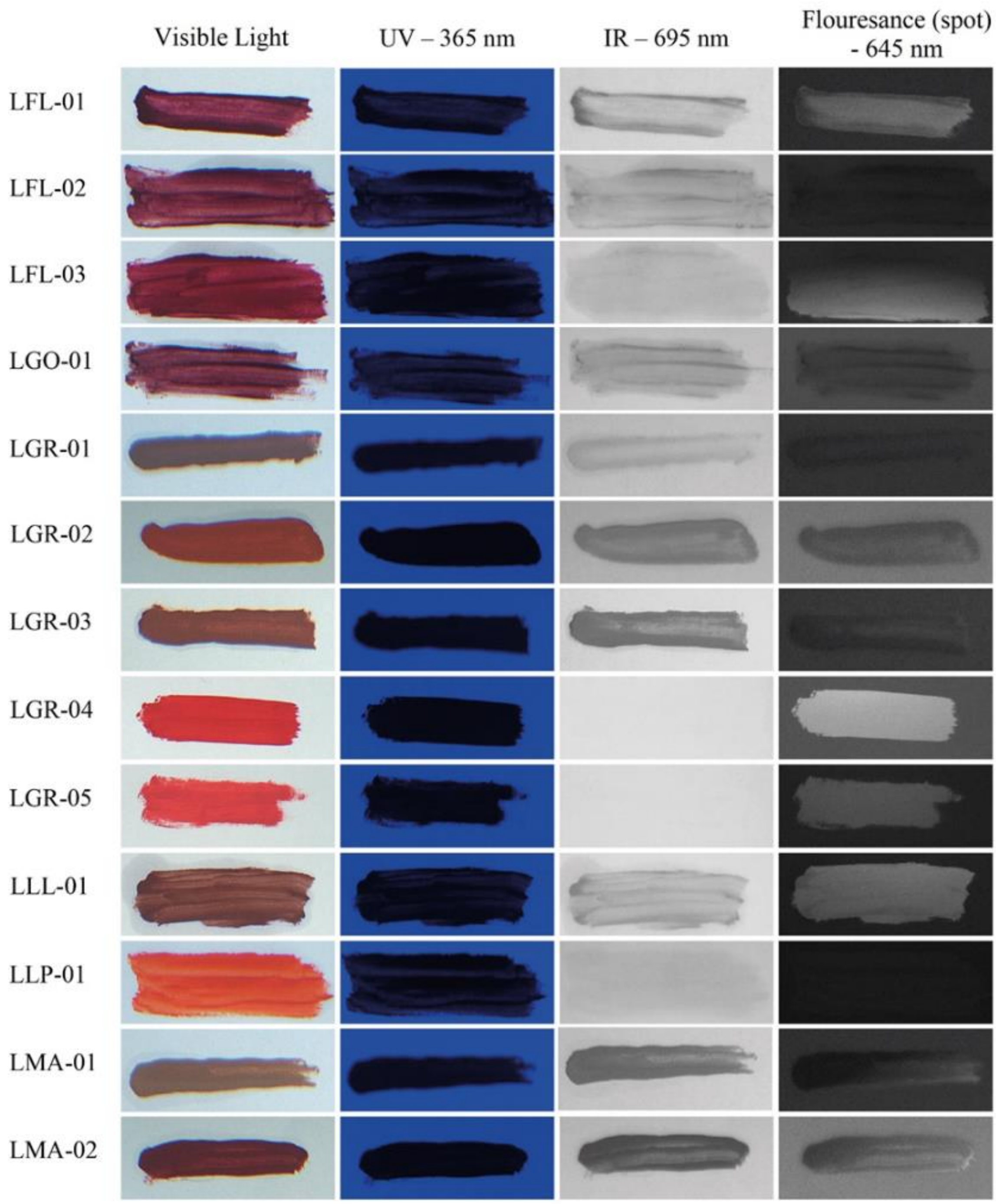

Figure 2. Liquid lipstick samples on VSC 8000 -2.

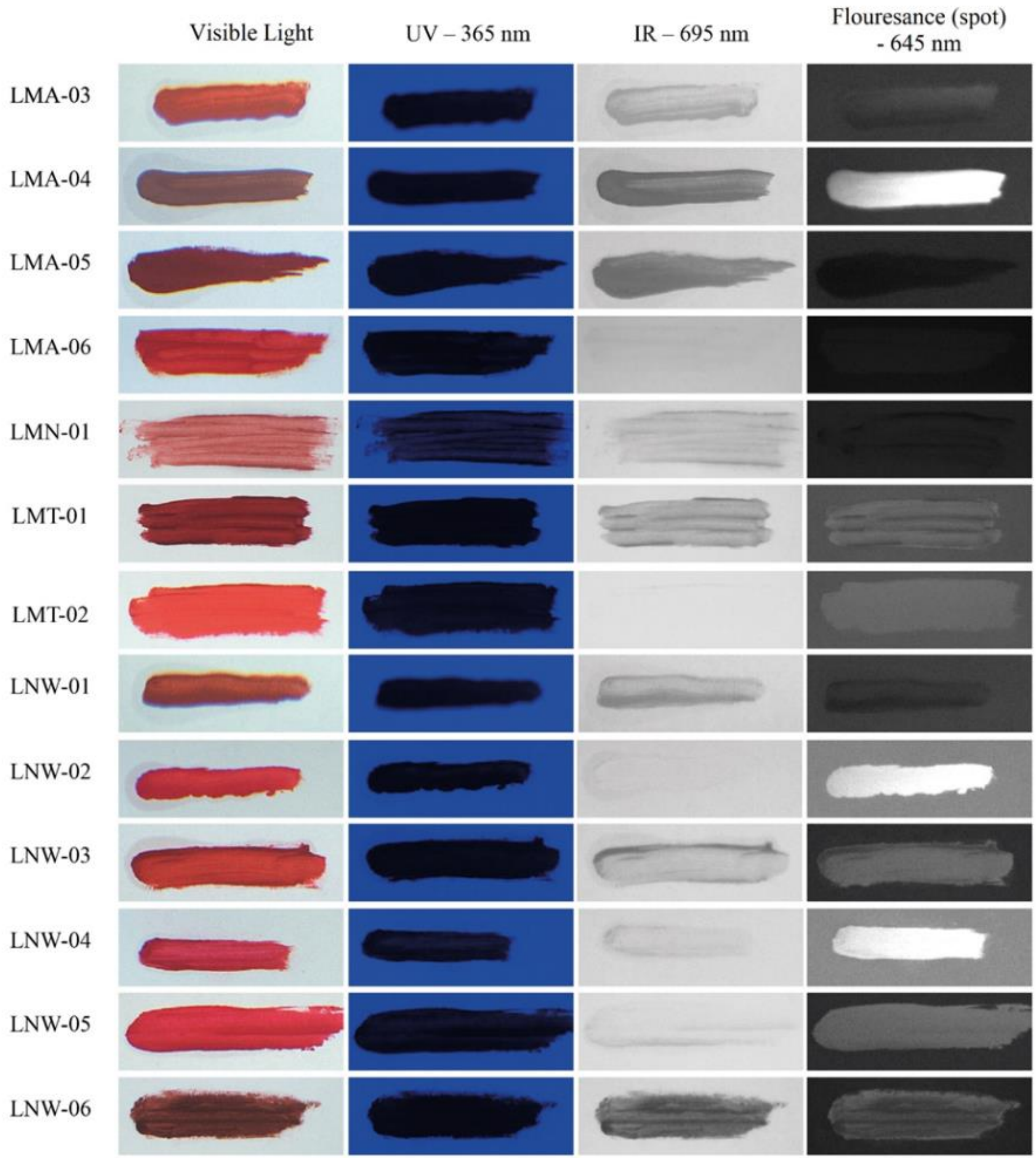

Figure 3. Liquid lipstick samples on VSC 8000 -3.

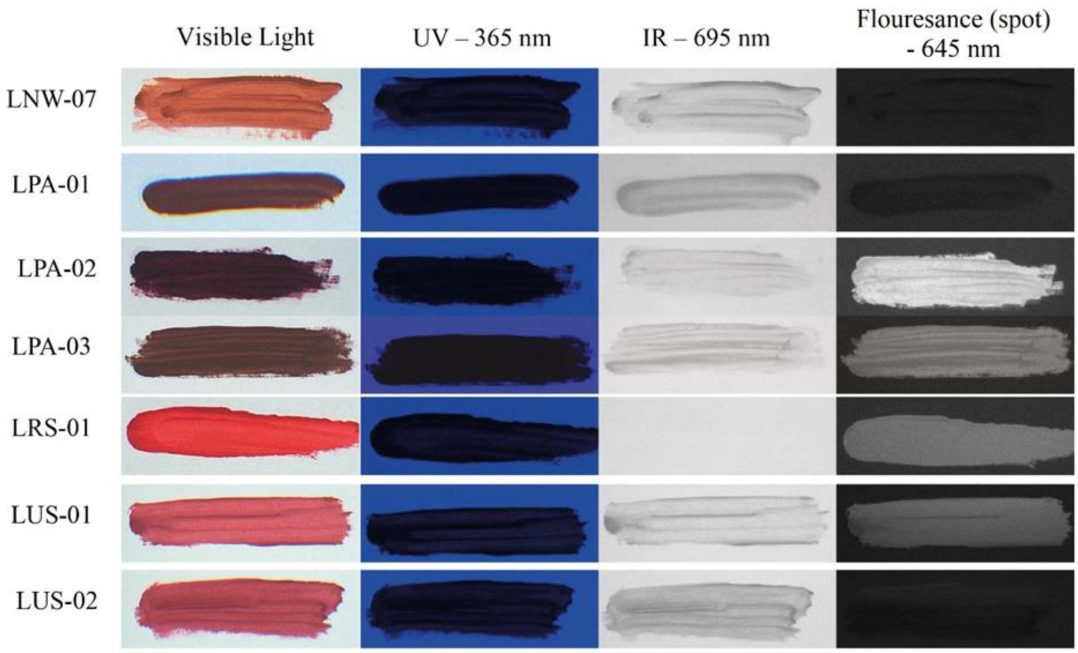

Figure 4. Liquid lipstick samples on VSC 8000 -4.

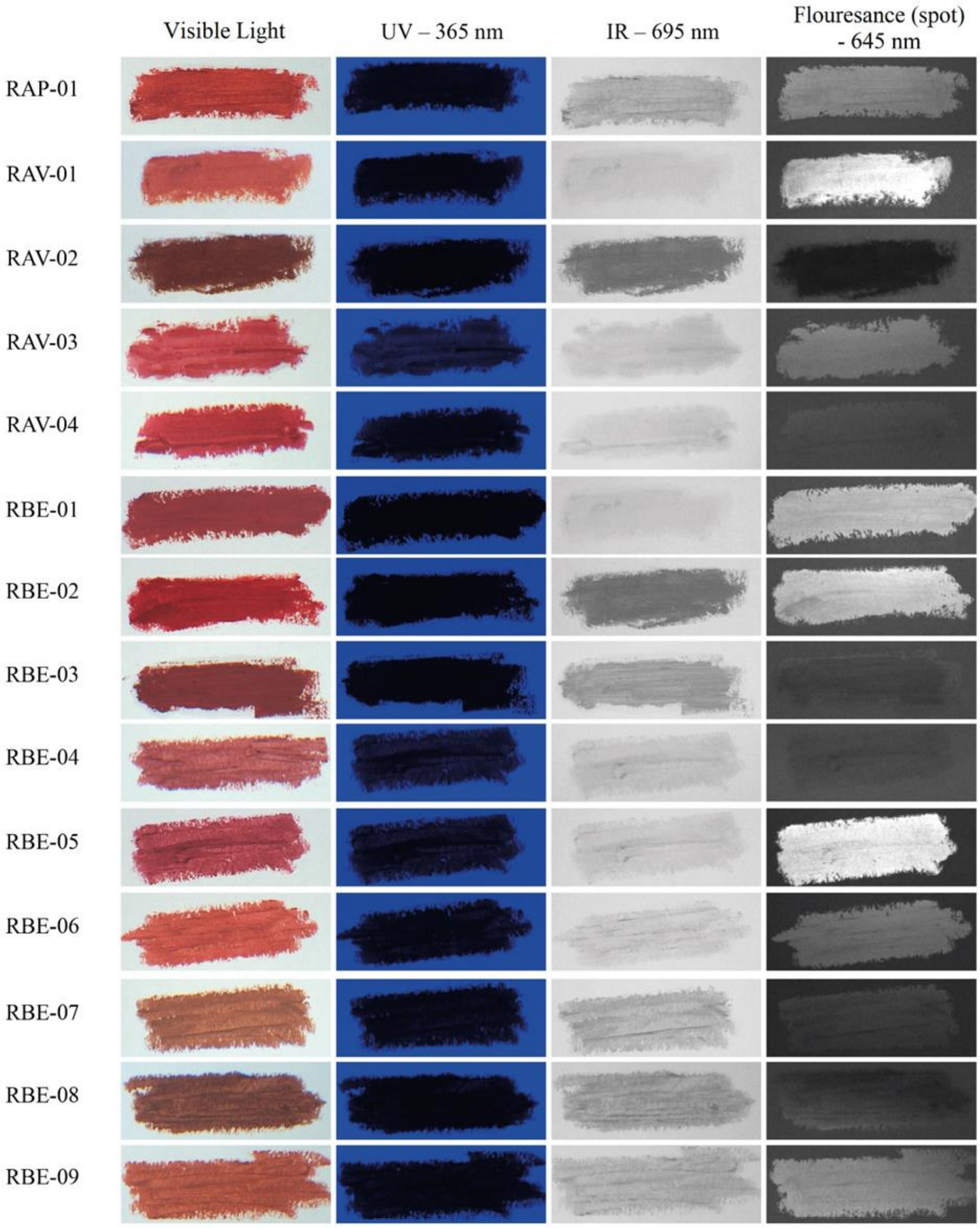

Figure 5. Lipstick samples on VSC 8000 -1.

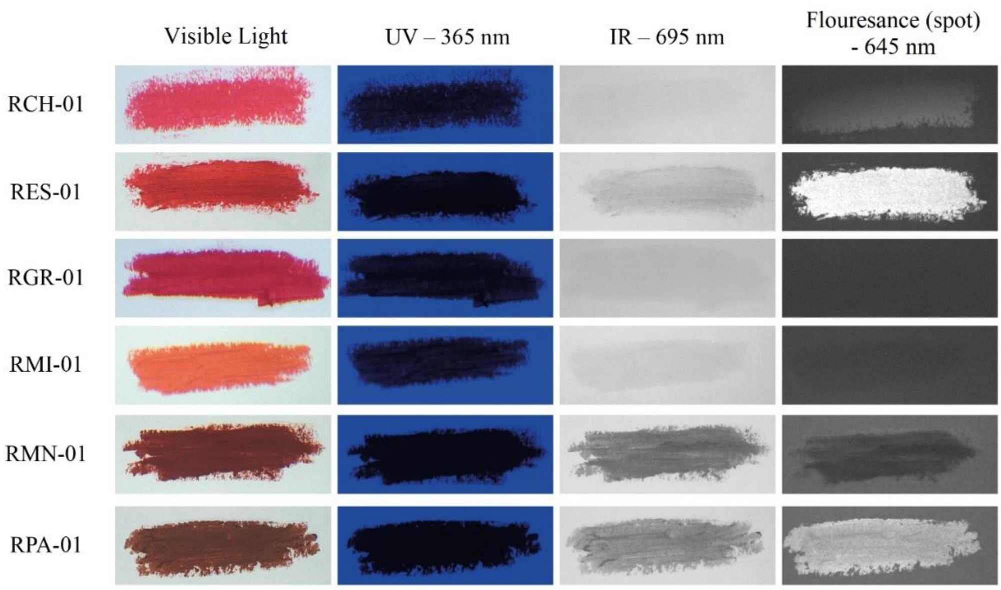

Figure 6. Lipstick samples on VSC 8000 -2.

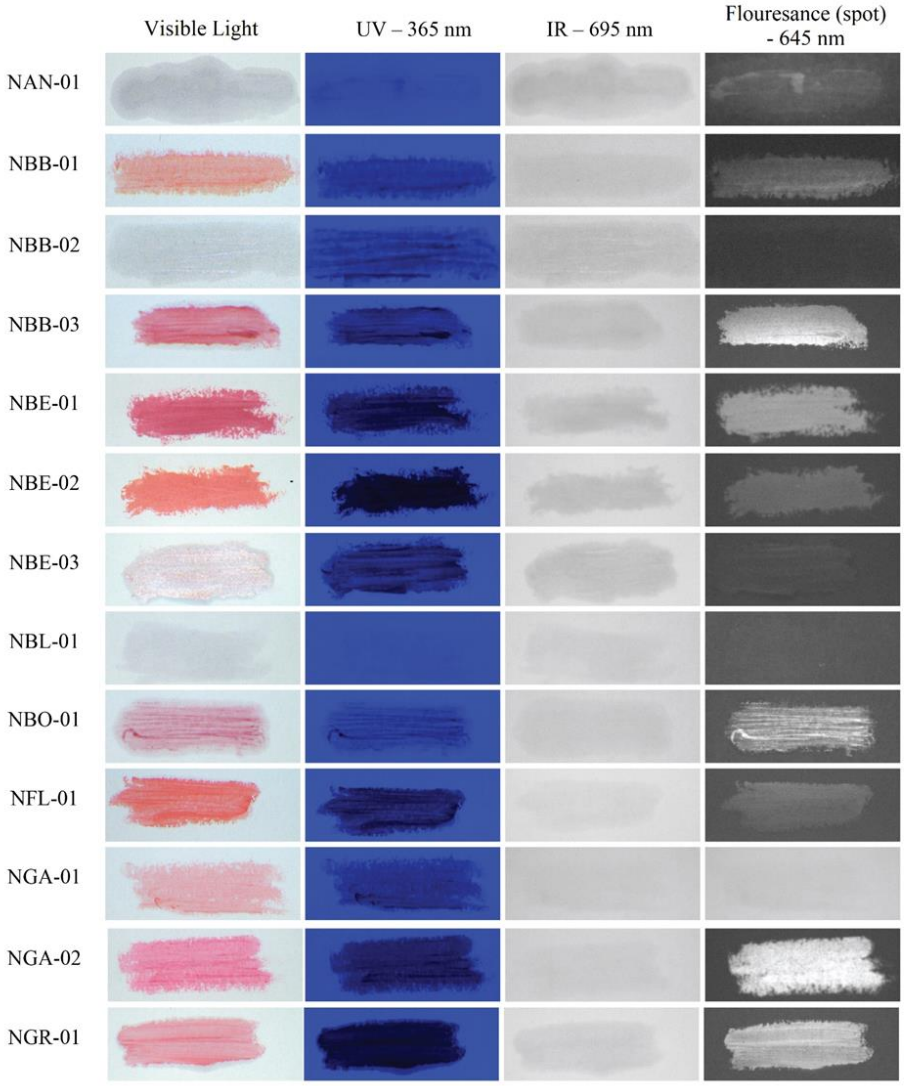

Figure 7. Lip balm samples on VSC 8000 -1.

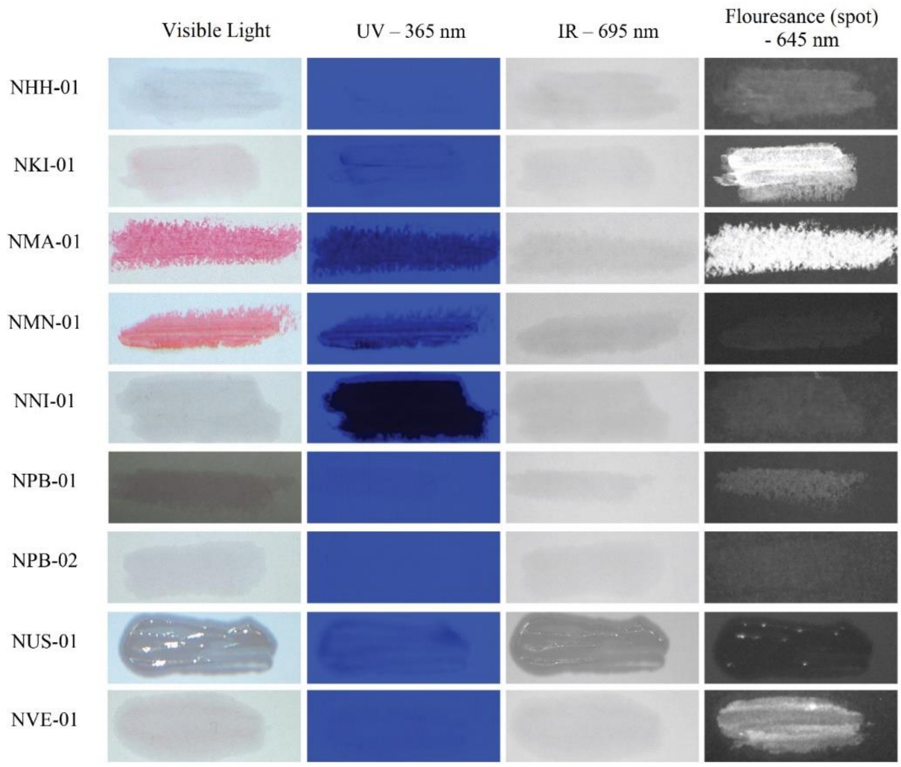

Figure 8. Lip balm samples on VSC 8000 -2.

