Istanbul GEDİK University
15th Anniversary

Vol. 3 | No 2
2025

IJONFEST

International Journal of New Findings in Engineering, Science and Technology

e-ISSN: 3023-4379

IJONFEST

INTERNATIONAL JOURNAL OF NEW FINDINGS IN ENGINEERING, SCIENCE AND TECHNOLOGY (IJONFEST)

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FROM EDITOR

Dear researchers,

We are pleased to present the September 2025 issue of the International Journal of New Findings in Engineering, Science and Technology (IJONFEST). On this occasion, we would like to express our sincere appreciation to the contributing authors who have submitted their original and labor-intensive research studies. We are equally grateful to our esteemed reviewers, whose expertise, commitment, and academic integrity have significantly enhanced the scientific rigor and overall quality of the published works, guided solely by a sense of professional responsibility and the shared purpose of advancing knowledge in their respective fields.

Furthermore, I would like to extend my heartfelt thanks to all members of our editorial team, who, as the third pillar of this scholarly endeavor, have played an essential role in ensuring the timely and meticulous processing of submissions and in delivering them to our academic readership with the highest standards of publishing ethics.

The current issue (Vol. 3, No. 2) features a total of six articles, comprising five original research papers and one review contributions. The thematic diversity represented in this issue demonstrates our journal's ongoing commitment to multidisciplinary coverage, which remains a foundational principle of our editorial policy.

We sincerely hope that the studies presented in this issue will make meaningful contributions to their respective fields and inspire further research. We also look forward to receiving your valuable submissions for consideration in our upcoming issues.

Sincerely,

Assoc. Prof. Dr. Redvan Ghasemlounia
Editor-in-Chief
International Journal of New Findings in Engineering, Science and Technology (IJONFEST)

September 2025

September 2025, Vol:3, Issue:2

International Journal of New Findings in Engineering, Science and Technology

journal homepage: https://ijonfest.gedik.edu.tr/

Received:31.05.2025 Accepted:19.09.2025 Pablished:29.09.2025

DDoSGedik30K: A Unique Dataset with FFNN and LSTM-Based Deep Learning Models for Detecting DDoS Attacks

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Abstract

The rapid advancements in network technologies, along with the increasing volume and scope of data transmitted over networks, have led to a rise in both the intensity and complexity of cyber threats and attacks. One of the most prominent and destructive types of cyberattacks threatening network and system security is the Distributed Denial of Service (DDoS) attack. This study examines the use of deep learning techniques to develop an effective detection mechanism against the growing number of DDoS attacks today. For this purpose, a dataset called DDoSGedik30K, which includes real-world attack scenarios, was created. Using this dataset, a total of 12 models were developed based on Feedforward Neural Network (FFNN) and Long Short-Term Memory (LSTM) deep learning architectures. The fact that all models exceeded a 99.9% accuracy rate proves that the proposed dataset is highly effective in detecting DDoS attacks. Additionally, cross-validation (CV) was employed in the model evaluation, and the experimental results are consistent with the obtained performance metrics, demonstrating the reliability and robustness of the proposed approach. This study introduces the DDoSGedik30K dataset and deep learning models that significantly improve DDoS attack detection. These contributions enhance cybersecurity research and provide actionable insights for future advancements.

Keywords: DDoSGedik30K, DDoS Dataset, DDoS Detection, DDoS Analysis, Deep Learning.

1. INTRODUCTION

The rapid increase in digitalization has led to a parallel growth in cybersecurity threats. A Denial of Service (DoS) attack is a cybersecurity threat that causes a resource or service to become unavailable or unresponsive for legitimate users. The resource could be a single server, a group of machines (such as a dedicated server pool), or a network. If an attacker successfully renders the targeted resource inaccessible to legitimate users, the DoS attack is considered successful. This type of attack can be carried out through various methods and at different layers of the OSI and TCP/IP models [1].

Attackers often lack the computing power to launch a DoS attack, especially when large amounts of traffic are required. This need for high computational power has led to the rise of a related attack known as a Distributed Denial of Service (DDoS) attack. Executing a DoS attack with significant computational resources is a unique challenge. Today, DDoS attacks are considered one of the most common and destructive types of cyberattacks threatening network and system security [2-4]. DDoS attacks aim to overwhelm a system or network, causing it to become unavailable and leading to significant financial losses and service disruptions. For this reason, early detection and effective prevention of such attacks have become a critical necessity in the field of cybersecurity.

https://doi.org/10.61150/ijonfest.2025030201

Each type of DDoS attack has its own unique execution technique, driven by various factors such as the software tool used to generate the attack traffic, the communication layer, the target protocol, and more. The ultimate goal of the attacker is to render the target resource inaccessible to legitimate users. Although various protection mechanisms can secure critical resources, system vulnerabilities are often exploited by hackers. Table 1 provides information on different types of DDoS attacks.

Table 1. Overview of different DDoS attack types along with their targets and associated vulnerabilities [5].