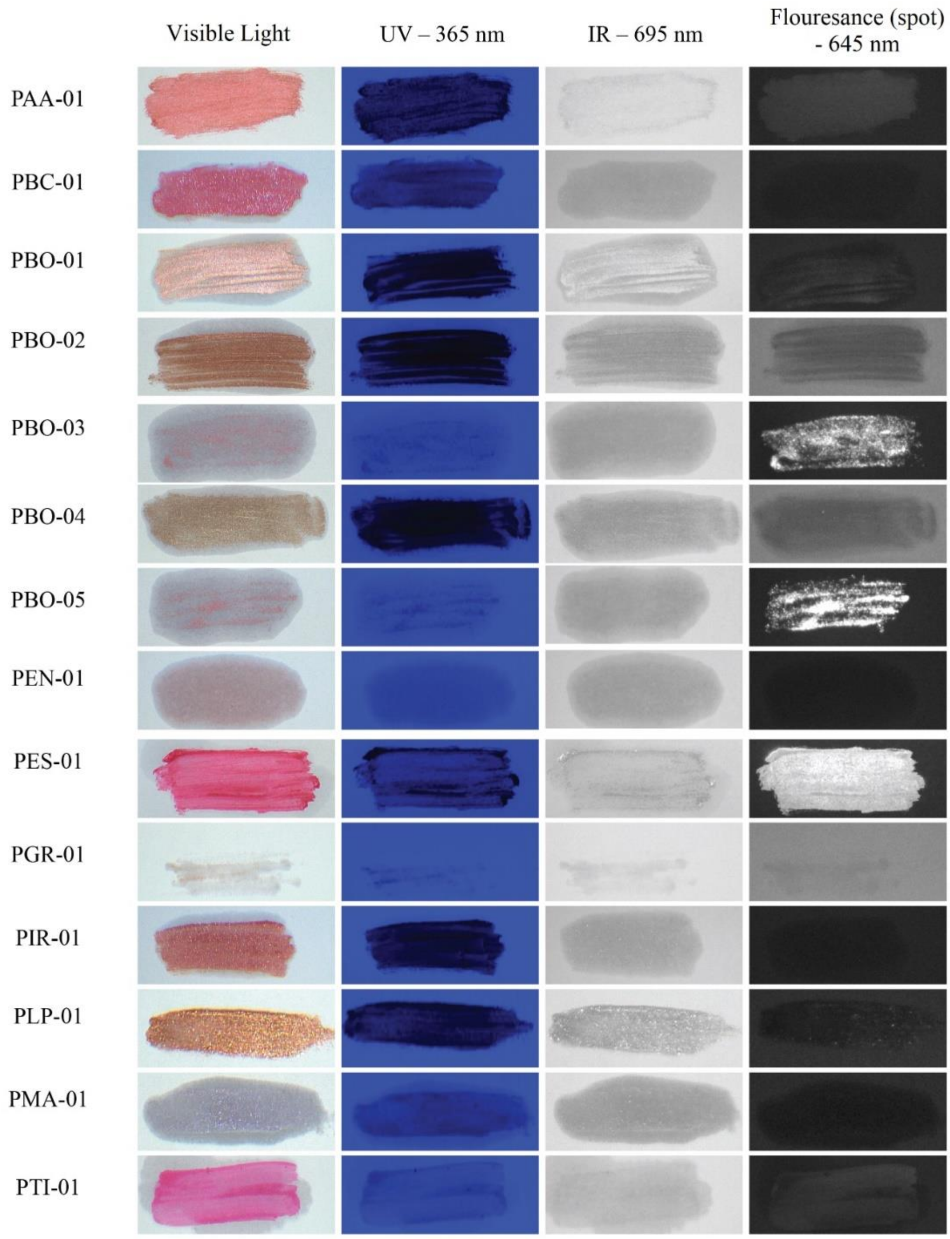

Figure 9. Lip gloss samples on VSC 8000.

3.2. Characterization of lip cosmetic samples

ATR-FTIR was used to identify the compositional variations among the samples. In order to get a reproducible result. FTIR are acquired from 3 different part of lip cosmetics. The results are given in Figure 2. The results have shown that all spectra for L (liquid lipstick), R (lipstick), N (lip balm) and P (lip gloss) samples were exactly superimposed with each other, which confirms the homogeneity test studies for all lip cosmetic samples.

3.3. Stability test

Lip cosmetics are physical evidence which could be transferred to paper, clothes or another person. The presence of lipstick-stained evidence could play an important role in order to solve the case [33]. The evidence could be everywhere such as inside a trash box, in the forest, in the lake or sea water etc. for this, we investigate the effect of different parameter in order to comprehend the structural chance towards to time, substrate type and water source.

The study on the effect of substrate is vital in order to simulate crime scene. To simulate the substrate type, lip cosmetic products are stained to glass, fabric and paper towel. For these surfaces, a laboratory slide as a glass, a fabric cut from a 100% cotton t-shirt, and Z-fold paper towels were used. Then, lip cosmetic-stained substrates are dipped in different water source including tap water, distilled water, and simulated sea water. Moreover, to examine the time, stained substrates is kept in water sources at different time of intervals. Images of lip gloss stained on the glass surface in different water sources are shown in Figure 3. As a representative example, lip gloss-stained glass in water were shown. It can be seen that lip gloss stains undergo change in different water sources. All lip products stain in water sources have spread to surface. Lip gloss stains become lost in distilled water at the end of 1 month. On the tap water, the lip gloss stains get loose when the test is maintained from 1 hour to 1 month.

Nevertheless, lip gloss stains are observed at the end of 1 month. Similarly, lip gloss stains can be seen in the simulated sea water on the whole stability test process. The stability images of lip cosmetic-stained objects in different water source were shown in supplementary document (Figure 10-20).

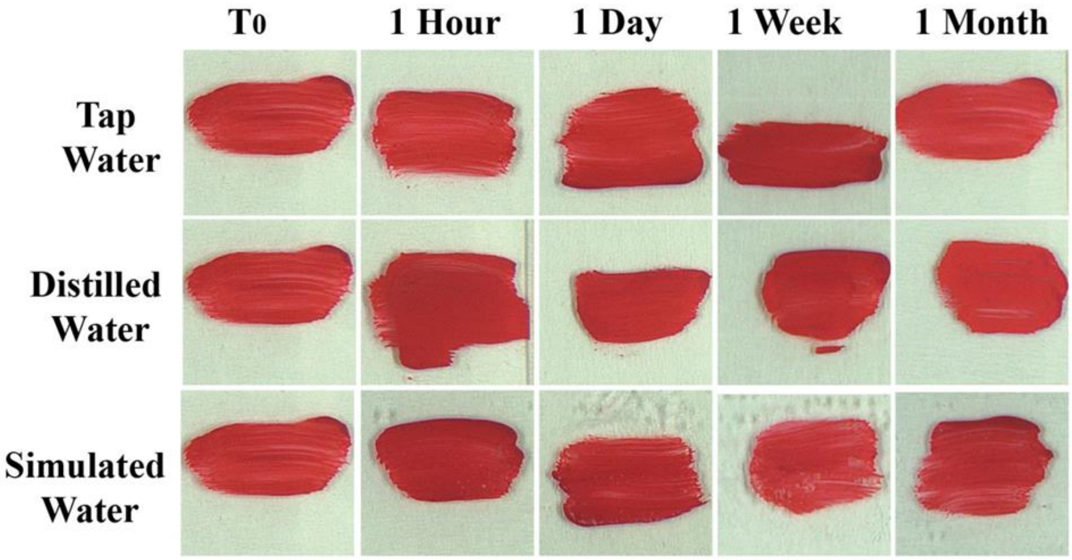

Figure 10. Stability test of liquid lipstick on glass.

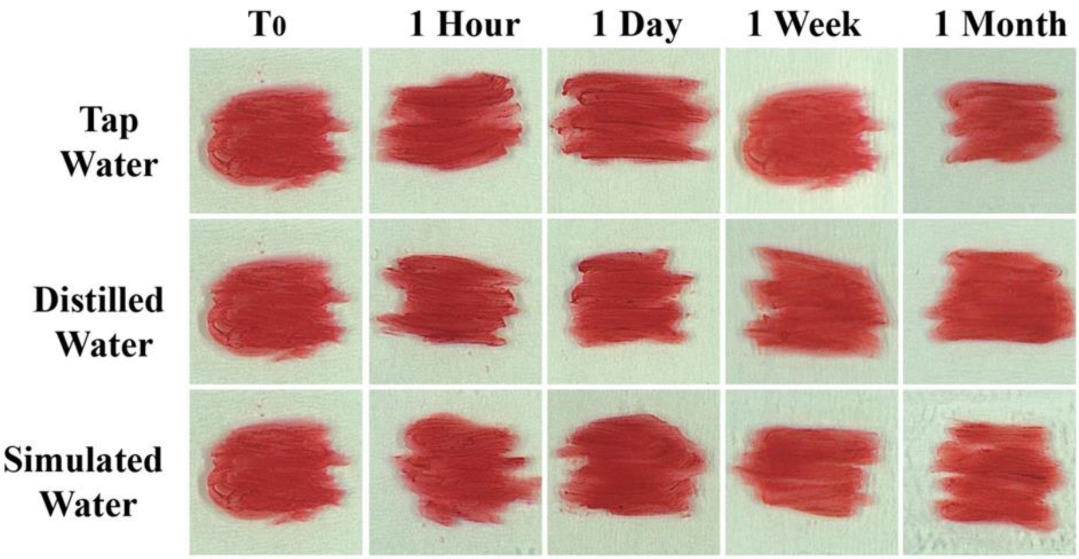

Figure 11. Stability test of lipstick on glass.

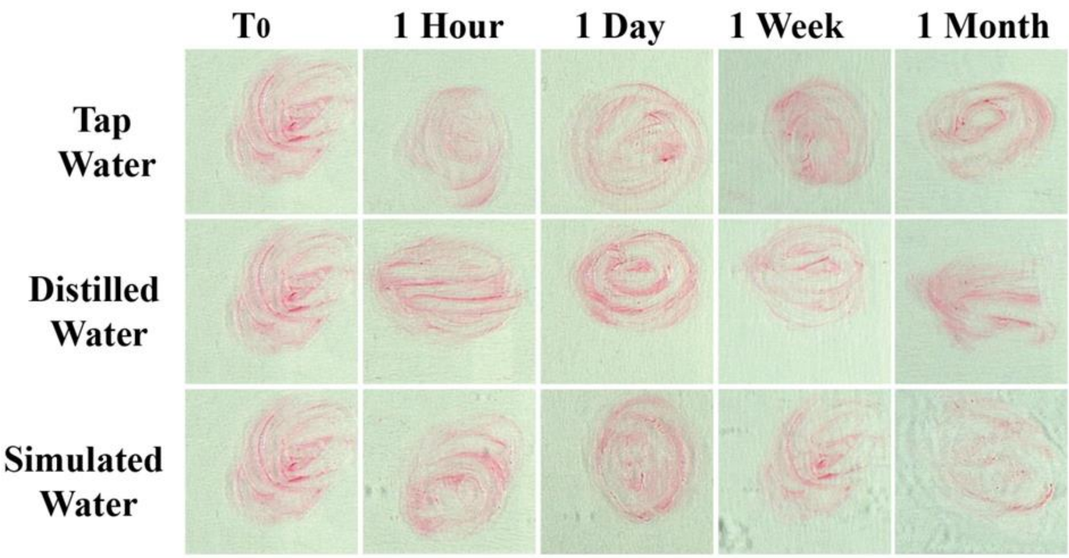

Figure 12. Stability test of lip balm on glass.

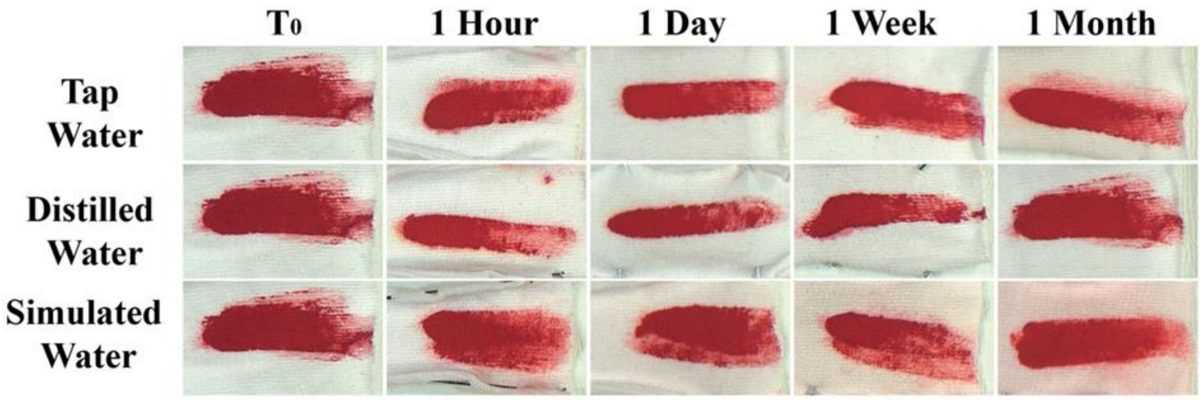

Figure 13. Stability test of liquid lipstick on fabric.

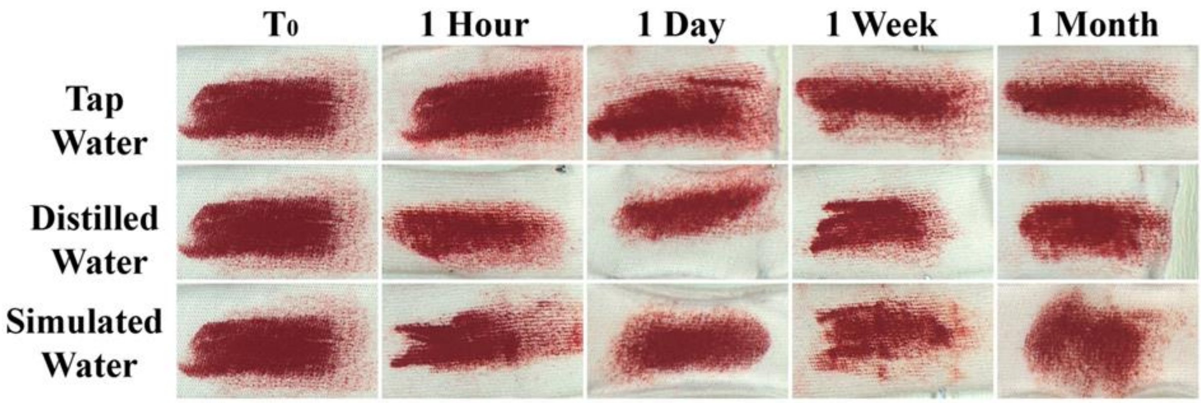

Figure 14. Stability test of lipstick on fabric.

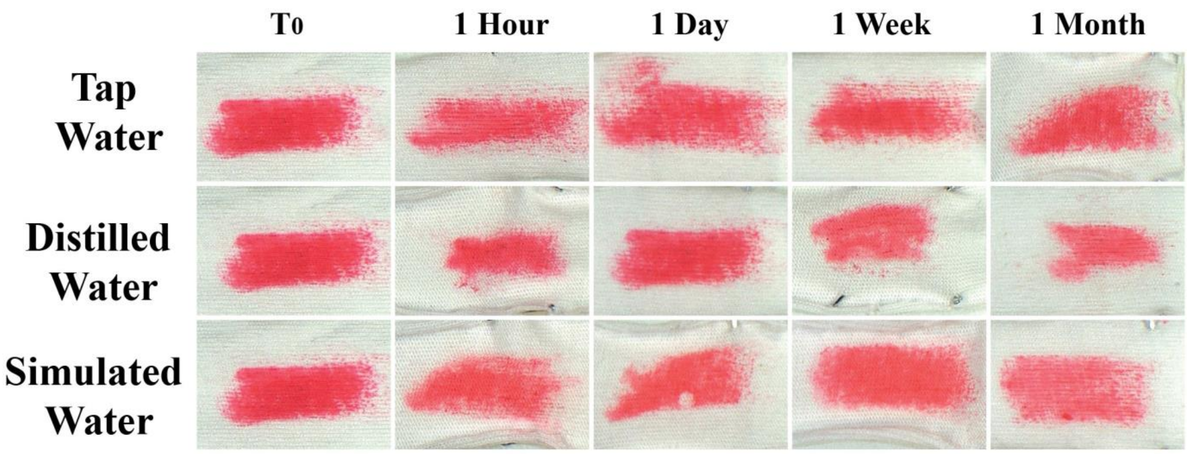

Figure 15. Stability test of lip balm on fabric.

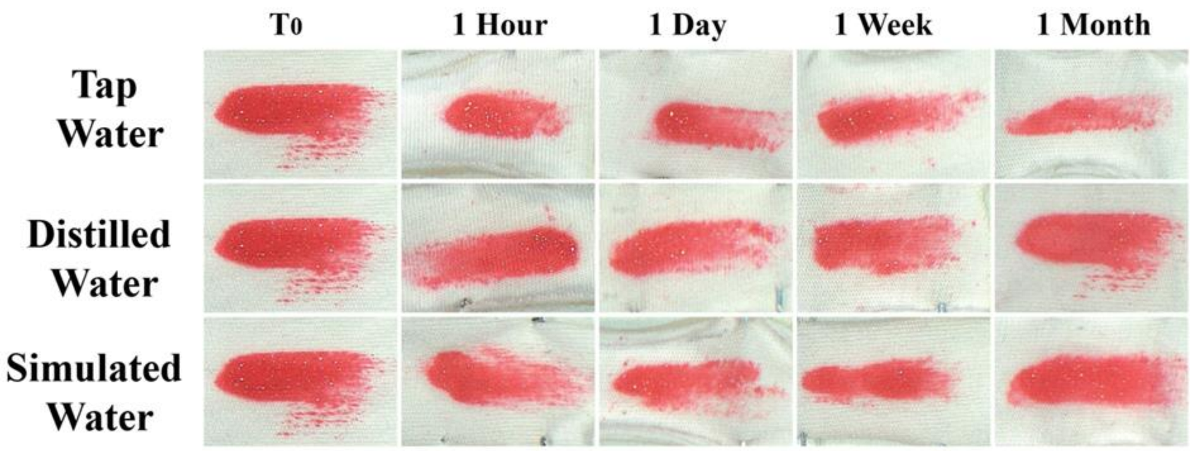

Figure 16. Stability test of lip gloss on fabric.

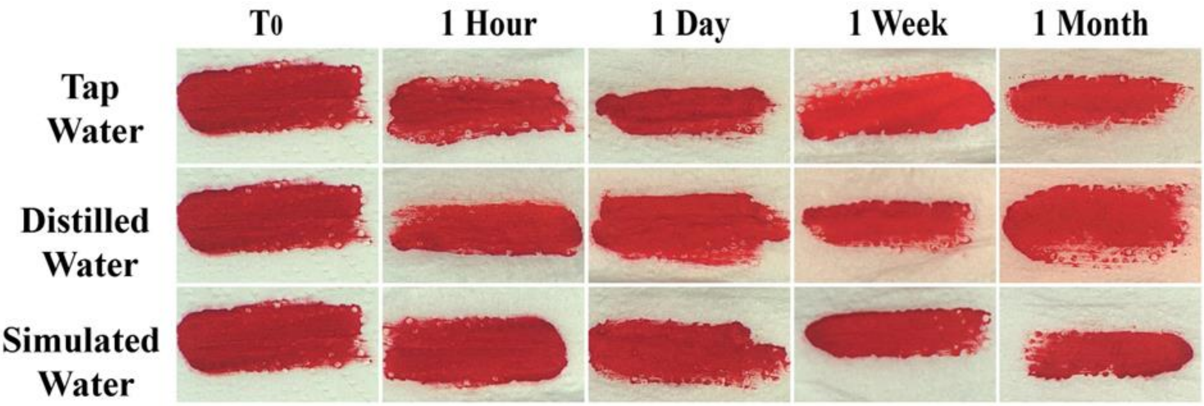

Figure 17. Stability test of liquid lipstick on paper towel.

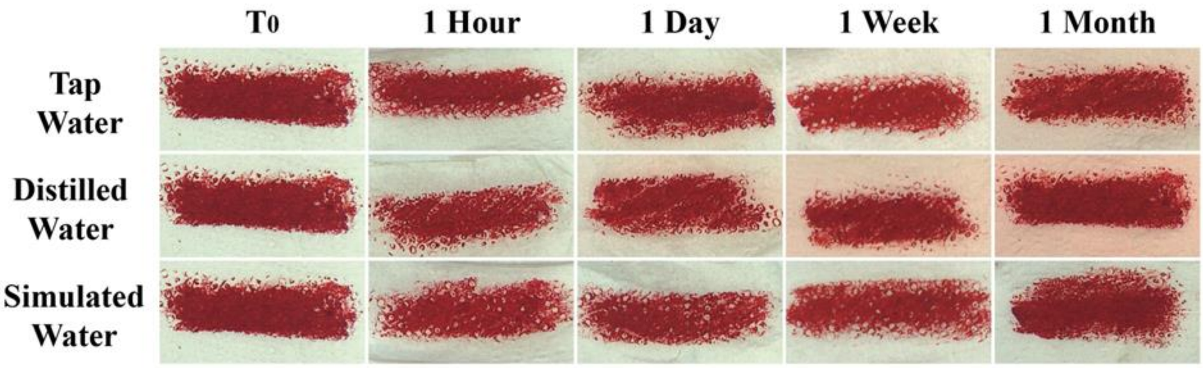

Figure 18. Stability test of lipstick on paper towel.

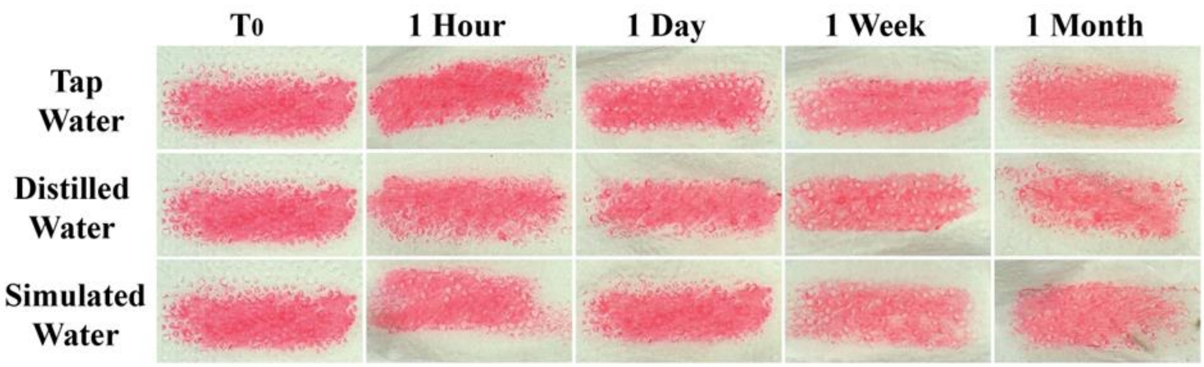

Figure 19. Stability test of lip balm on paper towel.

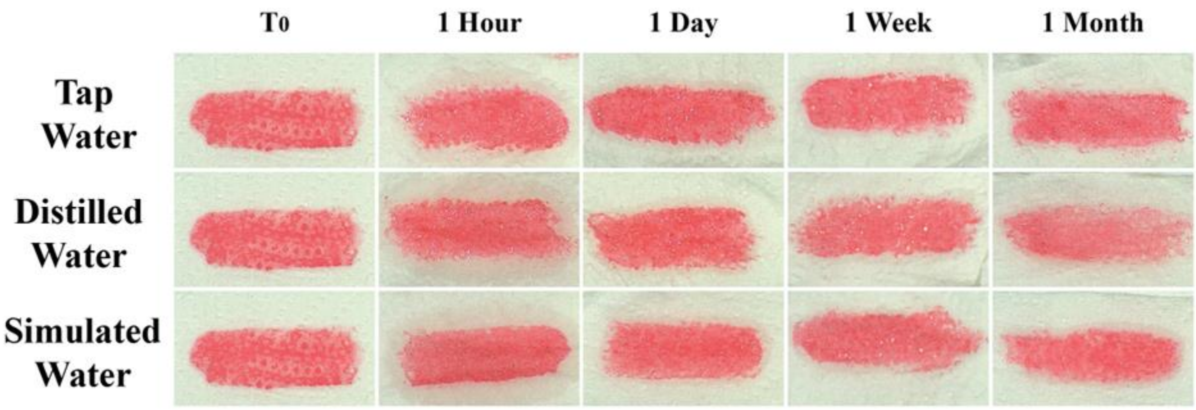

Figure 20. Stability test of lip gloss on paper towel.

In order to examine the chemical stability of samples on different surfaces, a series of experiment were carried out. For this, all lip cosmetic products are stained to different surfaces.

Besides, all samples are kept under different water source at different time of intervals. The structural of lip product samples analyzed by FTIR (Figure 4). The band between 3100-3700 cm^{-1} indicated the presence of hydroxyl groups due to intermolecular hydrogen bonding. The peaks occurring between 2800-3050 cm-1 were attributed to the presence of -CH bonds [6,25]. The peaks in the ranges 1730-1740 cm^{-1} confirms the presence of C=O stretching vibration. Peaks between 1370-1560 cm-1 are attributed to aromatic compounds, peaks between 1440-1465 cm^{-1} are attributed to $-CH_2$ shear deformation. The peaks between 850-1270 cm^{-1} attribute Si-O stretching of silicates, and peaks between 630-790 cm^{-1} are attributed to Si-O and Si-O-Al stretching vibration [25,34,35]. The peak in 1040 cm-1 is attributed to the Si-O-Si stretching vibration of siloxanes [17,36]. It could be seen that FTIR results give a distinctive result among the samples. For instance, there is no clear peak on the sample L in spectral range 1730-1780 cm^{-1} while sharp peak of carbonyl groups is observed in the sample R, N and P. Besides, there is hydroxyl peaks between 3300-3600 cm^{-1} in the sample of L and R while no visible peaks are seen in the sample of N and P.

In order to investigate the effect of time on the chemical stability, all lip product samples are kept under water (tap water, distilled water, simulated sea water) from 1 hour to 1 month. The results showed that there is no significant change of samples under the water from 1 hour to 1 month. It could be said that it is hard to determine the applied time of lip cosmetic products on glass. Furthermore, lip cosmetic products on different surfaces including fabric and paper towel are characterized by FTIR. The FTIR results of other lip products including liquid lipstick, lip balm and lip gloss on fabric and paper towel are given in Figure 21 and Figure 22 and Figure 23 respectively. Similarly, there is no significant change in the FTIR to discriminate the time of applying, the substrate and the water.

3.4. Principle Component Analysis (PCA)

PCA analysis was applied to all T_0 samples and classification was observed (Figure 5-6). In the PCA analysis of the samples, it is generally seen that the liquid lipsticks are separated from the other samples. Especially LMT-01 and LMA-01 coded samples are clearly separated from other samples.

Lipstick, lip balm and lip gloss samples are grouped together to show their similarities.

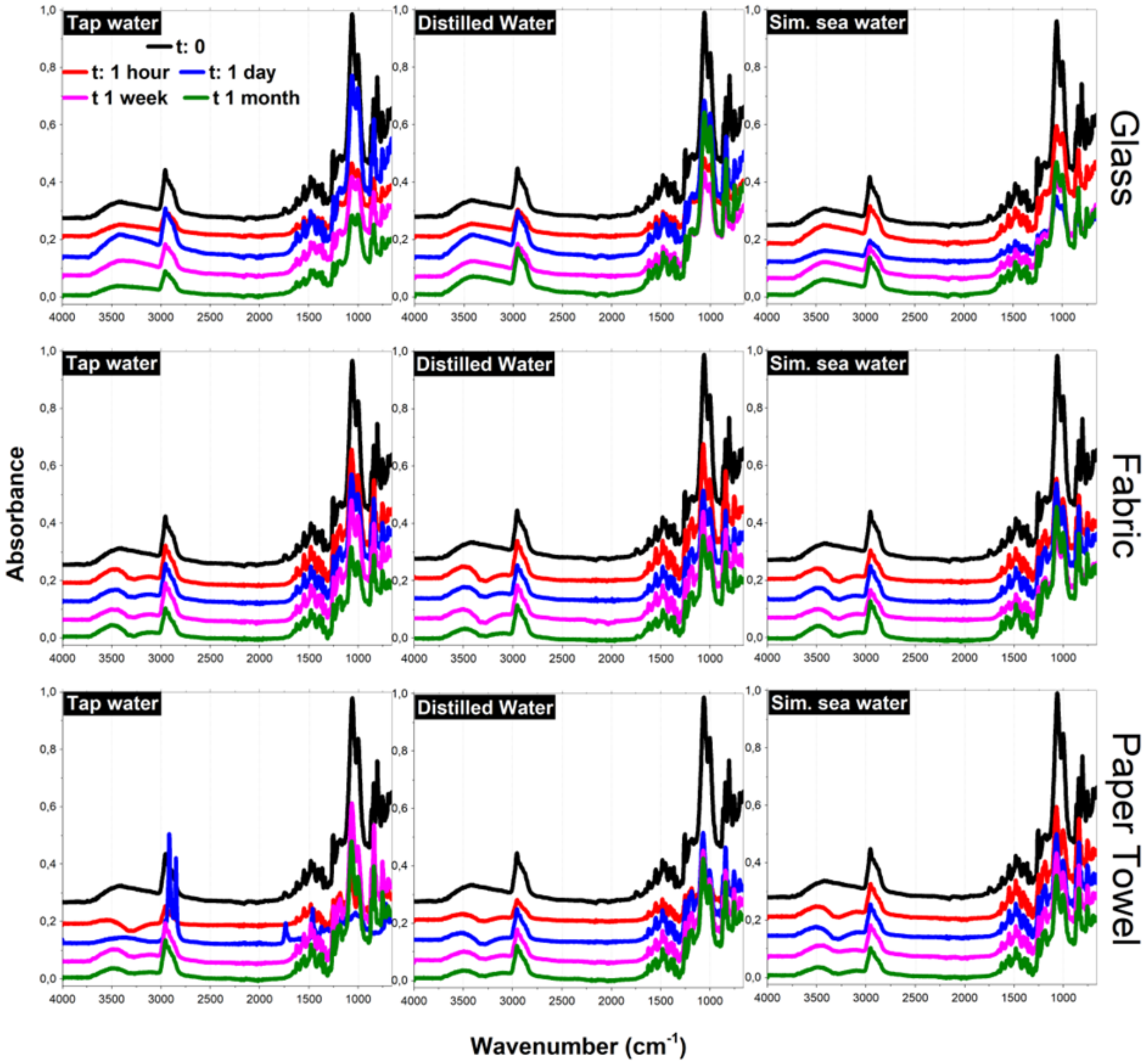

Figure 21. The FTIR spectra of liquid lipstick in water sources at different time of intervals.

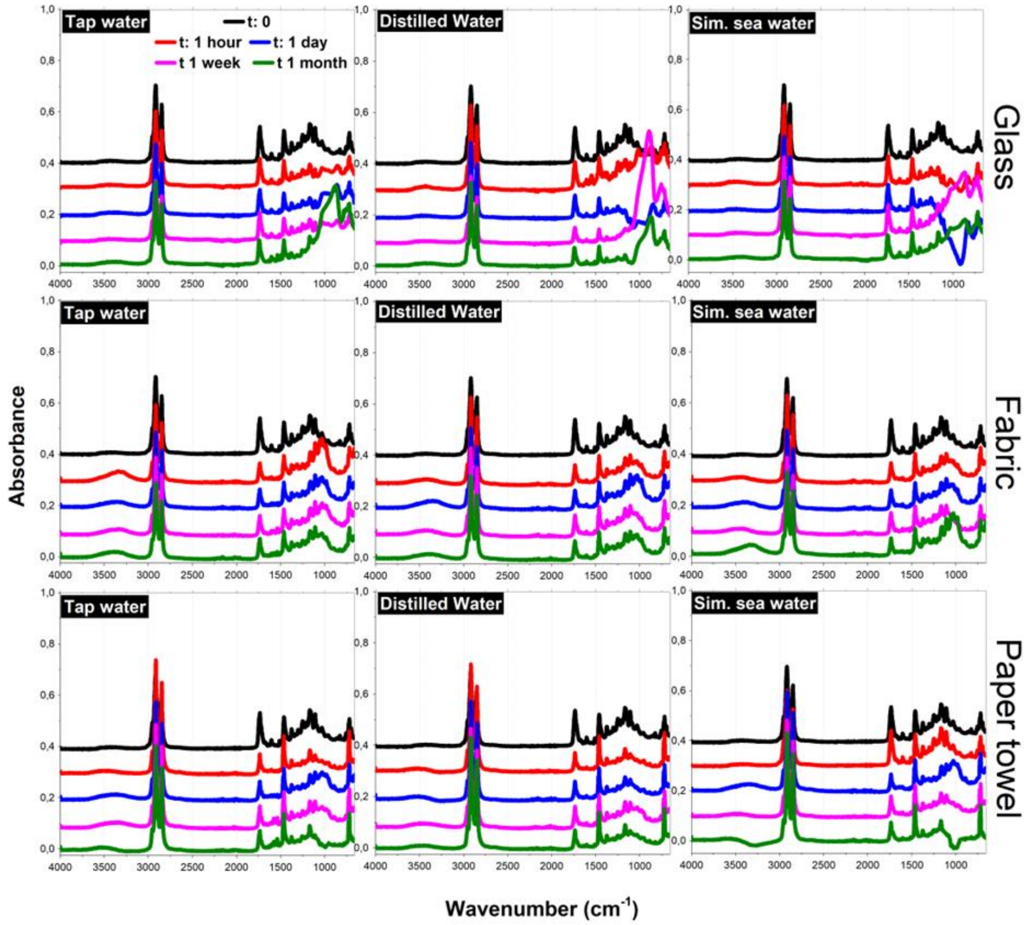

Figure 22. The FTIR spectra of lip balm in water sources at different time of intervals.

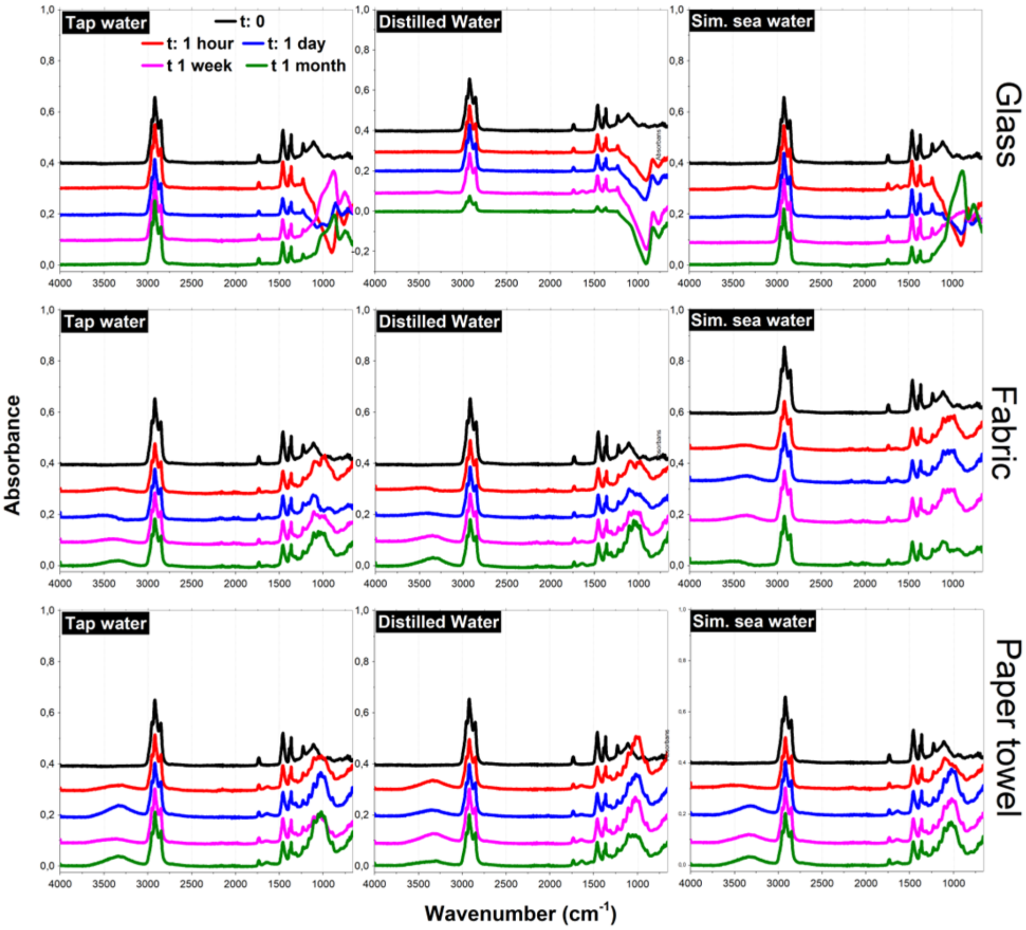

Figure 23. The FTIR spectra of lip gloss in water sources at different time of intervals.

4. Conclusion

In this study, four different lip cosmetic products including wax lipstick, liquid lipstick, lip balm and lip gloss have been examined as forensic evidence. FTIR is carried out to identify the characterization and differentiate samples. Moreover, VSC 8000 have been used for imaging of lip cosmetic-stained substrates under different light of sources to observe the structural change against the environmental conditions. The effect of lip cosmetic product types, time, type of substrate, and environmental conditions are systematically investigated. The stability studies have demonstrated that the stain on the different substrates shows differentiating results which is captured by VSC 8000. By taking account that stained (with lip cosmetic products) evidence could be encountered in different environment, the effect of chemical and physical change of stained objects in purified water, tap water and simulated sea water are investigated. Accordingly, there is no significant structural change in water source and as the times changes, however, they can be discriminated visually using optical microscopy or Video spectral comparator.

Author contributions

Seyda Turkay: Investigation, analysis, writing-original draft, visualization, methodology **Soner Kizil:** Investigation, analysis, writing-original draft conceptualization, methodology, visualization, writing-reviewing and editing, supervision.

Conflicts of interest

The authors declare no conflicts of interest.

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Development of elbow rehabilitation device with iterative learning control and internet of things

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Abstract

In this study, we present a novel approach for rehabilitation devices through the design of an active elbow joint orthosis, inspired by the fundamental principles of robotic exoskeletons. The device not only enables home-based usage but also facilitates the transmission of exercise data from patients to physiotherapists via the Internet of Things (IoT) device. This approach offers the possibility of increased therapy sessions for each patient while allowing physiotherapists access to data for real-time or subsequent analyses, thereby establishing a database. This permits a single physiotherapist to manage multiple patients more effectively. The developed mobile application within this research incorporates a distinct entry interface for both patients and physiotherapists. Maximum force and position values generated during each exercise period are displayed within the application. The device enables active exercise with a single degree of freedom at the elbow joint and is equipped with force sensors to ensure safety against potential high-shear forces. Furthermore, it can be worn on the upper extremity using adjustable Velcro straps to accommodate users with varying arm circumferences. Specifically, this system amalgamates two primary components: a microcontroller operating control algorithms and IoT technology, and a smartphone application containing interfaces for physiotherapists and users undergoing therapy. The control design of the device employs a P-Type Iterative Learning Control (ILC) due to periodic exercise movements, reducing the error norm by approximately 20% during each exercise period (excluding the initial period). The controller consistently diminishes error values with each iteration, ultimately converging to zero. Throughout an exercise lasting around 3 minutes, the average error norm is recorded as 0.229^0. In essence, this study presents a pioneering approach that sets itself apart from other research by minimizing shear forces and errors through a specialized controller, all while enabling remote, home-based rehabilitation under expert supervision.

1. Introduction

Stroke is a prevalent health issue among adults in Turkey. The annual number of stroke-related deaths in the country is estimated between 35,000 to 40,000 [1]. The functionality of upper extremity joints holds significant importance, especially in fulfilling basic needs like eating, bathing, among others. Functional losses post-stroke, particularly those affecting the upper extremities, significantly impact individuals' abilities to carry out daily life activities and meet essential needs [2]. However, the rehabilitation process is laborious and costly. Despite the proven effectiveness of stroke rehabilitation when administered early, it's known that not all patients receive the necessary treatment during this period. The increasing number of cases exacerbates the challenge of meeting rehabilitation needs. Intensive sessions and targeted home-based rehabilitation are essential steps aimed at enhancing effectiveness.

Rehabilitation robots enable therapists to treat multiple patients simultaneously, reducing their workload and potentially lowering treatment costs. Furthermore, these robots possess additional functions like recording and analyzing patient performance data. Monitoring this data aims to alleviate hospital congestion and promote home-based rehabilitation. However, factors such as the high cost and lack of mobility in rehabilitation robots need consideration.

Exoskeleton robots, designed for both lower and upper extremities, can be categorized as therapeutic or assistive motion systems [3]. The effectiveness and usability of home-based exoskeleton robots hold significant importance in terms of performance. Certain criteria need to be considered to achieve optimal performance with these robots:

- Home-based exoskeleton robots should not only be structurally but also functionally ergonomic, enabling users to comfortably perform daily activities [4].
- These robots should have a stable control mechanism.
- The number of actuators and sensors should be adequate to enhance mobility effectively.
- Cost-effectiveness is essential for home-based exoskeleton robots.
- The energy requirement of the robot intended for home use should be sufficient and rechargeable when necessary [5].

The system developed in this study supports upper extremity rehabilitation using innovations in IoT technology, sensing devices, control algorithms, and mobile applications. Specifically, this system integrates two fundamental components. Firstly, a microcontroller card operating control algorithms and IoT technology, and secondly, a mobile phone application containing user interfaces for physiotherapists and patients. This study focuses specifically on the device called "MentArm", denoted as a home-based elbow joint rehabilitation kit. This research will demonstrate that the use of an active elbow joint orthosis provides more effective home-based rehabilitation compared to traditional methods. Thanks to this system, patients' therapy sessions will increase, a database will be created that provides access to data in real-time or for subsequent analysis, and will allow a physiotherapist to manage multiple patients more effectively. How does this system, which combines a microcontroller board with control algorithms and IoT technology and a smartphone application, affect the therapy processes of patients and physiotherapists?

Various robotic exoskeleton systems used in upper extremity rehabilitation have been examined based on information obtained from multiple studies. The functionality of these rehabilitation robots in the literature tends to be limited concerning upper extremity mobility. However, the shoulder exoskeleton plays a significant role in the stabilization of the upper limb in existing robots. Ball et al. developed an adjustable exoskeleton robot named MEDARM to assist therapists [6]. This mechanism utilizes an electric motor as an actuator to facilitate planar shoulder-elbow movements and transmits motion through a combination of cables and belts. This design provides the robot with an advantage against the factor of gravity, optimizing the power-to-weight ratio. The device named MEDARM, capable of independently controlling five degrees of freedom, also offers a notable advantage in adapting to different limb sizes [6].

The electromechanical elbow rehabilitation robot developed by Vanderniepen focuses on executing specific joint movements and preventing excessive force. It requires personalized braces to accommodate the unique characteristics of each patient's extremity [7]. This device features a smaller spring in its actuation mechanism compared to other similar systems, making it more suitable for anterior loads. Moreover, the device boasts a prominent actuation system in terms of rapid accessibility and adjustability as shown in Figure 1 [7].

Figure 1. Vanderniepen home-based exoskeleton device [7].

ULERD stands out in home-based rehabilitation due to its lightweight and portable design. Specifically designed to support elbow joint movements, it employs two degrees of freedom with passive rotational potentiometer sensors. The device is optimized in terms of mass and power balance, using an aluminum frame and brushless DC motors [8].

Ripel et al. [9] developed an active elbow orthosis inspired by the principles of robotic exoskeletons. This orthosis determines the patient's movement activity using a force sensor and transmits this data to an actuator to control the device.

Zhang et al. [10] NEEM device is a reinforced elbow exoskeleton system designed to provide maximum comfort and safety. Featuring dual linkage, it offers an enhanced robot-human interaction zone, optimizing interaction comfort through its compact structure.

Recent studies have focused on developing elbow rehabilitation devices for home use, aiming to facilitate effective rehabilitation outside traditional clinical settings. Ceccarelli et al. [11] introduced L-CADEL v2, a specific therapeutic device designed for elbow movement, highlighting advancements in devices tailored for elbow rehabilitation. Wu et al. [12] developed a device beneficial for individuals with mild to moderate elbow joint symptoms, emphasizing a home-use elbow rehabilitation system that integrates a smartphone and cloud database to potentially execute elbow joint rehabilitation programs at home. Additionally, Said et al. [13] introduced a smart elbow brace aiming to reduce rehabilitation costs outside hospitals, alleviate therapist workload, and encourage patient adherence to programs.

Erin et al. [14] have devised an Android application grounded in the IoT to facilitate real-time operations. This application transmits accelerometer data to the cloud environment. Through software crafted in the Python environment, real-time data is fetched from the cloud, initiating a classification process that effectively identifies individuals' movements. Delays encountered during the research process have been pinpointed, and the classification process has been observed to function seamlessly.

Studies in the literature often do not completely focus on devices exclusively designed for home use but predominantly tailor them for clinical environments. Factors such as high cost and the requirement for domestic electrical power can limit the usability of these devices at home. Limitations like the lack of remote expert control further restrict their use in home settings. The MentArm device stands out as a home exercise device with stability in its control mechanism. Its capability to enable exercise under remote expert control, its low cost, compatibility with home energy requirements, and its iterative learning-based controller all contribute to its usability at home, filling the gap observed in the literature.

2. Material and method

In the design process, the concept of function can be defined as the relationship between the inputs and outputs of the intended system to be designed. In a large and complex design problem, breaking down the entire function into sub-functions simplifies the process of finding a solution. The detailed flowchart of the MentArm device is illustrated in Figure 2.