Types of DDoS Attacks	Targets	Exploited Vulnerabilities
Data Overflow	Network bandwidth or the capacity of networks or servers.	Limited network bandwidth / Limited server capacity to process requests.
Attack on Network Devices	Network devices/hardware such as routers, switches, and firewalls.	Vulnerability/error in device firmware.
Protocol Attack	Protocol Services.	Protocol limitations and vulnerabilities such as ARP poisoning, IP spoofing, and TCP SYN flooding.
Application Attack	Application Services.	Application Limitations and Vulnerabilities.
Operating System Attack	Operating System Services.	Vulnerability/error in operating system software.

A key feature of DDoS attacks is that they are executed simultaneously from multiple devices, rather than a single source. These devices are typically computers that have been compromised by malware, commonly referred to as a botnet [6]. The objective here is to prevent legitimate users from accessing the system, network, or service. The targeted system can be a website, a server, a gaming platform, or another online service. The attack method overwhelms the target by flooding it with fake requests, exhausting its resources such as CPU, memory, and bandwidth [7]. As a result, the target system may slow down, malfunction, or completely crash. The effects of the attack can include the targeted service or network becoming completely unavailable, business losses due to service interruptions, customer dissatisfaction, and damage to reputation.

A DDoS attack is established by organizing a network composed of connected machines. These machines are referred to as "Zombies," and they form a part of the network known as a "Botnet." A botnet consists of many computers that have been compromised and are remotely controlled by cyber attackers [8]. This traffic consumes the bandwidth, processing power, or other resources of the target system, leading to its slowdown, crash, or complete inaccessibility [9]. The mechanism for controlling the network is established by assigning the Command and Control (C&C) function to special high-capacity resources that give direct instructions on behalf of the attacker. The next layer consists of "Handlers" selected by the C&C function to transmit commands and receive responses. Beneath each handler is a series of zombies used to send attack traffic directly to the target (victim). They also relay information about the victim back to the relevant handlers through the C&C function [10]. Therefore, client-server technology is used for communication within the botnet.

There are several methods to protect against DDoS attacks. The use of continuous monitoring and analysis tools allows for the detection of unusual spikes in network traffic, enabling the identification of early signs of DDoS attacks [8]. Security Information and Event Management (SIEM) tools collect and analyze network traffic and security events, facilitating quick responses by detecting anomalies [11].

With the rapid advancement of Artificial Intelligence (AI) technologies, particularly deep learning techniques used in many fields, these methods can also serve as a precise and robust solution for detecting DDoS attacks [12]. AI and Machine Learning (ML) based tools can analyze traffic to identify abnormal behaviors and enable automated responses. Machine learning represents a promising approach in predicting and simulating human behavior with computational intelligence, having been successfully applied to widespread real-world problems [13]. For ML-focused detection of DDoS attacks, evaluating datasets that encompass DDoS attacks is widely accepted for building ML models. In this study, a dataset containing a mixture of specific attack types was created, and deep learning-based models were developed for attack detection using this dataset.

1.1. Contribution of Study

This study provides significant contributions to the literature by comprehensively examining the effectiveness of deep learning models developed to detect DDoS attacks in the field of cybersecurity. These contributions can be summarized in several points:

- A high-quality dataset for cybersecurity research (DDoSGedik30K) has been contributed to the literature through a system created in the laboratories of Istanbul Gedik University, using real network attacks and normal connections. The relevant dataset has been developed to mimic real-world scenarios through various firewall configurations. It includes vulnerabilities that could be encountered in the real world, particularly focusing on changes in firewall configurations and intentionally created vulnerabilities.
- The effects of different architectures, epoch counts, learning rates, and optimization algorithms on model performance have been analyzed in detail. These analyses guide the selection of the most suitable deep learning model for different scenarios.
- This study illuminates future research aimed at developing real-time and effective models for DDoS attack detection. It emphasizes that deep learning techniques can also be utilized in cybersecurity solutions, laying an important foundation for the integration of these techniques into future security solutions. As cybersecurity becomes increasingly critical, such efforts will play a key role in protecting networks and systems.

2. RELATED WORKS

Many studies have been conducted on DDoS attacks and their detection. An examination of these studies reveals the use of various methods, resulting in different outcomes depending on the approach.

Erhan and Anarım [14] investigated the statistical modeling of network traffic observed during DDoS attacks. To conduct this analysis, they utilized 16 traffic attributes, employing the BOUN DDoS dataset, which is derived from Boğaziçi University's (BOUN) network and includes TCP SYN flood attacks. The first method used was to create a statistical dataset for both attack and non-attack scenarios from the training dataset. This statistical dataset was then used to detect attacks within the experimental distributions of the test data. The second method employed was the K-Means clustering algorithm. The results showed an accuracy rate of 98% for the attack model and 97% for the normal model.

Asarkaya et al. [15] examined the prediction of DDoS attacks using machine learning classification algorithms. They used the DDoS Attack Network Logs dataset downloaded from Kaggle, which contained a total of 902,186 entries classified into 'Normal', 'Http-Flood', 'SIDDOS', 'Smurf', and 'UDP-Flood' categories, using 27 different attributes. The methods employed included K-Nearest Neighbors (KNN), Support Vector Machine (SVM), Multi-Layer Perceptron (MLP), and Random Forest (RF) algorithms. The model created using KNN achieved an accuracy of 93%, SVM reached 98%, MLP achieved 99%, and RF also obtained 98%.