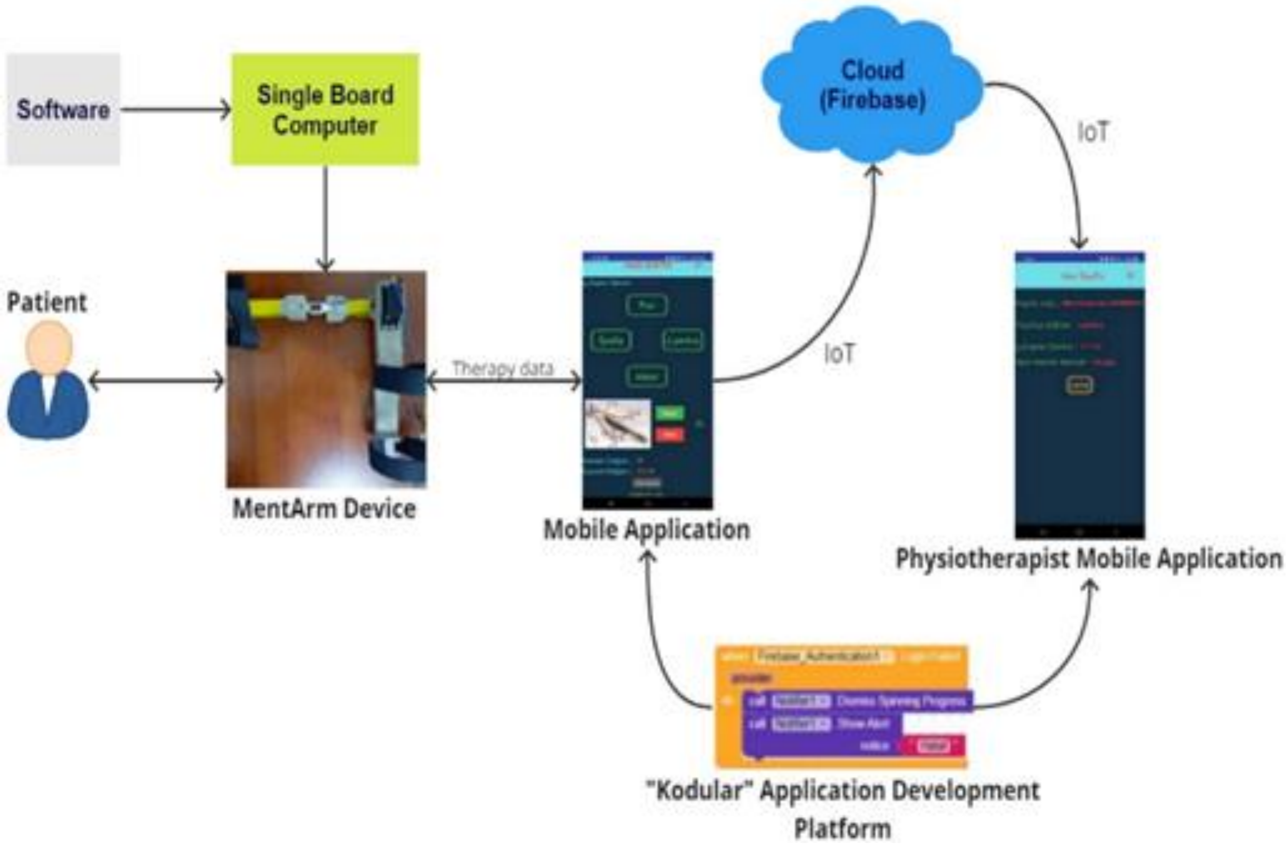


Figure 2. Flowchart of the MentArm device.

2.1. Functional structure and mechanical design

The full functionality of the elbow rehabilitation device is illustrated in Figure 3, according to the design criteria. The system boundary is delineated by axis lines in the diagram. Energy input into the system is denoted as E, while the outgoing energy from the system is represented as E'. The designed rehabilitation device operates through a combination of electrical energy and muscle power. As the device is suitable for both active and passive rehabilitation, muscle power can be considered part of the energy input. The electrical energy supplied to the actuator in the elbow region is transformed into mechanical energy, resulting in frictional losses during this conversion process. Additionally, users may support the device using their own muscle power, which could lead to muscular fatigue during exercises. The entry of patients into the system is denoted as H, while the output of rehabilitated individuals is indicated as H'. The system's operation is governed by the input from the control unit, designated as K, while the actuator output and movement of the system are symbolized as K'.

The functionality defining the elbow rehabilitation device developed within the scope of this study explicates the system's intricacies through detailed sub-functions. In this context, the device's sub-functions encompass attaching the device to the arm, executing elbow exercises, adjusting device operating parameters via the mobile application, and establishing communication between the mobile application and the device. Figure 4 visually illustrates these specified sub-functions.

The ease of wearing the device is a fundamental requirement, achieved through the use of Velcro straps, facilitating effortless application. This approach enables individuals with diverse conditions or arm issues to easily don the device. Accordingly, different sizes (small, medium, large, etc.) for the upper and forearm parts of the device can be produced to suit various body measurements. Additionally, a custom-sized device can be designed based on specific measurements taken from the individual's arm, enabling its production through three-dimensional (3D) printing. The connections for the upper and forearm should be adjustable or produced in different sizes. Moreover, it necessitates a microcontroller for adjusting and monitoring exercise tasks. Furthermore, a dedicated mobile application needs to be developed to visualize the acquired data and establish an Internet of Things (IoT) connection to transmit data to the physiotherapist.

The mechanical design ensures the prevention of excessive force effects and adaptability to different users. In Figure 5, the mechanical design of the device (a) and its manufactured form (b) are depicted. This design mitigates the risk of arm injury to the user and includes a force sensor for safety purposes, thus alleviating some constraints in actuator selection. Moreover, it diverges from conventional designs by not integrating a spring element found in previous studies. This design allows users to engage solely in active rehabilitation, ensuring secure flexion and extension movements at the elbow-arm joint.

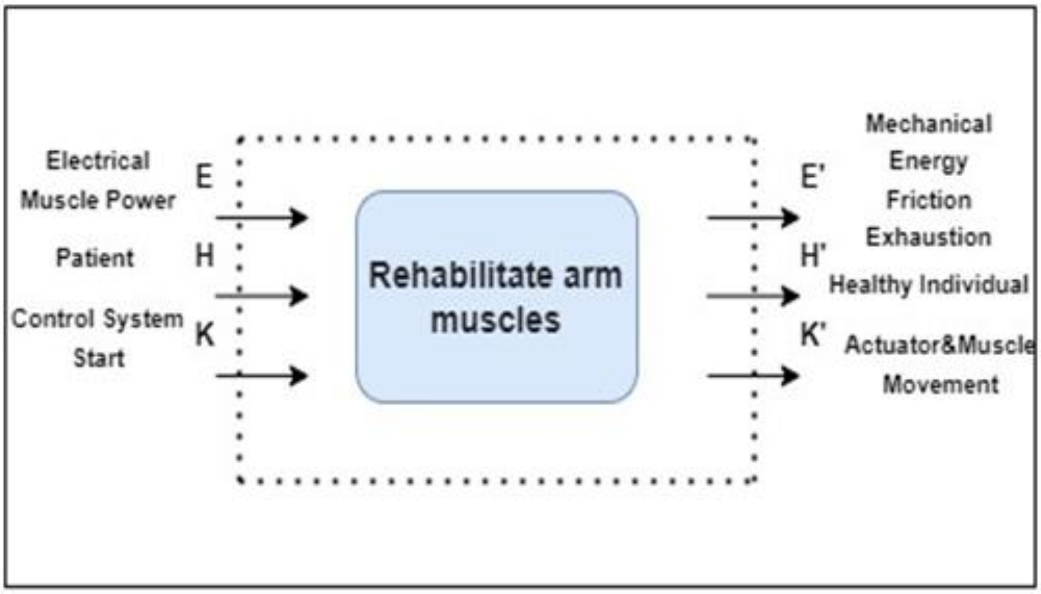


Figure 3. The entire function of MentArm.

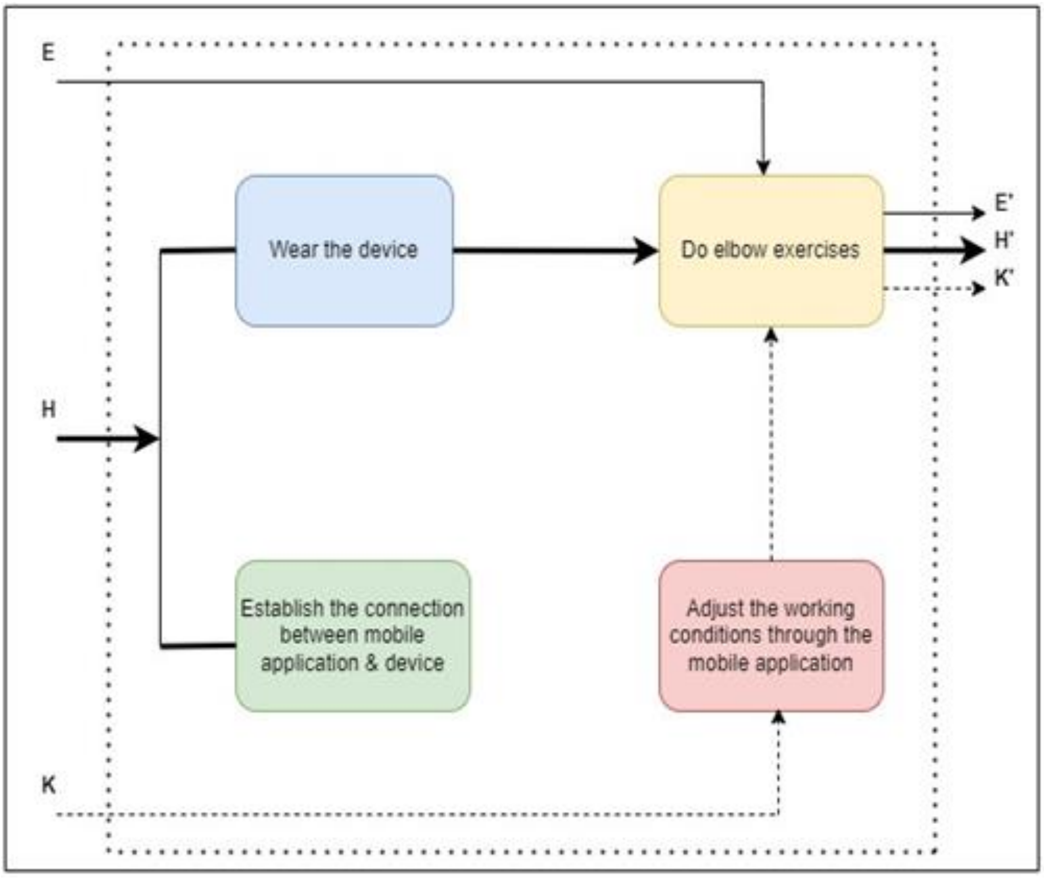
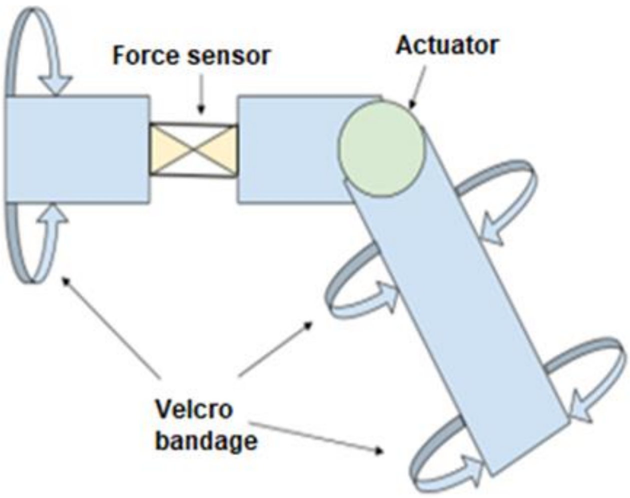


Figure 4. Sub-function of MentArm.



(a) (b)

Figure 5. (a) Mechanical design of the device and (b) Manufactured device.

2.2. Biomechanical model design

The human arm exhibits various axes of movement in its different joints. The shoulder, elbow, and wrist serve as the primary centers enabling this motion. This study aims to determine the center of the single-degree-of-freedom elbow position using a biomechanical model and develop a suitable exoskeleton model. Specifically, the study focuses on the uniaxial movement at the elbow joint in the human arm model, where the elbow joint axis is represented by the ϕ axis. In the constrained human arm model, movement is restricted to flexion and extension along a single axis at the elbow joint. The ϕ angle allows movement in the x and y planes in the elbow region. I_{u1} and I_{u2} represent the upper arm section from shoulder to elbow, while I_{f1} and I_{f2} denote the forearm section between the elbow and wrist joints. m_u and m_f represent the masses of the upper arm and forearm, assuming their concentration at the midpoint of these sections. Figure 6 illustrates the constrained human arm model.

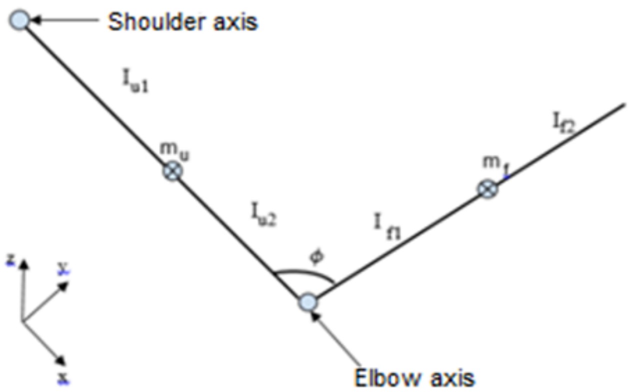


Figure 6. Constrained human arm model.

In Equation 1, J and C represent inertia and Coriolis effects, respectively. F_h and G_h stand for friction and gravitational effects, respectively. Here, h_h denotes the externally applied force [15].

$$J(\ddot{\phi}) + C(\dot{\phi}) + F_h(\dot{\phi}) + G_h(\phi) = g(\phi) - h_h \qquad (1)$$

The difference in the angle of the elbow joint between the exoskeleton model and the constrained human arm model has been reasonably determined.

2.3. Mobile application and IoT design

A mobile application has been specifically developed to facilitate the device's use at home, ensuring users exercise under expert supervision. This application was designed using the Android application development platform called 'Kodular'. It was meticulously crafted to offer a user-friendly interface for both patient users and expert physiotherapists. Additionally, it integrates the widely used IoT (Internet of Things) technology for data transfer. Patient users' data are stored in the cloud via IoT, allowing physiotherapists to access this data from their mobile applications by pressing the 'getir' button in the doctor's menu. Figure 7 showcases the interface of the mobile application (MentArm).

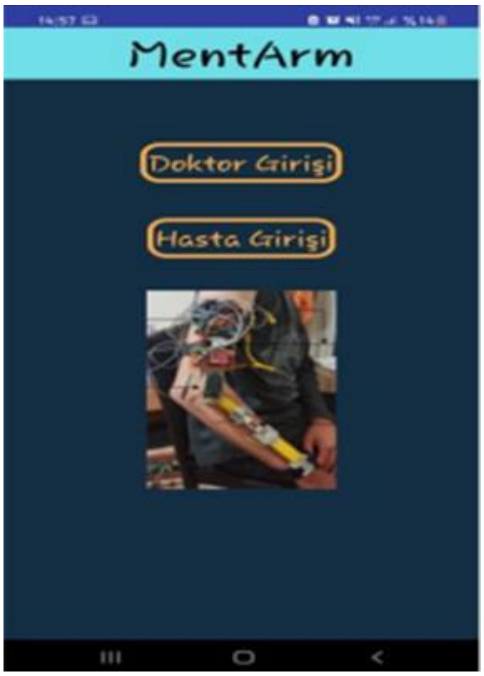


Figure 7. Mobile application home interface.

Users receiving therapy will encounter the exercise screen after logging in. Initially, they need to establish a connection with the device via Bluetooth on this screen. Once the connection is established, they will press the relevant button to select one of the four exercises available. These exercises are respectively labeled as 'far,' 'contra,' 'near,' and 'ipsila.' 'Far' represents the far movement, 'contra' denotes the opposite movement, 'near' explains the close movement, and 'ipsila' signifies the movement in the same direction. The panel displays force and position values after each reference signal period. Upon initiating the exercise by pressing the 'Start' button, the timer begins measuring the duration. To conclude the exercise, users can utilize the 'Finish' button. If the force value falls within the range of +10 to -10 N, no specific value is displayed. However, if it exceeds these limits, a warning message appears on the screen, and the exercise is terminated. This termination is implemented to prevent potential excessive force and ensure user safety. Figure 8 illustrates the interface for users undergoing therapy.

Figure 8. Exercise interface for users undergoing therapy.

In Figure 8, the user undergoing therapy is depicted with details including their name, exercise type, duration, and a cloud-stored error message triggered in case the predefined force limits are exceeded, facilitated by IoT. These data are accessible to physiotherapists through the mobile application when they press the 'fetch' button, displayed on the panel. The real-time monitoring screen, where exercise data is transmitted via IoT to the Firebase cloud platform, allowing instantaneous observation of data, is illustrated in Figure 9.

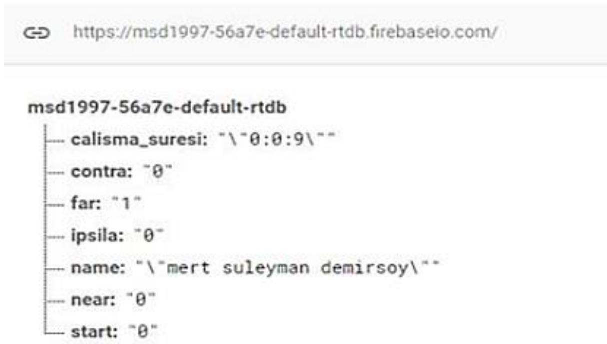


Figure 9. Firebase real-time database.

This allows the data to be collected, and processed, and the condition of the therapy-receiving user to be recorded in a cloud environment (Firebase) through IoT communication.

2.4. Controller design

Controller design involves the management mechanisms employed to ensure that a system or device exhibits the desired performance. This design tracks and analyzes variables within the system and intervenes when necessary to achieve the desired behavior. Controllers are typically built upon a feedback loop; they monitor the current state of a system compare this information, and initiate corrective actions to align with the desired state.

For the controller design of the device, a P-type iterative learning control will be utilized, aiming to settle into the stable region with minimal error and in the shortest possible time.

Iterative learning control is a novel method designed for systems performing periodically repeated operations. The simple proportional structure of P-type iterative learning control (ILC) does not demand detailed knowledge of system dynamics. The principle behind this controller involves retaining output and error values from the previous cycle in memory to approach the reference signal in the subsequent cycle. Initially, for the first cycle, output signals and error values for each sampling are set to 0 in memory. In subsequent cycles, the output signal values and error values from the previous cycle are stored and utilized. Each ILC attempt starts from a fixed initial position, and the positional error occurring in each attempt is used to update control parameters, enhancing the accuracy of subsequent attempts. In this system, a structure that does not rely on system dynamics is formulated mathematically, as shown in Equation 2.

$$u_{k+1} = u_k + \gamma e \tag{2}$$

Equation 2 represents the current output signal u_k of the system. γ denotes the learning gain, a continuous scalar value influencing the convergence rate of the system, and the amount of error. This learning gain is chosen as a value between 0 and 1, considering system dynamics and error tolerance. As this gain value approaches 0, the system converges slower to the reference signal but reduces the error. Conversely, as the gain value approaches 1, the system approaches the reference signal faster but increases the error amount. The new output value (u_{k+1}) is determined by multiplying the learning gain (γ) with the error value (e) in the formula shown in Equation 2 and adding it to the previous output value. This method enables the system to approach the reference signal slowly or rapidly depending on the chosen learning gain.

The block denoted by C in Figure 10 represents the proportional controller, with the proportional gain value (k_p) determined as 0.5 based on experimental tests. The ILC block possesses a memory feature. The value obtained from the proportional controller 'u' is added to the value from the ILC controller and transmitted as u_k for the motor. Figure 10 illustrates the block diagram of the P-type ILC.

In Figure 11, a graph illustrating the sinusoidal reference signal tracked by the P-Type ILC controller applied to the servo motor is presented. The experimental test results have led to the selection of a proportional control gain (k_p) of 0.5 as the controller parameter. Additionally, the learning gain (γ) for the ILC controller is set at 0.4. As represented in Figure 11, due to choosing a learning gain closer to 0, it is evident that the error magnitudes are reduced, albeit resulting in a longer time to precisely reach the reference signal. This observation highlights a decrease in error magnitudes from the 1st to the 4th period compared to previous periods.

The sinusoidal waves consist of 100 samples per period. Initially, the presence of a high overshoot is attributed to the proportional controller's coefficient and the learning gain value. However, the system rapidly approaches the reference signal and stabilizes in approximately 12 samples.

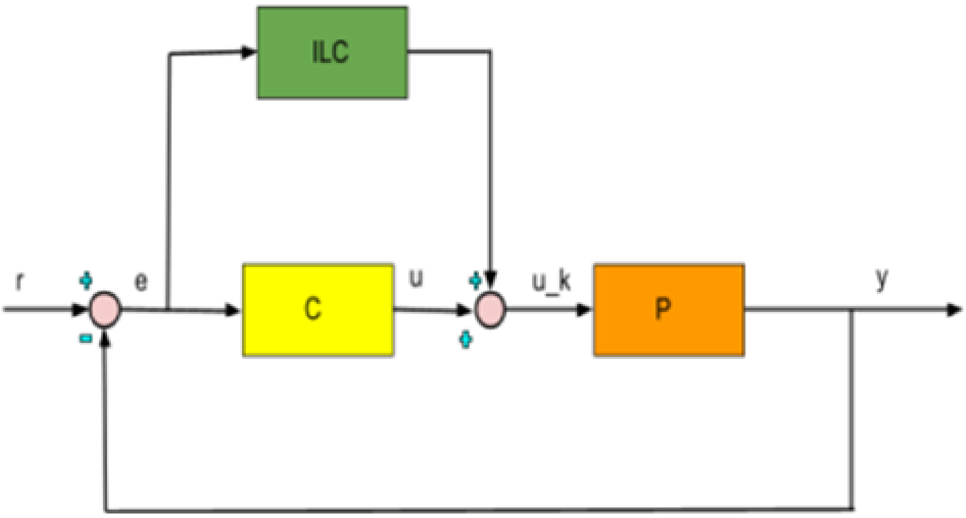


Figure 10. P-Type ILC block diagram.

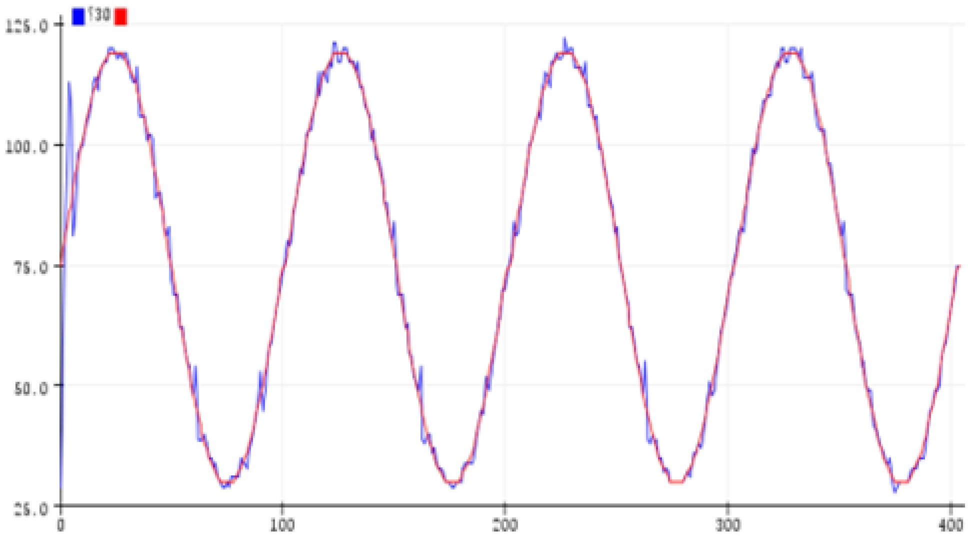


Figure 11. The input-output signal graph with P-Type ILC controller (The vertical axis of the graph represents an angle in degrees, while the horizontal axis shows the number of samples. The red line illustrates the sinusoidal reference wave, and the blue line depicts the system's instantaneous position.)

3. Results and discussion

The device introduces a novel approach to active elbow joint rehabilitation by adopting the fundamental principles of robotic exoskeletons. Additionally, the integration of a mobile application and IoT technology, facilitates the transfer of exercise data from patients to physiotherapists, optimizing the treatment process. The MentArm system increases home usability and flexibility of therapy sessions while aiding physiotherapists in analyzing patient data and formulating more effective treatment methods. Furthermore, the device's user-friendly mobile interface assists patients in monitoring their exercise routines and recording data. The strengths of this study encompass home usability, integration of a mobile app interface, and IoT for effective monitoring of patient data and enhancing physiotherapist accessibility. However, weaknesses such as actuator wear and data security need attention. Data privacy remains crucial as the communication follows an open path, necessitating end-to-end encryption for the data. The long-term effects of device usage, its effectiveness across different patient groups, and user experience require in-depth analysis.

The integration of mobile applications and IoT technology is emphasized, focusing on the swift and comprehensive transmission of patients' exercise data to physiotherapists, aiming to optimize the treatment process. The mobile application developed within the scope of the study successfully transferred patient exercise data to a database (Firebase) via IoT technology and seamlessly transmitted this data to the physiotherapist panel of the mobile application. Recent IoT-based studies demonstrate the rapid and accurate transfer of data through IoT, which has gained popularity, especially in object communication [16-20]. The tests conducted in this study revealed no data loss or delays. Consequently, the patient users' data was swiftly transferred from the cloud environment (Firebase) to the physiotherapists' application. Based on the results of exercise tests conducted in home settings, physiotherapists could remotely monitor this process. Tests on the device control system were performed using admittance, classical PID, and model-based ILC controllers. The admittance controller was deemed unsuitable for the device due to it generating an angle value against force. Therefore, classical PID and ILC controllers were found to be appropriate for the control system design. In the study by Demirsoy et al., [21] a PID controller was used in the device, explaining position errors as an average value. However, as the PID controller could not reduce errors to zero due to the system's nonlinearity, this study preferred a P-type ILC controller.

In this study, P type ILC controller was used to reduce error values and design a more stable system. The controller design was evaluated by considering the outcomes of the final device for the first four iterations. A total of 400 samples were used with a sampling frequency of 100 per iteration. The norm of the error between the reference signal and the device's motion was measured as 2.997343316^0 in the initial iteration. Subsequent iterations showed a decrease in error norms, measuring 1.422597331^0, 1.192201225^0, and 0.933405898^0, respectively. These results indicate an approximately 20% reduction in steady-state errors in each iteration with the P-type ILC utilized, showcasing how controller parameters can diminish errors to near-zero levels over increased iterations. However, Demirsoy et al., in their study designing a PID controller, found the error norm to be constant at 1.755^0. This means that the error throughout the entire exercise is 1.755^0. With the P-type ILC, controller we developed to reduce the error and approach it to zero as much as possible, the error norm decreases and approaches zero in each period. In Figure 12, it can be observed that the iterative learning controller converges toward the reference signal in each iteration, reducing the error. As the number of iterations increases, the error in the system response continues to decrease based on the parameters chosen for the controller. Figure 12 displays a graph illustrating the norm of errors obtained from comparing the data collected over 400 samples (4 periods) with the reference signal.

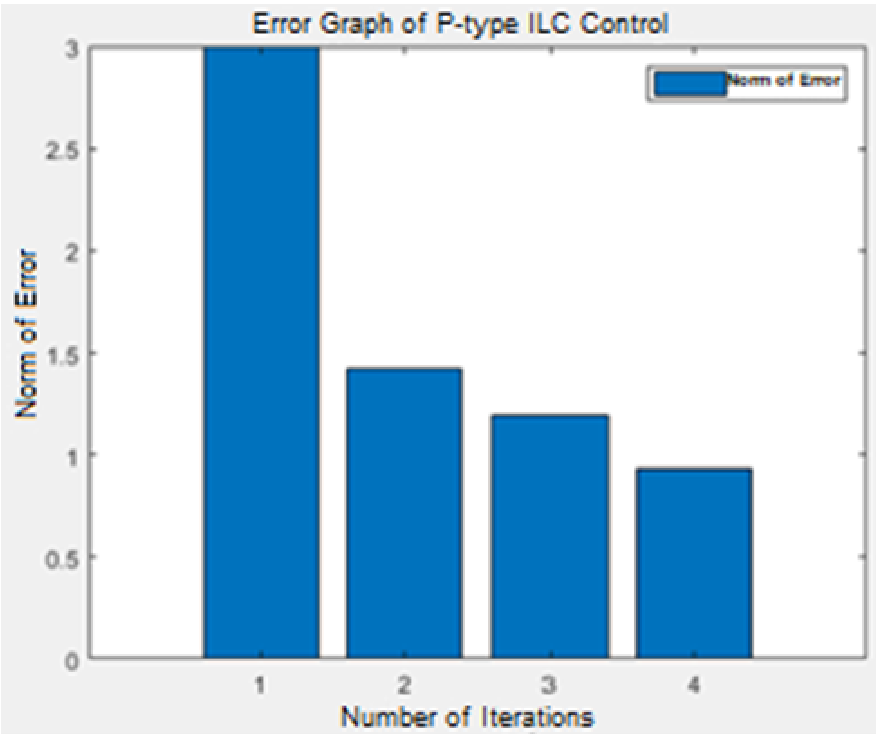


Figure 12. Column graph of error norms by iteration count.

The available data suggests the device's potential to offer effective and reliable rehabilitation in a home setting. As a result of this study, a prototype for a low-cost, portable, and remotely controlled home-based elbow rehabilitation device has been successfully designed and produced. In this way, it differs from other studies; Remote, home-type rehabilitation can be performed under expert control. In addition, there are fewer cutting forces and errors during the rehabilitation process with the controller used.

When looking at the existing studies, the distinctions of our study from the literature are outlined below:

- Real-time exercise data can be monitored through the development of an Android-based application.
- The Internet of Things (IoT) method has been incorporated into our study, allowing individuals' exercises to be continuously monitored by expert doctors, irrespective of their location.
- The developed Android application has the capability to offer 4 different personalized exercise options for patients.
- The device created is cost-effective and suitable for home use.
- The utilized controller has achieved significantly low error rates.

4. Conclusion

These results substantiate the problem and hypothesis of the study. Additionally, deductions for the target audience include expert-controlled home rehabilitation processes, a stable control methodology, and data transmission accuracy. The findings contribute to the existing literature by providing insights into the use of ILC controllers in elbow rehabilitation devices, potentially reducing positional errors to near-zero levels.

Following the evaluation of results, the study identified areas for improvement, particularly in refining control algorithms within the system and integrating additional features into the IoT system. Future studies could focus on the long-term efficacy of the MentArm system. The exercise data obtained with this device will be collected in the cloud and will serve as a repository for developing home type exercise devices, thus contributing to future studies. Additionally, broader clinical trials on diverse patient groups and increased user feedback on the device's user-friendly design could be obtained. Moreover, research into improving control algorithms using a metaheuristic optimization method and technological advancements to make the device more economical and accessible could be pursued.

Author contributions

Mert Süleyman Demirsoy: Investigation, Methodology, Software, Writing-Original draft preparation. **Yusuf Hamida El Naser:** Conceptualization, Methodology, Data curation, Validation. **Muhammed Salih Sarıkaya:** Investigation, Software, Writing-Reviewing and Editing. **Nur Yasin Peker:** Software, Visualization and Editing. **Mustafa Kutlu:** Conceptualization, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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Detection of cotton leaf disease with machine learning model

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Abstract

This study aims to use a machine learning (ML) model to accurately classify four datasets of cotton crop leaves as either infected or healthy. Bacterial blight, Curly virus, Fussarium Wilt, and healthy leaves were used as the datasets for the study. ML is a useful tool in detecting cotton leaf diseases and can minimize the rate of disease. The problem is that without machine learning technique it is very difficult and time consuming to detect the diseases then to sort out this problem a machine learning model is proposed and to test the accuracy of the proposed model, the confusion matrix concept was used. The researchers have done their research works to diagnose the diseases by using (ML) model but the drawback of their research was that the results which were given by the different (ML) models were not accurate. The target of the study was to identify diseases affecting the cotton plant in the early stages using traditional techniques. However, utilizing various image processing techniques and machine learning algorithms, including a convolutional neural network, proved to be helpful in diagnosing the diseases. This technological approach can simplify the detection of damaged leaves and minimize the efforts of farmers in detecting those diseases. Cotton is a natural fiber produced on a large scale, and it is grown on 2.5% of overall agronomic land. The detection of cotton leaf diseases is crucial to maintain the crop's productivity and provide reliable earnings to farmers. A confusion matrix is N X N matrix used for evaluating the performance of a classification model, where N is the number of target classes. The matrix compares the actual target values with those predicted by machine learning model. This technique has four parameters to test the accuracy of the results which is given in my research work.

1. Introduction

1.1 Machine learning (ML)

The machine learning (ML) is a field of inquiry developed to understand methods a machine learning is closely related to computational statistics, which focuses on making predictions using computers, but not all machine learning is a statistical learning. machine learning algorithms build a model based on sample data, known as training data, in order to make predictions or decisions without being explicitly programmed to do so. Machine learning algorithms are used in a wide variety of applications, such as in medicine, email filtering, speech recognition, computer vision and agriculture. Many researchers have used a machine learning concept to detect the cotton leaf diseases but as I have used in my research work to detect the diseases in the cotton leave and show its accurate results which are tested through the confusion matrix method by using its four parameters. Then the accuracy which is given by the proposed model is validated [1].

1.2 Cotton crop

Cotton (*Gossypium hirsutum* L.) is a widely cultivated crop that is frequently affected by pests and diseases. The management of cotton pests and diseases usually involves the use of chemical pesticides. Although chemical pesticides are often effective, their long-term use can lead to increase pest resistance to the pesticides, reduce natural enemies, decrease natural control, and environmental degradation. Due to the growing awareness of the importance of ecological sustainability and the need for sustainable cotton production, the use of organic methods such as intercropping is gradually gaining attention as an alternative approach for cotton pest and disease control. Intercropping of cotton with other crops can often improve the overall yield, provide additional income from the intercropped crop, and offer significant economic benefits without compromising cotton quality [2]. The authors used this approach for the detection of cotton leaf diseases.

Agriculture makes a significant contribution to Pakistan's economy, making up around 20% of GDP (Gross Domestic Product) and 65% of the country's exports, 73% of which are cotton-based goods [3]. However, due to rising introduction costs and the harm caused by cotton diseases, cotton production has decreased during the last few years [4] reported that the four datasets of diseases in their research work. The researchers must make decisions in order to maintain the cotton harvest. In this way, our objective proposed a method for identifying bug-based diseases in cotton crops through in-depth learning [5]. The identification of the cotton leaf diseases through the naked eyes creates a blunder that’s why machine learning technique is very useful to identify the cotton diseases. Researchers demand a convenient and affordable method to identify diseases in cotton crops due to the remarkable production of cotton [6]. They stated that the four different diseases are differentiated through the machine learning technique a tensor flow framework is used to identify the cotton leaf illnesses. However, the strategies used in previous exams, such as SVM (Support Vector Machine) and SVM-GA (Support Vector machine - Genetic algorithm), suggest that grouping is a low-speed process, necessitates large computational devices, and is constrained for extremely high numbers of diseases, which increases the overall rate of the framework. According to the tools used, the region of cotton diseases is finished with considerably less calculation and execution. The customer may write the supplied method using one's skill. For example, the given method/method may be written in Python, C++, JavaScript (JS), and so forth. The state's economy is being improved by increasing cotton production and making sure that any problems are caught early on and controlled. This requires that the project's progress be monitored at various times as the day's temperature and the sun's position change [7].

1.3 Background of cotton crop

Florida in 1556 and Virginia in 1607 are said to have been the first two states to grow cotton crop seeds. Near the middle Nile Basin, where cotton is grown, in eastern Sudan circa 5000 BCE, the cotton crop may have also been domesticated. Since there are so many indications and symptoms of illnesses that may be detected in cotton, it is a fibre crop. And it is by far the most well-known cash crop that has a variety of effects on the Pakistan financial system [8]. These types offer the majority of yield on a worldwide scale. Vicinity wise so if we need to discuss about Pakistan so it's far 1/3 region production smart. So, in recent times many pathogens illnesses arises in a Cotton crop. So, its product should be maintained through the ML model. This crop is very profitable. The Cotton crop is very absorbent and can easily absorb the moisture from the skin of the leaves.

The Figure 1 is taken from the [9] that shows the production rate of the cotton crop of the countries.

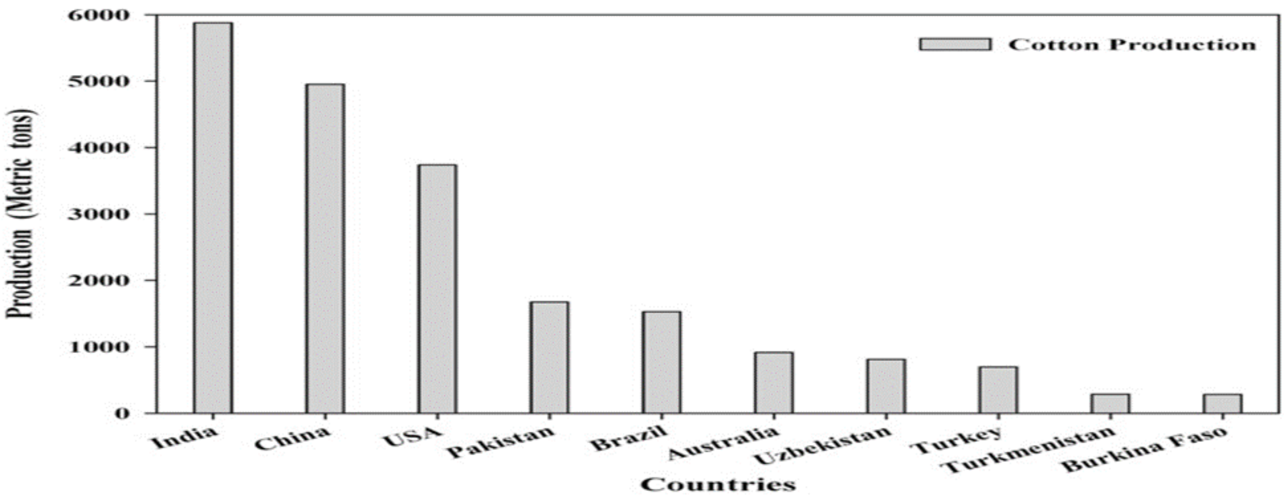


Figure 1. Cotton productions by the various countries (“cotton production,” 2017).

Cotton is fiber crop in which such plenty of symptoms and symptoms of illnesses arises in it so we are capable of going to detect it [10]. And it is a most famous coins crop that outcomes India’s financial device in lots of methods. These varieties yield all over the worldwide. Vicinity smart so if we want to talk about approximately Pakistan so it's far 1/3 location production smart. So, these days many pathogens ailments arise in a Cotton crop [11].

Many studies have been conducted in the past few years to categorize cotton leaf illnesses, and now researchers are attempting to find ways to identify the diseases using ITbased machine learning approaches. Various studies were conducted in 2015 to categorize cotton leaf illnesses utilizing various pattern recognition techniques for classification and identification of cotton leaf diseases. The horticultural area in which the production level of the cotton crop is identified by using different technological strategies [12]. For the detection and categorization of three cotton leaf diseases—Alternaria, Myrothecium, and Bacterial blight—Rothe PR and Kshirsagar RV presented a pattern recognition method. This cotton dataset was gathered from cotton fields in their natural state using two separate Cannon digital cameras, the A460 and EOS550D. Preprocessing was done using a Gaussian filter to reduce noise in the pictures, and image segmentation was done using an active contour model. Image preprocessing and segmentation were followed by the extraction of several characteristics [13].

The deep convolutional neural network (CNN) is being used in this research to distinguish between diseased and healthy leaves as well as to identify sick plants. The CNN model is likewise intended to distinguish between healthy and sick leaves. Photos are also used to train the model, and the input leaf determines the model's output. In order to classify plants and detect plant diseases and illnesses, convolutional neural networks (CNNs) were crucial [14]. Without them, farmers would have to spend a lot of money and effort on the labor intensive and time-consuming task of identifying plant diseases. So, the main benefit of the model is to minimize the time identify and classify the four datasets of the cotton leaf diseases using convolutional neural network in a machine learning model.

The Figure 2 which is taken from the [15] shows the artificial neural network.

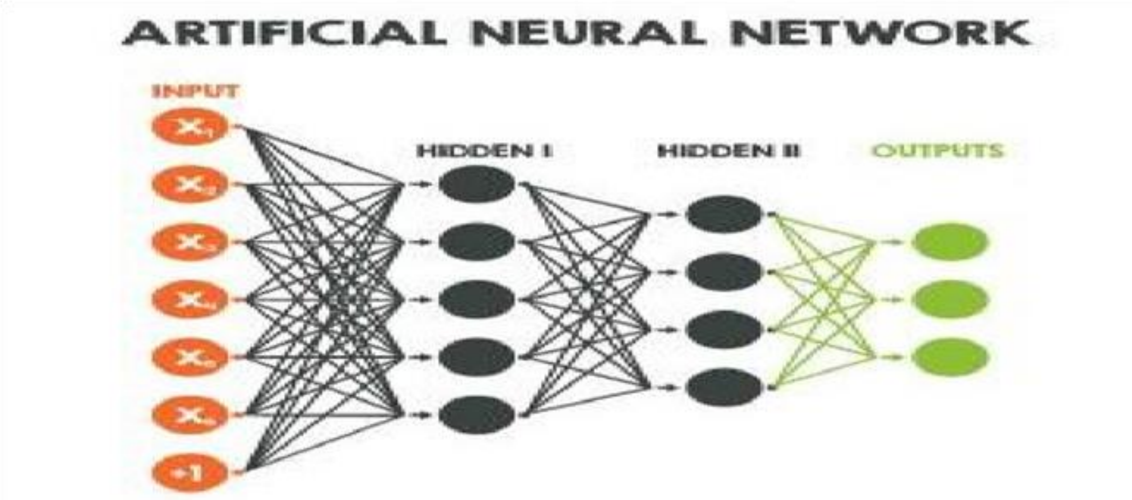


Figure 2. Artificial neural networks.

It recognizes through the image in machine learning model and the best classification of the diseases are also done in machine learning model to view the harmful diseases in which we have four diseases which we have already discussed and all are identified by the ML model and it mention its accurate results to the researchers. So, by using the machine learning concept the IT specialist make it easy to detect the diseases in a cotton leaf.

Figure 3 is taken from [16] and some have been taken in a real-world condition.

All these four dataset samples which are given above are the difference between the leaves which are infected or diseased and healthy leaves these all have done through the machine learning model the accuracy rate of the cotton leaves decide that which leaf is how much infected the dark spots shows the infected parts of the leaves.

Figure 3. Gallery of four dataset samples which detect from machine learning model (Healthy vs. Infected leaf).

1.4. Proposed system to show the viability of the ML model

Pham et al. [17] proposed a system to improve the viability of the Deep Learning model. The dataset is also created using a variety of models, including the Meta Deep Learning model that we have presented as well as bespoke CNN, VGG16, ResNet50, and other models. We discovered several different cotton illnesses in our research, including leaf spot, verticillium shrivel, target spot, fine accumulation, supplement deficiency, and leaf twist. With a precision of 98.53%, the suggested model performed quite well on the cotton dataset. Unmistakable models advance various element extraction techniques in deep learning. The ability to identify leaf diseases is a crucial test that has to be addressed. The suggested methodology will provide a method for identifying diseases in enormously big crops using. The suggested model will provide a mechanism for identifying diseases in tremendously important crops by using a speculating method. The suggested model makes use of a Meta Deep Learning approach [18]. This method takes into account infection identification over different harvests. A compiled technique is wise for effective decision. The suggested model's organization on mobile devices is one of its limitations. Later, the model may also be made better in terms of managing low goal images and by making the model smaller. This will make it easier to submit the model on mobile devices.

1.5 Researchers who used framework to detect the cotton leaf diseases

Mhatre and Lanke [19] proposed an online framework which has been effectively carried out for crop illness recognition for cotton leaves utilizing a Convolutional Neural Network. The Convolutional brain network has been created with three secret layers to order the cotton leaf infection pictures. The System effectively processes input from the client and gives yield as illness distinguished. Given adequate information is accessible to preparing, profound learning methods are equipped for perceiving plant leaf illnesses with high precision [20]. The significance of gaining huge datasets with high fluctuation, information expansion, move learning, and perception of CNN enactment maps in further developing grouping precision. India is a country with a rich history of horticulture. Thusly, our work would assist ranchers with forestalling plant illnesses, increment efficiency and benefit. Our future work focuses on a superior informational collection with countless qualities and furthermore execution of yield expectations, preventive activities, and restorative activities, pesticides required and plausible expense for proposed pesticides [21]. This framework can be stretched out to some other yield having the accessibility of enough huge datasets for that harvest. Various different infections can be incorporated for recognition. The System likewise can execute equipment involving IoT for Image catching in fields. The Web connection point can likewise include a gathering for formers to have conversations with respect to the latest things they are looking in changed illnesses.

Ramacharan [22] invented a mechanized sickness discovery framework provides the researcher with a fast and precise finding of the plant illness, permitting the demonstrative cycle to be accelerated, so the researcher can get more harvests out of his fields. Thus, it is vital to make the sickness discovery framework mechanized to accelerate crop analysis. - is paper discusses how to utilize AI and picture handling to sort out whether or not leaves are wiped out. As a beginning stage, this structure can be utilized with an image of a leaf. Most importantly, leaf photographs are tidied up to eliminate any commotion from them. To dispose of clamor, the mean channel is utilized. Division is the demonstration of separating a solitary picture into parts or sections [23]. It can assist you with sorting out how enormous the image is. - e K-implies calculation is utilized to separate the picture into parts. - e head part investigation is utilized to track down highlights. In the subsequent stage, pictures are ordered in light of their substance with assistance from calculations like RBF-SVM, SVM, irregular timberland, and ID3. RBF-SVM performs better in exact leaf sickness location.

1.6 Results taken via convolutional neural network by different researchers

Annabel et al. [24] proposed a network which gave us the essential step towards AI by producing a model. Through mirroring neuron communication inside the body, analysts around quite a while back were genuinely ready to overcome something that had never been finished. Before brain nets, there have been a couple, if by any means, models that were really prepared on how our body learned. During this paper we will generally gift a survey of the usage of brain network models inside the field of plant infection discovery. The writing shows that tone, surface and morphological attributes are the most appropriate to the ID and arrangement of sicknesses in plants. Counterfeit brain organizations (ANN) and Convolutional brain organization (CNN) are the most normally utilized brain network models. Programmed discovery of plant sicknesses would settle the question of expensive space proficient. Location of plant illnesses in beginning phase would work with ranchers to help the harvest yield that effectively works on nation's GDP. Future examination can embrace an assessment of the capacity of the calculation rule to analyze the reason for the injury (what nuisance or infection). Besides, the arranged calculation will be upheld with the use of a product which can be used all through real field visits to work with the formation of guides of the degree of pervasion by nuisances and illnesses.

1.7 Detection of the diseases by picture strategy done by different researchers

Saha and Nachappa [25] calculated a picture division strategy that may be used for later grouping and programmed identification of plant leaf infections, this research reviews numerous sicknesses organization approaches used for plant leaf sickness discovery. Some of those 10 species on which the suggested computation is tested are bananas, beans, jackfruit, lemons, mangoes, potatoes, tomatoes, and sapota. These ailments were used as differentiating evidence for these plants. The best results were obtained with a remarkably little amount of computing work, demonstrating the effectiveness of the suggested calculation in classifying and recognizing leaf disorders. Utilizing this method has added the benefit of allowing for the early or underlying detection of plant ailments. Artificial neural networks, Bayes classifiers, fuzzy logic, and mixture computations may all be used to further improve the acknowledgement rate in order processes.

Patil et al. [26] stated that the farmers in India rely heavily on agriculture for their income. Depending on where they are, farmers cultivate numerous seasonal local crops. In India, cotton is the most widely grown crop. Cotton is a crop that can be sold, and farmers get a lot of money from it. The farmer will earn more money as a result of this. However, cotton's vulnerability to a wide range of diseases is one of its fundamental flaws. To prevent production loss, these diseases need to be identified as soon as possible. The prediction model is created using the TensorFlow Keras API and the CNN algorithm in this paper.

Singh and Misra [27] stated that cotton is one of the financially critical rural items in Ethiopia; however, it is presented to various requirements in the leaf region. For the most part, these requirements are recognized as illnesses and irritations that are difficult to distinguish with exposed eyes. 'Is a study that uses CNN, a deep learning technique, to create a model that can better detect pests and cotton leaf disease. The researchers have done this by utilizing pests and common cotton leaf diseases like bacterial blight, spider mite, and leaf miner. The K-fold cross validation strategy was used to split the dataset and improve the CNN model's generalizability. For the purpose of training, nearly 2400 specimens (600 images per class) were accessed for this study. Python version 3.7.3 is used to implement the developed model, and Jupyter, TensorFlow-backed, and the deep learning package Keras serve as the development environment. The model was able to identify classes of cotton plant pests and disease with an accuracy of 96.4%. It is shown that its use in real-time applications is possible and that IT-based solutions may be needed to support manual or traditional disease and pest identification.

Tripathy [28] proposed one of the most important cash crops in India is cotton, which is grown in large quantities by many farmers. In the past few decades, cotton diseases ought to have resulted in a significant reduction in productivity. It's important to diagnose cotton diseases early. This study aims to present a method for automatically diagnosing cotton leaf diseases that makes use of convolutional neural networks. Separation based on selecting appropriate Deep Learning-create image features like color and texture. [29] examined to make a framework which will actually want to analyze the sickness present on the leaf of the cotton plant. Since identifying the sickness present on cotton crop with naked eyes could bring a few blunders, so doing likewise with the assistance of machine will decrease the possibilities of misprediction. Wang et al. [30] addressed that plant sickness conclusion framework helps the rancher's general public and agribusiness industry to build the harvest creation limit by shielding their yields from a few illnesses tracked down in their homesteads by recognizing the side effects of infection in its beginning phase and finding a suitable way to control them. The model is intended to recognize the side effects of cotton plant illness. The model effectively pieces the impacted piece of the pictures of leaf tests utilizing thresholding strategies. Zhou et al. [31] summed up and audits various strategies in light of administered, solo, and half breed for multi-crop leaves illness location and characterization. The various leaves sickness identification approaches for multi-crops have been proposed in the space of the horticultural business.

2. Material and Method

2.1. Dataset

The dataset comprises of four classes 1. Bacterial blight, 2. Curly virus, 3. Fussarium wilt and healthy leaves of cotton, the dataset contains 1710 images those were captured under real world conditions and from internet (Figure 4).

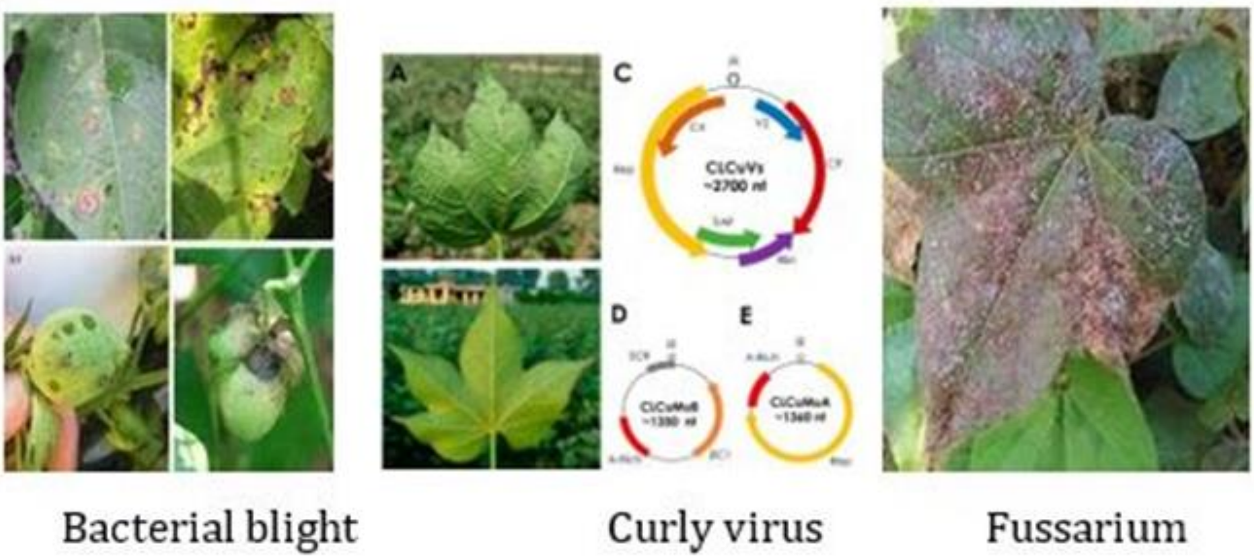


Figure 4. Datasets of diseases.

The images were taken from the [8] in which he shows the two datasets of the diseases in a cotton crop leaves.

The pictures in Figure 5 show the two categories of the diseases in cotton crop leaves which are identified through the machine learning model. The results through this model are clearly mentioned the darkspots shows the infected parts of the cotton leaves [8]. They also proposed a machine learning model for cotton leaf disease detection [9].

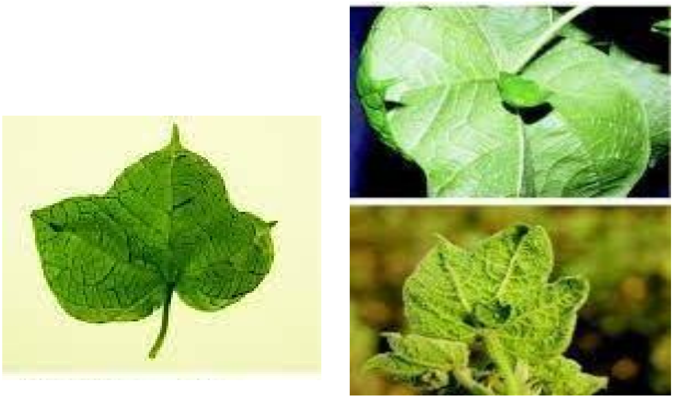
The Figure 6 categories two samples of the leaves which has been taken in the real-world condition.

Some points of the contribution are given below:

1. The numerous databases which have been used to behavior those studies also are mentioned.

2. The comparative analysis of the present strategies is done to evaluate their blessings and drawbacks.
3. The several cotton diseases are labeled and their signs and symptoms also are provided.
4. The numerous performance metrics that can be used to assess the performance of the disorder prediction are also presented.

Bacterial blight



Leaf curly virus

Figure 5. Bacterial blight and curly virus**.**

(a)

(b)

Figure 6. Fussarium wilt (a) and healthy leaves (b).

2.2. Dataset

A machine learning model has been trained using a cotton disease dataset and has implemented in an android application that has been developed in python. In the android application an image of a cotton leaf will be provided by the end user and it has been predicted by the model whether the leaf is healthy or it contains some diseased based data. The model has been able to detect only three cotton disease that is 1. Bacterial blight 2. Curly virus, 3. Fussarium wilt 4. Healthy leaves of cotton finally the result of the cotton leaf has been displayed with the solution on the android-based application

The Figure 7 which is design to shows the process of the detection of the diseases.

With the aid of Tensor Flow, machine learning is used to develop high-accuracy models for applications that deal with pictures, text, video, or audio. Google has provided a platform for working with deep learning called Tensor Flow. a deep learning subset of machine learning that use CNN for large-scale data processing. Tensor Flow is used by the developers to swiftly launch the apps. Our methodology makes advantage of transfer learning. Transfer learning refers to the process of retraining a model on our data after it has already been trained on a different issue. We don't have to waste time or effort starting over as a result. On the ImageNet dataset, the Deep Neural Network inception-V3 pre-Trained model is employed. In 1000 distinct classrooms, ImageNet is taught alongside Dalmatian and dishwater. Run inference on the pre-trained model to comprehend its input and SoftMax layer before retraining an Inception V3. The Inception of data-file contains this picture of a panda. With a classification score of nearly 89% and the next-highest score being just about 0.8% for an indri, another exotic mammal, the Inception model is pretty certain that this image is a panda. A "SoftMax-function" is what the Inception model produces as its output. Because the SoftMax outputs add to one and range from zero to one, they are sometimes referred to as probabilities rather than possibilities. However, since they are not the results of repeated tests, they are not probabilities in the conventional meaning of the word. Because they show how strongly the neural network thinks the input picture belongs to each potential class, it may be preferable to refer to the output values of a neural network as classification scores or rankings. INCEPTION-V3 INFERENCE: In contrast to training, inference does not reevaluate or modify the neural network's layer structure in light of the findings. Inference takes information from a trained neural network model to infer a conclusion. As a result, when a fresh batch of unknown data is fed into a trained neural network, a forecast is produced depending on the neural network's level of predictive accuracy. Due to the need for a learned neural network model, inference occurs after training. However, the trained model is still on our local host (laptop), thus it must be deployed on a cloud server before it can be used for client inference. This is when platforms like Heroku come into play. RETRAINED INCEPTION-V3 RUNNING INFERENCE: The next phase will be used to do a straightforward inference on a retrained model that is locally accessible (on a laptop).

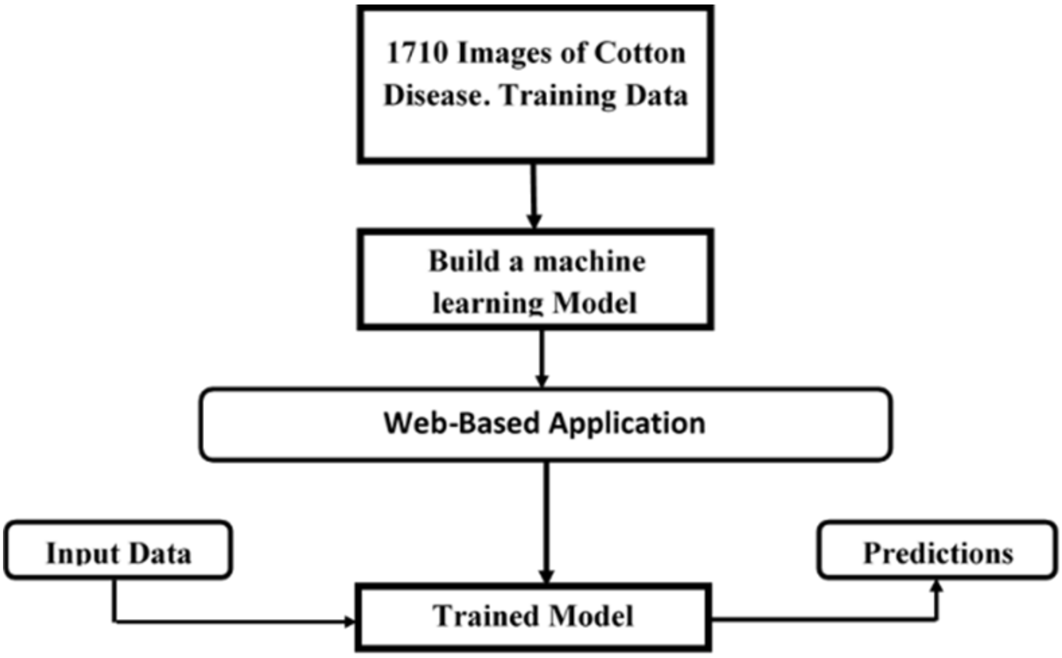


Figure 7. The process to detect the diseases effects on cotton leaves.

2.3 Machine learning model

The machine learning (ML) which shows the main function the machine learning model is main purpose tool which is used to detect diseases or to predict diseases now we will discuss how it works first of all we capture the pictures in a real world and then put it in a machine learning model to detect the diseases to differentiate the datasets of different diseases as I have already define that the four datasets which we have put in this research work now it's time to detect them with the help of this ML model. This is the main usage of machine learning in disease detection. So, it is minimizing the time of farmers the cotton crop is very healthy and their results through this ML model is accurate. The process of ML model in which the images of cotton crops mean Training data of the images of the cotton crop are defined that some fields shows that the leaves are diseased and some are healthy so the model easily identified this main difference between these two categories. I have two data sets one will be the input data and the other will be the output data of the leaves so it mentioned that the AI played the vital role to prove these two categories. The machine learning model is the tool that enables the system to automatically carry out an action based on the machine learning's experience and does not require explicit programming. The main idea behind machine learning is to let computers learn on their own without human intervention, which simplifies the process. Now, the machine learning model, also known as the ML model, determines what should be done when a particular pattern in a dataset shows up. The creation of computer programs that can access data and a set of algorithms that utilize the data to determine for themselves what action should be taken based on that data, for which we will give this model, is known as machine learning (Figure 8).

2.4 Tensor flow framework

The framework (Figure 9) which is used here is Tensor Flow. As we have already discussed above the Tensor Flow is provided by the Google to work with the deep learning. The Tensor Flow is used to flow the process of the detection of diseases now the Tensor Flow framework is very useful in machine learning model. So, we will point out this Framework in our research work. The data of the leaves of the infected and healthy are analyzed by this Framework in a machine learning model. Now the questions arise here shows that how the data is processing in a machine learning model the model uses this framework to process this data by capturing the pictures and put it in a model then by using this framework the model shows the final results. Model tracking, data automation, performance monitoring, and model retraining are all done with or built using the tensor flow platform. Success depends on using production tools to monitor the model training, service, or business process. Developers may now use the framework to build dataflow graphs, which are structures that show how data flows via a network of processing nodes. The connections between the nodes of a network now represent multidimensional data arrays or sensors, and each node itself represents a mathematical action. In the other words tensor flow is the end-to-end encrypted platform which is very secure now data will be hacked out of this platform so it is very beneficial to improve the quality to detect the crop leaves diseases so in this research work it very beneficial to use this work to analyze the best results of the diseased leaves of the cotton crop. The TensorFlow is the open-source software which is used in machine learning and artificial intelligence it is also used across the range of tasks but has a particular neural network. Now the TensorFlow is the helpful to support traditional machine learning. It is also used as an ecosystem of tools, community resources and libraries which help to develop easily build ML applications and the installation of the TensorFlow is directly through pip.python jupyter-notebook.

The link to install the tensor flow is given below and Figure 10 is taken from google.

The work flow of the ML model in Figure 11 is to identified the diseases which are diagnosed so with the help of disease detection the farmers can be easily avoid from the field losses, time consuming or through the detection of these diseases the farmers can get a quantitative crop so it's a main objective of the proposed model is to get the quantitative crop by the diagnosing and removing of the diseases through this ML model.

Figure 12 shows the model accuracy through different ML models custom CNN, VGC16, ResNet50 and proposed model.

The different images of the cotton leaves in Figure 13 which shows the different categories of the diseases which are mentioned in the above pictures these infected leaves are predicted by the technological based concept which is using machine learning algorithms.

The Figure 14 shows the three categories of the dataset which defined that the images of the background soil, lesioned leaf and healthy leaf as well it is a best technique to identify these three categories of the images of the soil which are defined by the machine learning model whose process which we have already defined so by the machine learning farmers get a lot of benefits and they are taking are quantitative cotton crop after the detection of the leaf disease.so the pictures shows the clear differences between these images. In the (b) image category the dark spot shows the infected leaf of the cotton crop.

Figure 8. The process of Machine learning model (ML).

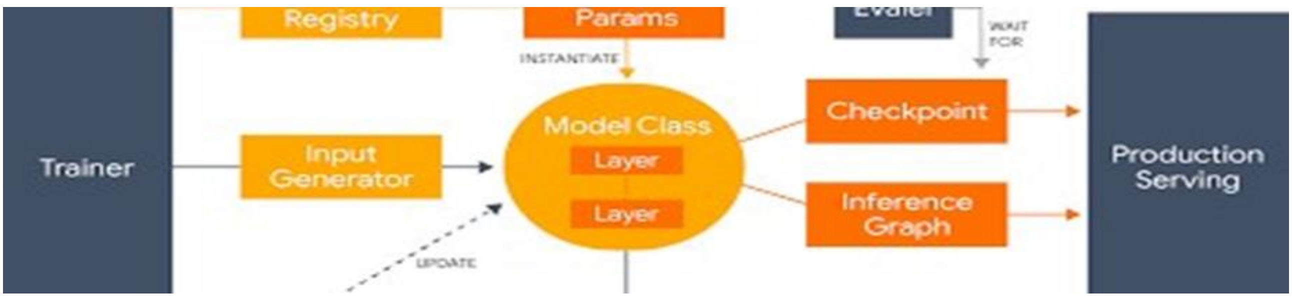


Figure 9. The picture shows the Tensor flow framework.

Figure 10. The logo of Tensor flow framework.

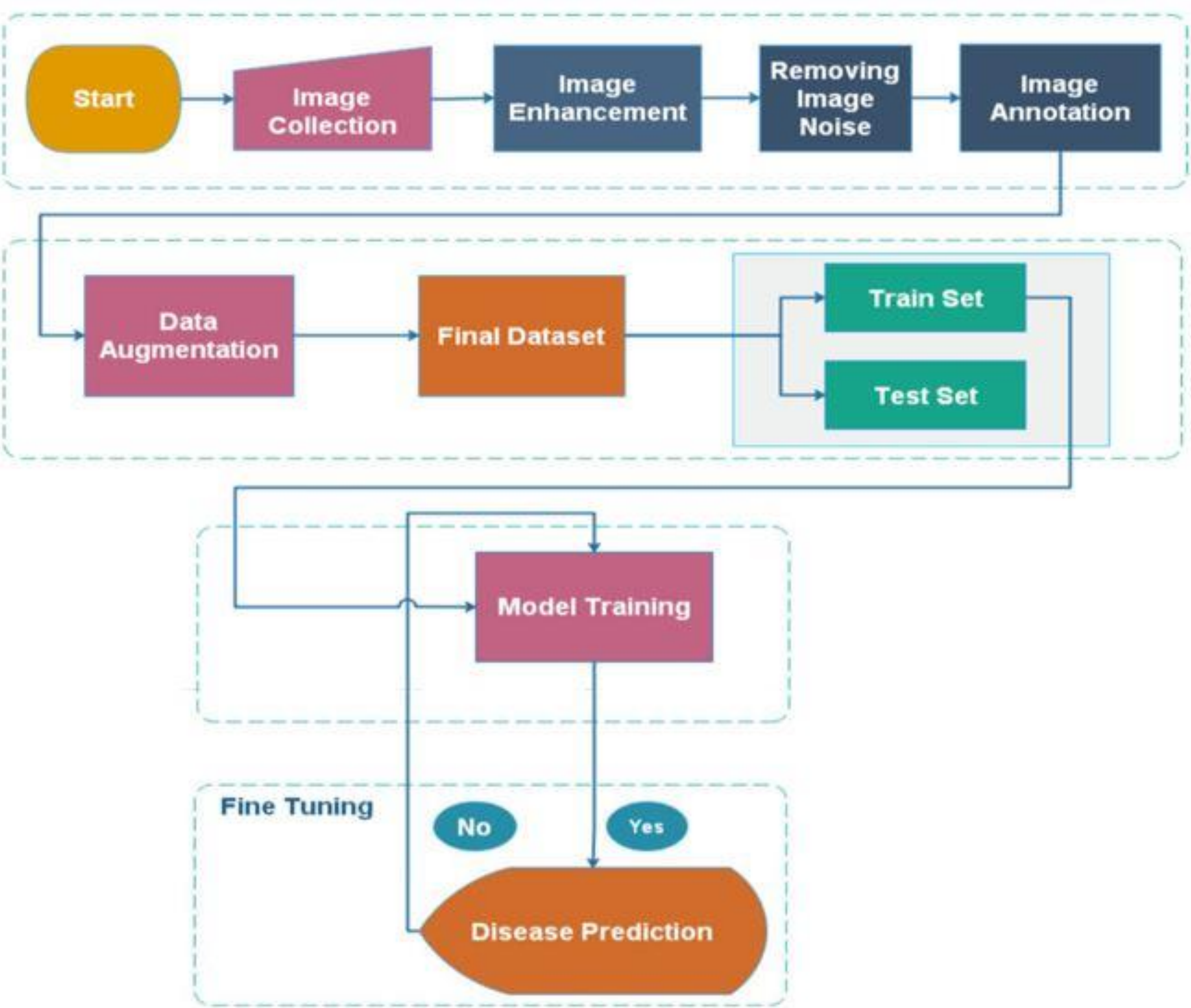


Figure 11. The workflow of the model for the leaf disease identification.

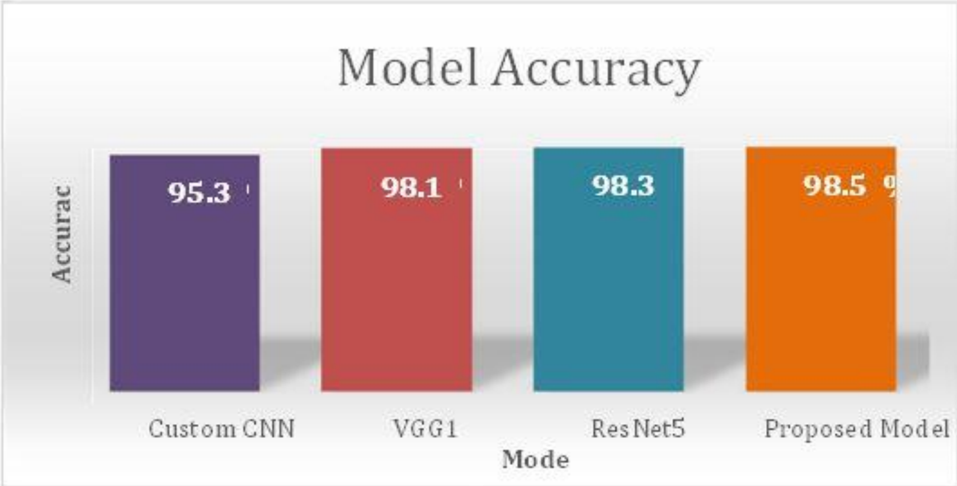


Figure 12. The model accuracy through different ML models custom CNN, VGC16, ResNet50 and proposed model.

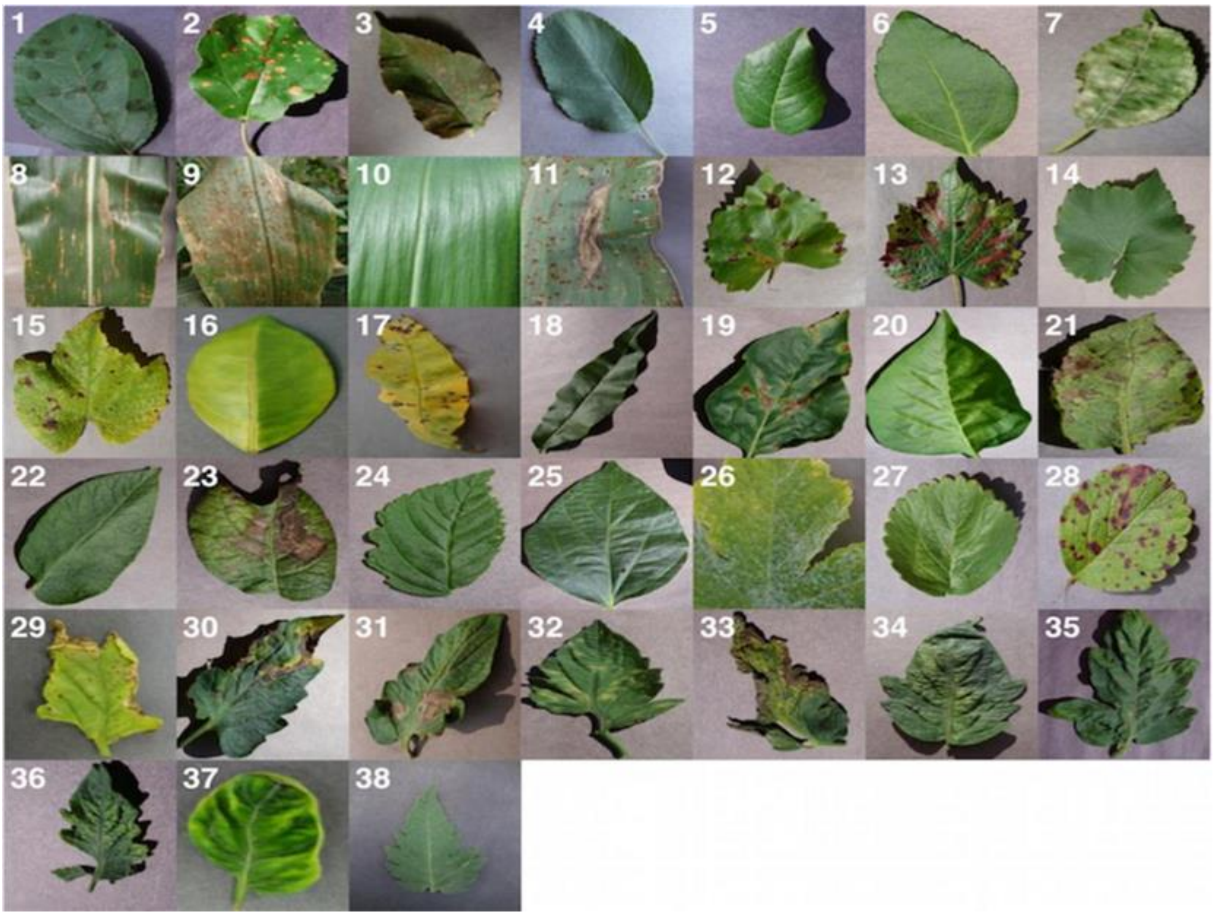


Figure 13. The different images of the cotton leave using ML Model.

(a) (b) (c)

Figure 14. Images of the background soil (a), lesioned leaf (b) and healthy leaf (c).

3. Results

Epochs are single iterations of the data through the model during training. The same data would be periodically cycled across several epochs after each one. When this procedure is repeated, the model is said to be learning. Remember what we mentioned at the conclusion of the network when we indicated that the model is initially initialized with its set of arbitrary weights? To get strong performance on illness classification, the convolutional neural network must be tuned for a few key hyperparameters. By adjusting the specifics of the learning process, outcomes can be improved. STEPS IN TRAINING: The longer a model is trained, the slower the rate of accuracy increase becomes, and eventually it will stop entirely (or possibly decline owing to overfitting). We ran three tests with 500, 1500, and 1000 participants to see which was most effective for our model. HYPER-PARAMETERS: The model may be tweaked with more parameters to see whether the outcomes are improved. The value of the weights that are given to the final layer to be updated during training is controlled by the learning rate hyperparameter. Although it is sense that a lesser learning rate would need more time during training, it may actually improve overall accuracy. But since that isn't always the case, it must be carefully chosen to examine what functions in our situation, where we have found it to be 0.01. As the name implies, the train batch size determines the number of pictures that are weighed during each training phase in order to determine the changes to the final layer. We tried 5 and 10 photographs in our experiments, and it turns out those 10 images per batch work nicely with our model. SETS FOR TESTING, VALIDATION, and AND TRAINING: Three independent data sets—a training, validation, and test set—should be created from the training data. The biggest dataset is often the training set, which includes all of the photo's input into the ML model.

3.1 Tested results of different ML models.

Convolutional neural network is trained, and the weights of the model are updated based on the outcomes. A training set is a collection of data that is used to train a model at each iteration (iteration). The model will continue to learn more about the features by being trained again using the same data from the training set. The validation set is different from the training set. In order to prevent model overfitting, it is utilized to verify the model during training. This validation method provides data that might be used to modify the model hyper parameters. The data in the validation set will be validated while the model is being trained on the training set. TESTING Collection: This set of data is used to test the model once it has been successfully retrained. This set is different from the validation and training sets.

The pictures in Figure 15 were taken from the real-world condition that shows the results of the infected and healthy leaves of cotton crop whose accuracy is tested through different (ML) model.

Figure 16 shows the diseased rate detection of the cotton crop leaves using the ML model. The ML model or the machine learning model which is used here is Convolutional neural network (CNN) model which detect the results and shows in the Table 1-4 and in the Figure 15 form which is a particular most commonly used model in machine learning.

Table 1. Results of retraining model (Accuracy Graph).

Parameters	1st Run	2nd Run	3rd Run
Training Steps	500	1500	1000
Learning Rate	0.01	0.01	0.01
Training Batch Size	10	05	10
Misclassified Pictures	11	09	05
Testing %age	5	5	5
Validation %age	10	10	10
Final Test Accuracy (%)	86.3	88.6	91

Table 2. Results summary of different ML Models.

S.No	Model	Accuracy (%)	Dataset
1	Custom CNN	95.37	Cotton
2	VGG16	98.10	Cotton
3	ResNet50	98.32	Cotton
4	Proposed Model	90.53	Cotton

Table 3. Results to differentiate the diseased and healthy leaves through ML model.

S.No	Models	Diseased leaf Accuracy (%)	Healthy leaf Accuracy (%)
1	Custom CNN	4.87	96.87
2	VGG16	13.75	87.85
3	ResNet50	4.45	96.45
4	Proposed Model	9.64	90.56

Table 4. Cotton crop rate observation per year diseased.

Disease Names	Diseased Rate per year	Disease Samples
Bacterial Blight	56.8% (2020)	15
Curly Virus	66.7% (2021)	25

Figure 15. Infected and healthy leaves.

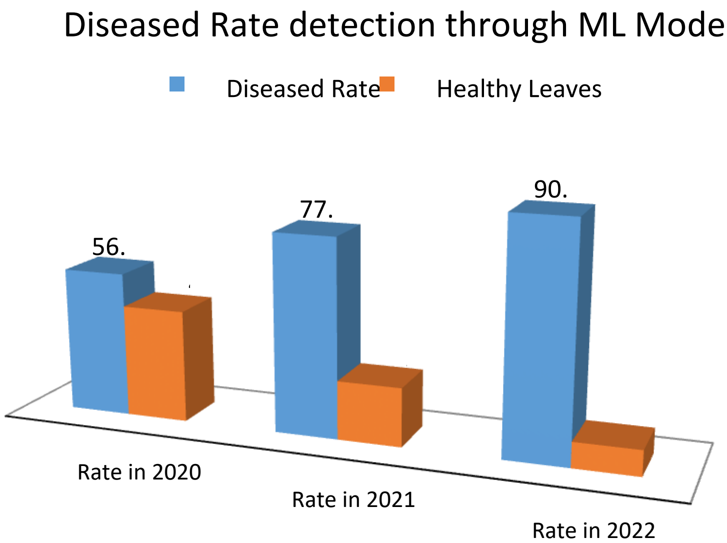


Figure 16. Diseased rate detection through ML model per year.

3.2. Confusion matrix method

A confusion matrix is a table that is used to define the performance of a classification algorithm. a confusion matrix visualizes and performance of classification algorithm. technique has four parameters to test the accuracy of the results which is given in my research work. The pattern to identify the accurate results through this technique is given in the Figure 17.

The results which are given by the confusion matrix technique are valid I have used its four parameters in my research work to detect proper results so the results through this technique are given in Table 5.

n=165	Predicted: NO	Predicted: YES	
Actual: NO	TN = 50	FP = 10	60
Actual: YES	FN = 5	TP = 100	105
	55	110	

Figure 17. The pattern to identify the accurate results.

Table 5. Tested results through confusion matrix method per year.

Year	Infected leaf (%)	Healthy leaf (%)
2019	10.45	80.55
2020	85.50	15.00
2021	80.00	20.00
2022	75.56	25.00

4. Conclusion

The goal of this research was to examine and comprehend the illnesses that affect cotton crops and to develop a machine learning model for diagnosing cotton diseases. The work begins with the history and development of the cotton crop, the issues it is currently experiencing, and the goals of our challenge, which may be used to address those issues. After that, a survey of the literature was conducted to have a great idea of the most recent investigations into the identification of illnesses in cotton crops. After reviewing the literature, the thesis focuses on the methods used to create the model; it contains the task description seen via the usage of the extracts and their physical characteristics. The experimental outcome is then presented, and it is concluded that the model was properly built in this thesis work and project designing and can be easily applied to the Go platform. The accuracy ranges for unusual cotton ailments were examined after the model's creation. The readings were obtained at a level of accuracy better than 90%, indicating the success of the project. Because this version is based on machine learning, it will continue to improve accuracy with each use by analyzing each new picture that is taken using the model. On the other hand, a smartphone that is entirely built on technology may provide the option to purchase pesticides online.

Recommendations

The population of the sector is increasing at a pace of 1.08% per 12 months. With time, the need for meals will increase. To meet the demands, we must thus obtain the majority of our produce from agricultural lands. However, global warming has grown into a significant issue that has to be addressed, and one of the causes of global warming is also agriculture. Therefore, to stop agriculture from contributing to global warming and to increase productivity. In agriculture, monitoring, diagnosing, and ethical usage of pesticides have become crucial. With the aid of system learning, Cotton Care Assignment will help in identifying the illnesses and keeping an eye on the cotton crop. However, it is also necessary to monitor various types of flora and plant life in order to improve production and reduce the usage of chemical compounds.

Author contributions

Unain Hyder: Conceptualization, Literature Review, Methodology, Writing Original.
Mir Rahib Hussain Talpur: Machine Learning Model, Data curation, Software, Validation, Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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Harnessing earthquake generated glass and plastic waste for sustainable construction

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Abstract

On February 6, 2023 Türkiye witnessed two massive earthquakes of magnitudes 7.6 and 7.8 centred near Gaziantep Province. The aftermaths of the earthquakes were devastating. Thousands of people were dead under the rubble of collapsed buildings and millions displaced. The challenge was the disposal of tons of debris generated due to the destruction of structures and roads, and the construction of new buildings for relocation of displaced people. Not only being uneconomical, the disposal and new construction also became a major environmental concern. A solution to this problem lies in the constructive disposal of earthquake wastes i.e., the utilization of waste materials from debris generated after an earthquake in order to ensure its proper and beneficial disposition. The article provides a two problems one solution technique in this regard. Research techniques and outcomes of modification of glass and plastic waste in the industries for the manufacture of good quality construction materials and the subsequent use of these materials in construction are reviewed. Further analysis is carried out to determine whether the application of this knowledge in practical field ensures that both environmental and economical requirements are met.

1. Introduction

Natural disasters are the naturally occurring, mostly unpredictable and highly uncontrollable events that cause huge loss to life and property. High magnitude destruction and economic disruption are due after such disasters. Cyclones, Tsunamis, Landslide, floods, earthquakes etc come under the category of natural disasters. Earthquakes are the most unpredictable of all. The intensity of earthquakes determines the magnitude of destruction which mostly is quite high. As a result of it many buildings collapse or get affected severely enough to be demolished for safety purposes. Huge number of casualties are reported in such cases. The earthquakes result in huge destruction of cities and towns, deaths of people on large scale and loss of livelihood. After a high intensity earthquake, huge amounts of debris are generated due to the collapse and sometimes subsequent demolition of buildings and other structures. Considering the material point of view the debris comprises mostly of fly ash, broken concrete, steel pieces, plastic, glass, ceramics, wood, brick etc. The quantity of each of these materials varies from one structure to another. Most of this waste is disposed of into land fillings or water bodies, ignoring the environmental concerns and health hazards. With loss of localities, people are rendered homeless. Another civil engineering aspect is the construction of new residencies for the accommodation of these people and their wellbeing. A huge scale construction of cities and towns should be initiated which requires raw material worth a lot of money. This is the economic aspect of the earthquake which needs to be dealt with. For third world nations, this situation is quite grave and might result in the economic collapse of the whole country. A solution is thus proposed in order to ensure the proper disposal of earthquake waste which is the re construction of buildings using material made from some modified components of the debris of collapsed structures. The materials that would be used for the manufacture of these materials are otherwise harmful for the environment if disposed of directly and take centuries to decompose. Also, the need for new raw material is minimized resulting in the economic safety of the country in the aftermath of a disaster.

1.1. Türkiye Earthquake

Türkiye is a country of 84.78 million inhabitants located on the west of Asia with some parts in the

European continent. A major portion of Türkiye lies on a microplate called Anatolian plate. Anatolian plate itself is located on the line of tension of the two plates – Arabian and Eurasian plate. Another plate bordering the Anatolian plate is the African plate. Therefore, the microplate on which Türkiye sits is located at the interaction point of three tectonic plates. As a result, high seismic activity is observed in the country. Major and densely populated cities of Türkiye lie on fault lines of these tectonic plates posing great threat to the lives of people living there. As per the Turkish disaster and Emergency Management Authority, in the first half of the year 2023 more than 60 thousand tremors were registered. For the year 2022, the recorded tremors were lesser, about 20 thousand.

Table 1 shows the data of the number of earthquakes corresponding to the years of occurrence for the last 25 years.

Table 1. Record of earthquakes in Türkiye for the last 25 years [1].

Year	Number of earthquakes
2023	60,546
2022	20,277
2021	23,763
2020	33,824
2019	23,481
2018	22,899
2017	38,287
2016	20,541
2015	22,290
2014	24,132
2013	23,607
2012	26,973
2011	29,831
2010	19,023
2009	15,211
2008	11,754
2007	7820
2006	5,038
2005	9,481
2004	7,682
2003	1,914
2002	1,078
2001	599
2000	745
1999	2,101

Türkiye has a history of major earthquakes dating back to 17 CE. earthquakes are therefore much expected in Türkiye; however, their occurrence time and magnitudes are unpredictable.

On morning of 6 February 2023, at 4:17 am a massive earthquake occurred in the south of Türkiye. The magnitude of this earthquake was 7.8 and it was observed on the northern border of Syria with epicentre in Pazarcik, Kahramanmaras at 8.6 km depth from ground. After approximately 10 hours another earthquake measuring 7.5 magnitude, struck a region just 95 kilometres from the first earthquake zone with epicentre at Elbistan, Kahramanmaras at a depth 7 km from ground. Within 24 hours of the earthquakes, more than 570 aftershocks were recorded [1]. Aftershocks continued for months after the earthquakes. More than 14 million people were affected and large-scale destruction of property and livelihood was experienced. Level-4 emergency was declared for three months in 10 provinces of Türkiye and international assistance demanded. The death toll in the regions was estimated about 46 thousand [1]. Millions of people were left homeless and had to move to other cities. The aftermath of the earthquakes was even worse. The economic loss as a result of the earthquake was estimated with 35 percent probability to be between US$ 10 billion to US$ 100 billion. And with 34% probability, it was estimated to exceed US$ 100 billion.

Direct collapse of about 6000 buildings was observed. Tons of debris was generated from the structures destroyed by the earthquake. After survey, many buildings were deemed unsafe and thus had to be demolished.

Table 2 is a rough estimate of the number of buildings that collapsed directly due the earthquake or had to be demolished immediately after.

Table 2. Rough estimate of number of collapsed and demolished buildings in 2023 Türkiye earthquake [1].

Place	Collapsed and demolished buildings
Kahramanmaras	10,800
Adana	1,333
Malatya	36,046
Gaziantep	16,211
Islahiye	200
Hatay	21,643
Kirikhan	1886
Defne	943
Reyhanli	2042
Arsuz	381
Kumlu	215
Payas	727
Adiyaman	76,600
Diyarbakir	8086
Sanliurfa	201
Osmaniye	1739
Kilis	119
Batman	234

1.2. Debris generated

Near about 364 $million^2$ of structures were demolished or damaged. Between 520 to 840 million tons of debris was generated as a result of direct collapse of buildings in Türkiye earthquake. Furthermore, the demolition waste was accounted to be between 450-920 million tons [2]. This data gives us the insight that about 250,000 buildings had been damaged overall. As per UGSC assessment the amount of debris to be cleared from Türkiye was estimated to be around 116-210 million tons. A volume of $100m^3$ was estimated to have been generated [3].

The debris generated was reported to be able to cover two Manhattans. In other words, the debris could make a three feet high stack when spread on an area equal to 14,000 soccer fields [4].

Xiao et al. [2] estimated the amount of debris generated in the Türkiye earthquake. He represented the data through a pie chart. The contents of the debris were analysed as shown in Figure 1.

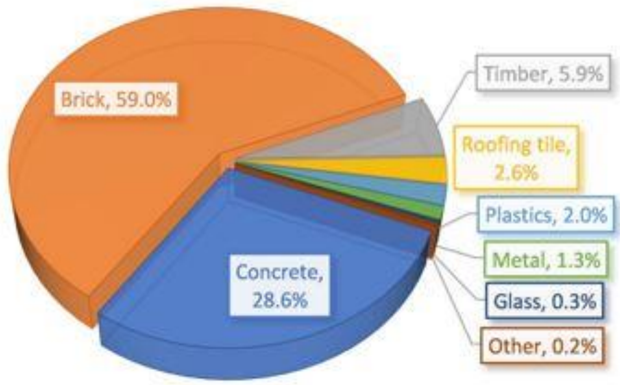

Figure 1. Pie chart representation of the percentage of different components of debris generated from Türkiye Earthquake 2023

With 685 million tons as the approximate total waste generated, 404 million tons of brick waste and 191 million tons of concrete waste was generated. Timbre constituted about 5.9% of the total waste. 2.6% of the total waste comprised of roofing tile and metal waste was about 1.3% of total waste. Glass waste generated was found to be 0.3% of the total waste of 685 million tons which is 2.055 million tons. Plastic waste concentration was found to be reasonably high i.e., 2% of 685 million tons which accounts to 13.7 million tons. This amount of plastic is clearly not suitable for dumping due the health and environmental hazards.

2. Usage of debris

The focus of this article is on the proper disposal or utilization glass and plastic waste. It provides an insight as to how the glass and plastic waste from earthquake can be used in the manufacture of bricks, concrete and other materials which can in turn be used for the construction of buildings or pavements. A review has been done on the work of scientists and the data has been analysed. This article provides suggestions as to how the wellbeing of citizens can be achieved and the economy of a country saved. All this being done while making no compromise with the safety and sustainability of the environment.

2.1. Use of glass waste

The earthquake and subsequent demolition of buildings produces tons of glass waste. In Türkiye the earthquake generated about 2.055 million tons of glass waste. This glass waste could be put to use in the construction of bricks or concrete. Following research has been done by scientists in the same regard. Research done by Demir [5] is in line with the technique of converting glass waste to bricks.

2.1.1. Method

Glass waste crushed in jaw crusher and ground in a ball mill was sieved through 0.5mm sieve. Brick clay was crushed and sieved through a sieve of size 1mm. The clay particles were very fine and the only coarse particles were the calcium carbonate. Four different classes were formed for comparative analysis- A, B, C and D. Class A was the standard brick, class B had 2.5% by weight of fine glass, Class C contained 5% by weight of fine glass and Class D comprised 10% by weight of fine glass mixed with the brick clay. The samples were 75mm x 40mm x 100mm in size and dried under laboratory conditions for 24 hours and further dried to constant weight at 110 degrees in oven. The changes in plasticity and drying shrinkage were observed with respect to the change in glass content. Then the samples were fired in an electrically heated kiln with 3 degree Celsius/ min heating rate at three different temperatures of 850, 950 and 1050 degree Celsius for 2 hours. The samples were then allowed to cool naturally. Then the tests were done on at least 12 samples and the results were produced.

2.1.2. Tests

For determination of compressive strength of materials, a testing machine of testing capacity 25k N was used with 1 and 0.45 k N/s loading rates. Properties such as bulk and apparent density, porosity and water absorption were established on the basis of Archimedes Principle. Loss of ignition and total shrinkage was observed. Electron microscopy was done to understand the effect of addition of glass and firing temperature on microstructure of bricks. Table 3-6 illustrate the results:

Table 3. Variation in shrinkage and loss of ignition at different temperatures and glass contents of glass induced bricks.

Waste glass content (%)	Shrinkage (%)				LoI(%)		
	Dry	850 °C	950 °C	1050 °C	850 °C	950 °C	1050 °C
0	3.95	5.35	5.67	6.12	8.17	9.19	9.69
2.5	3.72	5.15	5.21	5.28	7.79	8.64	9.22
5	3.64	4.65	4.69	4.82	7.84	8.19	9.10
10	3.53	4.35	4.48	4.57	7.27	8.24	8.61

Table 4. Variation in bulk density and loss of apparent density at different temperatures and glass contents of glass induced bricks.

Water glass content (%)	Bulk Density (g/cm^3)			Apparent Density (g/cm^3)		
	850 °C	950 °C	1050 °C	850 °C	950 °C	1050 °C
0	1.66	1.60	1.69	2.58	2.31	2.34
2.5	1.62	1.55	1.66	2.55	2.23	2.25
5	1.67	1.56	1.64	2.56	2.22	2.24
10	1.68	1.59	1.65	2.56	2.25	2.25

Table 5. Variation in apparent porosity and water absorption at different temperatures and glass contents of glass induced bricks.

Water glass content (%)	Apparent Porosity (%)			Water Absorption (wt. %)		
	850 °C	950 °C	1050 °C	850 °C	950 °C	1050 °C
0	35.71	30.9	27.7	19.45	15.48	13.94
2.5	35.02	28.43	26.4	19.06	14.72	12.86
5	33.27	29.58	26.77	18.35	13.52	11.67
10	34.17	29.21	26.16	17.73	12.82	10.89

Table 6. Variation in compressive strength at different temperatures and glass contents of glass induced bricks.

Waste glass content (%)	850 °C	950 °C	1050 °C
0	16.45	19.50	20.37
2.5	18.75	22.65	24.50
5	20.15	25.13	27.15
10	20.62	27.56	29.35

Strength of brick was observed to increase with glass content and firing temperature. The lowest compressive strength was observed in clay bricks due to high porosity. The pores in glass bricks are filled with glass in glassy phase at firing temperature of 95 degree and 1050 degree. As a result, densification occurs and brick strength increases. Also, the risk of strength due to quartz transformation is reduced making a positive contribution to the overall strength. Except for the bricks made in kiln of firing temperature 850 degree, the compressive strength of all the samples of bricks with glass was found to be more than 18MPa which is considerably higher that compressible strength of brick prescribed in TS EN-771-1 code.

2.1.3. Results

All the bricks with additional glass content were found out to be crack free after being taken out of kiln. Decrease in Loss in ignition is observed with increase in glass content. Higher weight loss and drying shrinkage was observed in clay brick during firing than in the glass-additive brick. As a result, any chance internal shrinkage is minimized in glass additive brick. Apparent density was found to be more in the bricks heated at 850 degrees due to low glassy phase at this temperature than at 950 and 1050 degree Celsius. Another positive aspect was water content which was showing significant decrease with increase in temperature and glass content. Thus, it can be established that bricks with 10% crushed clay content made at a firing temperature of 950-1050 degree Celsius are suitable for construction and have higher compressive strength than clay bricks. These bricks also have low change of damage during production.

Another study titled 'Bricks Made from Glass Residues: A Sustainable Alternative for Construction and Architecture' by Cecilia I et al. [6] gives almost the same results. However, the researchers let the bricks to dry naturally without a kiln. The bricks were found to be suitably good in dimension, warpage, absorption and compression.

2.1.4. Method

The bricks were made of commercially obtained cement and sand and crushed glass waste which was obtained by subjecting 240 clear and dark glass bottles to cleaning, drying and crushing. The total weight of crushed glass used for making bricks was 252 kg.

The ratio of cement/sand/crushed glass was taken as 1:3:2 and water were steadily added until the mixture became plastic enough to be moulded and free of lumps. Further, the mixture was placed in a mould and compacted. The bricks were demoulded and left to dry for one day, to be subjected to curing with potable water for next 7 days. Lastly, the bricks were left to dry over a period of 28 days and then testing was done.

Tests: Following physical and mechanical tests were done on the bricks:

Physical Tests

1. 10 samples were tested for dimensional variation in mm
2. 5 samples were tested for absorption (%)
3. 10 samples were tested for warpage in mm

Mechanical Tests

1. 5 samples were tested for compression test in masonry unit in kg/cm^2
2. 15 samples were tested for compression in masonry piles in kg/cm^2

2.1.5. Results

For the composition ratio of cement: coarse aggregate: crushed glass of 1:3:2 the performance of the brick was remarkable under pile compression test surpassing the minimum value 35kg/cm^2. The best results for the mechanical properties were obtained only after 28 days of life. The values suggest that the bricks apart from being suitable for partition walls can be used for load bearing walls. Also, over the days, resistance of the brick was found to have increased between 58.96-98.16kg/cm^2. Brick V and brick IV classification has been given to bricks for 28 and 14 days of life in case of warping. With regard to absorption, minimum value of 7.2% was obtained in line with the specifications of NTP-E.070.

2.1.6. Discussion

Both the methods are quite efficient, however the technique used by Ismail Demer of brick production using kiln resulted in higher compressive strength of bricks. All the samples had Compressive strength greater that 18 MPa which is more than the clay bricks.

Waste glass can also be used in in concrete or mortar in place of aggregates. Research has been done by various scientists in this regard. Research has been done by various scientists in this regard.

2.1.7. Other studies

Penacho et al. [7] replaced fine aggregate in a concrete mass with glass in varying percentages of 20%, 50% and 100%. The aim was to enhance the compressive and the flexural strength of the concrete. It was observed that the replacement of sand with waste glass powder increased the strength of the concrete between 28 to 90 days. As for 100% replacement, the strength was found to be more than the reference sample at 90 days. The reason for the increase in strength was mainly due to the pozzolanic reactions that occur in glass.

Corinaldesi et al [8] conducted a study in 2004 where he made the analysis after 180 days for the compressive and the flexural strength of concrete made using glass. The size of glass particles varied between 36 micro metre, 35-50 micro metre and 50-100micro metre. The observations suggested that at 70% replacement of aggregate with glass powder of size 36-50 micro metre, the compressive strength was maximum. The 180 days strength showed slight variation. An increase in the compressive strength was noted for 50-100micro metre aggregate sample in comparison to the reference.

Le et al [9] in similar research observed that the compressive strength of concrete increased after 28 days in samples which had glass powder of particle size less than 600 micro metre.

A study done by Batayneh [10] showed that the waste glass if incorporated with fine aggregates resulted in the increase in the compressive strength of material while the splitting strength remained same (Figure 2).

Type	14 days of life									
	Variation of the dimension (maximum in percent)						Warpage	Obtained	Compressive strength per unit / kg/cm²	Obtained
	More than 150 mm	Obtained	Up to 100 mm	Obtained	Up to 150 mm	Obtained				
Brick I	± 4	±0.45	± 8	±1.17	± 6	±0.77	10	2.4	50	58.96
Brick II	± 4	±0.45	± 7	±1.17	± 6	±0.77	8	2.4	70	58.96
Brick III	± 3	±0.45	± 5	±1.17	± 4	±0.77	6	2.4	95	58.96
Brick IV	± 2	±0.45	± 4	±1.17	± 3	±0.77	4	2.4	130	58.96
Brick V	± 1	±0.45	± 3	±1.17	± 2	±0.77	2	2.4	180	58.96
Absorption (not more than 22%)	10.1 %									
Compressive strength per piles / kg/cm² (minimum 35 kg/cm²)	47.3 kg/cm²									
Type	28 days of life									
	Variation of the dimension (maximum in percent)						Warpage	Obtained	Compressive strength per unit / kg/cm²	Obtained
	More than 150 mm	Obtained	Up to 100 mm	Obtained	Up to 150 mm	Obtained				
Brick I	± 4	±0.32	± 8	±5.88	± 6	±0.15	10	2.6	50	98.16
Brick II	± 4	±0.32	± 7	±5.88	± 6	±0.15	8	2.6	70	98.16
Brick III	± 3	±0.32	± 5	±5.88	± 4	±0.15	6	2.6	95	98.16
Brick IV	± 2	±0.32	± 4	±5.88	± 3	±0.15	4	2.6	130	98.16
Brick V	± 1	±0.32	± 3	±5.88	± 2	±0.15	2	2.6	180	98.16
Absorption (not more than 22%)	7.2 %									
Compressive strength per piles / kg/cm² (minimum 35 kg/cm²)	67.17 kg/cm²									

Figure 2. Variation in dimension, warpage and compressive strength of bricks made with glass powder after 14 and 28 days of life.

2.1.8. Economic aspect

The need of raw material for the manufacture of bricks is minimized with the usage of crushed used glass. Good quality yet cheap bricks can be manufactured which would save billions when done on large scale. An approximate 50% of money is saved on one project by using these bricks. A household generally costing 30 million made with standard brick can be completed at about 10 million only using the brick incorporated with crushed glass [11]. In times of natural calamities, this initiative can prove to be economical for the common public.

2.2. Plastic waste

Huge amount of plastic waste can be put to use in construction by manufacturing bricks, blocks by using it directly or its components.

In research done by Aneke et al. [12] bricks were manufactured by using scrap plastic waste (SPW) and Foundry sand (FS) and tested against good quality standard brick to draw comparison and determine the suitability for construction.

2.2.1. Method

SPW was collected from landfill sites and washed and sanitized in laboratory to eliminate any virus present. Then the sample was dried for three days and later shredded using a shredder for the purpose of undergoing chemical compositional test in X Ray fluorescence machine. With a melting rate of 2 degree Celsius/min, the SPW was heated in a furnace to a controlled temperature of 220 degree Celsius. At the attainment of proper consistency of SPW, Foundry sand was added and the mixture was steered for smooth blending until a homogenous mixture was attained. The mixture was then put in silicon coated moulds of dimensions 220x106x73mm and compressed with a pressure jack of compressive strength 5MPa to reduce voids. The samples were then cooled at room temperature of 24 degree Celsius. Three compositions of SPW and foundry sand were used with varying ratios. For brick named SPW-1, the ratio for FS:SPW was 80:20, 70:30 for brick named SPW-2 and 60:40 for SPW-3 brick.

2.2.2. Testing

After undergoing chemical compositional test, the samples were subjected to various tests for the determination of their strength, durability and other properties. 18 SPW bricks are produced and cooled in open air for 2 days. For each test 3 SPW bricks were used on average and for the final test result, mean value of each was used.

1. Unconfined Compressive Strength Test (UCS):

According to ASTM D2116, UCS was carried out on the SPW bricks after series of wetting and drying. Bricks were placed between two clean plates of testing chamber and stress and deformation was recorded with electronic data logger. Maximum load was recorded in Newtons and the UCS was calculated.

2. Splitting Tensile Strength Test (STS):

The test was done in accordance to ASTM C496 with dimensions of bricks being same as the UCS test. After cycles of wetting and dryings the bricks were placed between the bearing blocks of tensile testing machine. In order to ensure that the pressure if uniformly applied, mild steel piece of 190x90x4 mm is placed horizontally along upper length of the brick and the lower length as well. Maximum tensile load rate of 0.5mm/min was recorded and split tensile strength was calculated.

3. Durability test:

Conducted as per ASTM D559/559-M procedures, weight of bricks was taken two times, once in dry stage and then after being soaked for 24 hours. The bricks were then dried for 48 hours and soaked again to complete one cycle of wetting and drying. The bricks were completely saturated and then subjected to the tests of compressive and tensile tests to determine the durability and effects of soaking on the brick. Furthermore, the bricks were soaked in varying molarities of acidic solutions and the effect of acidic environment on bricks was determined by observing the response of the bricks. The bricks were again dried for 24 hours before being tested for compressive and tensile strengths.

2.2.3. Results

For compressive strength test, the SPW-2 brick with composition ratio FS:SPW = 70:30 showed the highest compressive strength, independent of the number of wetting and drying cycles. The optimum strengths recorded by SPW1, SPW2 and SPW3 bricks were 29.45MPa, 38.14MPa and 33.25MPa respectively. All the data was higher than the Standard clay brick which recorded an optimum Compressive strength of 14.25MPa. Low water absorption and no loss of particles during wetting and drying was recorded for SPW bricks. However, for fire clay bricks a loss of 4.3g of initial weight of bricks and 2.4% loss of strength was recorded. SPW bricks were recorded to have high compressive strength, density and resistance to failure than the ordinary clay brick.

Tensile strength of SPW bricks was observed to be higher than the tensile strength of clay bricks because of the presence of melted plastic and low pore space. It was noted that compressive strength of SPW bricks was 4 times higher than tensile strength, however for clay bricks, compressive strength was 8 times higher than the tensile strength. The tensile strength of SPW bricks was independent of the number of wetting and drying cycles unlike the clay brick.

For durability test, again SPW bricks showed remarkable performance with more survival time in acidic medium and no loss in strength, therefore showing more resistance to the acidic medium. Higher absorption of energy on application of load was noted for SPW bricks indicating higher toughness.

2.2.4. Other studies

A study was done by Akinwumi et al. [13]. In this study Polyethylene Terephthalate (PET) and Clayey sand were used in the manufacture of Compacted earth blocks (CEB). PET waste was first shredded into fines pieces. These were then mixed with clayey sand in varying percentages of 0%, 1%,3% and 7%. In order to determine the properties of soil, the mixture was tested for Atterberg's limits, explicit gravity, molecule size dispersion etc. The compressive strength for the blocks was determined with different percentages of PET and the results were recorded. For 0% of PET, the compressive strength was very low having value 0.45MPa. However, 244.4% increment of strength was recorded with addition of 1% plastic waste of size 6.3mm to the mixture. Also, at this percentage the disintegration rate was minimum. Finally in order to attain high compressive strength for these blocks, cement, lime or any other cementitious binder was used.

A study was done to replace tradition bricks with construction and demolition waste materials and plastic bottles by Paihte et al. [14]. The study was based on the reuse of waste materials. Waste aggregate was recycled first and then compressed. Used plastic bottles were treated as containers and were filled with these aggregates at varying water contents of 0, 2.5, 5, 7.5 and 10%. The bottles were then tested for compressive strengths. At 5% water content the compressive strength was comparable to the compressive strength of conventional brick which is 17N/mm^2 and fly ash brick of compressive strength 12N/mm^2. The results suggested that the bottles with compressed aggregate of size less than 425micro metre showed the highest compressive strength of 15.25N/mm^2. For Recycled aggregate of size between 425 and 4.75 micro metre the compressive strength was relatively lower i.e., 9.84N/mm^2.

In a study done by Safinia and Alkanbani [15] concrete blocks were made from the waste plastic bottles. The tradition concrete blocks were compared to the plastic filled concrete blocks having same dimensions of 200x200x400mm. Both the weight and compressive strength were compared. It was observed that the plastic filled concrete blocks has weight and compressive strength 24.85kg and 10.03Mpa while as for the conventional block the values were 20.08kh and 6.38MPa. Thus, the addition of plastic bottles enhanced the compressive strength and increased the weight of hollow blocks.

In similar research done by Mukhtar et al. [16], plastic bottles were treated as containers filled with sand to replace traditional clay bricks. Waste plastic bottles are recycled into bricks by filling the with sand and compressing the sand with tamping rod for analysis. While the normal clay brick has a compressive strength of 8.58N/mm^2, the plastic brick was found to have a compressive strength of about 38.34N/mm^2 which is about 3-4 times higher. The highest outdoor temperature for plastic brick was recorded to have been 36degree Celsius and the lowest outdoor humidity and wind velocity were found to be 78% and 0.8m/s.

Research was done by Alaloul et al. [17] to produce interlocking bricks by replacing clay and cement by Polyethylene Terephthalate (PET) and polyurethane (PU) binder. Waste plastic bottles were considered for the experiment. The bottles were first chopped and grated to a fine size of 0.75mm. Then the grated plastic was mixed with polyurethane. The mixture was then condensed using interlocking brick machine. Different ratios for PET/PU were considered and the results were recorded. It was observed that for the PET/PU ratio of 60:40 the highest compressive strength achieved was lower than that of controlled group by 84.54%. The tensile strength and the maximum impact value were found to be 1.3MPa and 23.343J/m and thermal conductivity in the range 0.15-0.3 was observed. The bricks were thus found to be suitable for construction of curtain wall and non-load bearing masonry walls.

Hameed and Ahmed [18] conducted a study to make concrete using flake aggregates of PET. The range of percentage by weight of Portland cement in which PET was used was 1, 3, 5, 7 and 10%. On addition 1% PET, a reasonable increase in compressive strength of the concrete was observed with value of 20.720MPa. The flexural strength also showed an increase of 23.11% and 25.59% when compared to normal concrete. An increase in splitting tensile strength was observed with the increase in PET content particularly at 1% and 7%. The splitting tensile strength for 1 and 7% PET was 130% and 102% more than the normal concrete, respectively. However, a decline in density from 2.27-2.15g/cm^3 was observed with the increase in PET content.

A similar study was done in which concrete was made with waste PET as its content. The waste PET was taken in different percentages of 5,10 and 20 for analysis. A comparison was made between normal concrete and plastic concrete by recording the strength values for both in compression, tension and flexure and shrinkage values as per the codes ASTM C39, ASTM C469, ASTM C78, and IS:1199-1959. With 10% of added plastic, the compressive strength and Elastic modulus was noted to be the maximum in comparison to other percentages. A decline in density and flexural strength was observed with increase in the plastic percentage. It was observed that for PET 20% the water absorption was maximum [19].

In a study done by Khan et al. [20] the bitumen properties were modified by addition of LDPE, HDPE and crumb rubber in varying percentages of 2,4,8 and 10% by weight of bitumen. Data was recorded at varying temperatures and frequencies for the viscosity and elasticity of binders. An improvement in the elastic behaviour of binder was observed with the addition of Low density polyethene (LDPE), High density polyethene (HDPE) and crumb rubber thus ensuring increase in the service life of binder by the reduction of chances of rutting and cracking.

In yet another research cum review carried out by Zhenhua Duan et al in the year 2023, Plastic fiber was put under recycle and then used in the reinforced cement concrete. The review of all the mechanical, micro and early age properties and the methods of improvement of recycled plastic fiber suggested an enhancement of the mechanical properties, durability and tensile strength of concrete and an improvement in the crack resistance. In addition, increase in corrosion resistance of the reinforcement was observed [21].

3. Dust mitigation

The processing of debris and the recycle of materials results in the release of dust into the atmosphere. This leads to environmental degradation, dropping of air quality index, reduction in visibility and health hazards. Thus, a thorough mitigation is required to reduce these impacts. The most feasible method is the method of water suppression [22]. Other methods that can be accounted for the reduction in the dust production are the exhaust ventilation, the use of dust screens, chemical agents and electric sweepers and the application of water before cutting, grinding or processing [23].

4. Conclusion

The work done by various scientists can be used to understand that the waste generated from earthquakes has efficient disposal capacity. The two constituents of the waste under study, glass and plastic, can be put to use for the manufacture of other construction materials such as bricks or can be used in concrete as well.

1. Powdered glass can be mixed with brick clay to produce high compressive and tensile strength bricks. This would decrease the demand for high amount of raw material and would also reduce the amount of carbon emission in the atmosphere, which normally occurs during the manufacture of traditional brick.
2. Glass can also be used to substitute fine sand in concrete. The pozzolanic reaction occurring in glass results in high compressive strength of concrete. Within 28-90 days the concrete gains good strength with the addition of suitable size powdered glass to the mixture.
3. Scrap plastic waste (SPW) and foundry sand (FS) can be used in the ratio of 30:70 in the manufacture of bricks which can be used as an alternative to clay bricks. The strength in compression is observed to exceed the strength of traditional brick by multitudes and other properties as in durability and water absorption are more enhanced.
4. Scrap Plastic waste (SPW) and Manufacturing sand M sand in the ratio 1:2 can also be used in the manufacture of bricks exhibiting compressive strength higher than traditional bricks.
5. Glass can also be used to substitute fine sand in concrete. The pozzolanic reaction occurring in glass results in high compressive strength of concrete. Within 28-90 days the concrete gains good strength with the addition of suitable size powdered glass to the mixture.
6. Scrap plastic waste (SPW) and foundry sand (FS) can be used in the ratio of 30:70 in the manufacture of bricks which can be used as an alternative to clay bricks. The strength in compression is observed to exceed the strength of traditional brick by multitudes and other properties as in durability and water absorption are more enhanced.
7. Scrap Plastic waste (SPW) and Manufacturing sand M sand in the ratio 1:2 can also be used in the manufacture of bricks exhibiting compressive strength higher than traditional bricks.
8. Bricks for curtain walls and non-load bearing walls could be produced by using polyethylene terephthalate (PET) and polyurethane (PU) binder in place of clay and cement.
9. Compacted earth blocks can be manufactured from polyethylene terephthalate (PET) (1%) and Clayey sand with some cementitious additives to increase the compressive strength.
10. Direct use of recycled plastic bottles filled with sand, or coarse aggregate and binders exhibits higher strength than the clayey bricks and can be substituted for the same.
11. 1% or 7% of Flake aggregates of PET by weight of Portland cement can be used in making high strength concrete. However, with the increase in PET percentage a decrease in density and flexural strength was observed.
12. Even for the construction of pavements, Plastic scrap can be used. LDPE, HDPE and crumb rubber from waste can be used to enhance the elastic behaviour and increase the service life of binder.
13. Further research can be initiated to look for the disposal of other earthquake wastes in an economical and constructive way.
14. The filtration of glass and plastic material from tons to debris is a time consuming and tiresome process which needs to be simplified through proper research.
15. The quality of the building materials generated need to be thoroughly examined under different conditions of loading, temperature and environment.

Thus, in an event of a massive earthquake, the debris generated can be filtered and waste materials such as plastic and glass extracted. Instead of disposing these wastes directly into the environment, processing can be done and manufacture of new building materials can be attained. This would ensure that harmful effect on the environment due to direct disposal of waste is minimized. At the same time, the demand for new raw material is cut short and the economic benefit is attained. Reconstruction is thus cheaper, faster and more sustainable.

Author contributions

Fazilah Khurshid: Conceptualization, Methodology, Software, Writing-Original draft preparation **Ayse Yeter Gunal:** Data curation, Software, Validation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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