Sharif and Beitollahi [16] focused on the critical need for improved DDoS detection, aiming to minimize false alarms while accurately detecting both known and unknown DDoS attacks. They utilized multiple datasets (CICIDS2017 [17] and CICDDoS2019 [18]) for this purpose. Additionally, Genetic Algorithms (GA) were adopted for automatic hyperparameter optimization to ensure efficient and effective DDoS detection. In this study, the RF classifier achieved an accuracy rate of 99.9%, with precision, recall, and F1 score values of 100%, 99.8%, and 99.9%, respectively.

In another study, Ahmed et al. [19] addressed application layer DDoS attacks by analyzing the characteristics of incoming packets, including the size of HTTP frame packets, the number of sent Internet Protocol (IP) addresses, continuous port mappings, and the number of IP addresses using proxy IPs. Standard datasets such as the CTU-13 dataset-2011, real web logs from organizations-2019, and datasets experimentally created from DDoS attack tools were used. The MLP algorithm was utilized to evaluate the effectiveness of metric-based attack detection, including Slow Loris, Hulk, Golden Eyes, and Xerex. The simulation results demonstrated that the proposed MLP classification algorithm had an efficiency rate of 98.99% in detecting DDoS attacks.

Sharif et al. [20] aimed to fill the gap by investigating the impact of the accessibility of DDoS attack tools on the frequency and severity of attacks. They proposed a machine learning solution to detect DDoS attacks using a feature selection technique that improved speed and efficiency, resulting in a significant reduction in the feature subset. The CICIDS2017 dataset was used, in which the abstract behaviors of 25 users were profiled according to HTTP, HTTPS, FTP, SSH protocols, and emails.

After feature selection, six selected features were placed into a three-layer MLP. By using a deliberate approach for feature selection, they found that the model's effectiveness was greatly enhanced. The provided evaluation criteria indicated that the model achieved a high accuracy level of 99.9%, with 96% precision, 98% recall, and an F1 score of 97%.

Kareem et al. [21] proposed a detection system called eXtreme Gradient Boosting (XGB-DDoS), which utilizes a tree-based ensemble model to detect application layer DDoS attacks. The XGB-DDoS detection model outperformed other models used in the study (KNN, SVM, and PCA hybridized with XGBoost). The proposed method was observed to be effective in detecting application layer DDoS attacks. The CICIDS2017 dataset, created by the Canadian Cybersecurity Institute, was used for the training and testing of the most successful model. The performance results of the model were significantly high, with accuracy, precision, recall, and F1 scores of 0.999, 0.997, 0.995, and 0.996, respectively.

In their study, Salama et al. [22] used the CICDDoS2019 dataset to train and evaluate various machine learning algorithms, including Stochastic Gradient Boosting (SGB), Decision Tree (DT), KNN, Naive Bayes (NB), SVM, and Logistic Regression (LR). The results of the study demonstrated that all machine learning algorithms were capable of effectively detecting DDoS attacks with high accuracy, precision, and recall. However, it was observed that the SVM algorithm achieved the highest accuracy rate (0.99) compared to the others.

Teeb Hussein [23] proposed a new approach for DDoS attack detection using Denoising AutoEncoder (DAE) and Convolutional Neural Network (CNN) for feature selection and classification. The NSL-KDD dataset was used to evaluate the performance of this new model through three main steps (Data Preprocessing, Hyperparameter Optimization, and Classification). After applying the methods, the obtained accuracy, precision, recall, and F1 score metrics were measured at 97.7, 98.1, 97.7, and 97.8, respectively. The detection rate for DoS was found to be 100%.

Manaa and colleagues [24] utilized three significant datasets: UNSW-NB 15, UNSW-2018 Botnet, and Edge IIoT, in an Anomaly-Based Intrusion Detection System (AIDS) to detect and mitigate DDoS attacks. The proposed study used methods such as RF, SVM, LR, MLP, Deep Artificial Neural Network (ANN), and Long Short-Term Memory (LSTM) to identify DDoS attacks. These methods were compared against the fact that the database stored trained signatures. As a result, RF exhibited promising performance with 100% accuracy and minimal false positives when testing both the UNSW-NB 15 and UNSW-2018 Botnet datasets.

Najar, Sugali, Lone, and Nazir [25] proposed a new framework for detecting and classifying DoS attacks with high accuracy and low computational cost. Random sampling was used to address class imbalance, and feature selection techniques such as low information gain, semi-fixed elimination, and principal component analysis were employed for optimal feature selection and reduction. The proposed CNN-based model achieved outstanding performance with 99.99% accuracy for binary classification and 98.44% for multi-class classification.

In their study, Zekri et al. [26] discussed DDoS attack detection in cloud environments using machine learning algorithms. In this research, a simple dataset of five features was analyzed using the C4.5 decision tree algorithm that works on the gain ratio as a splitting criterion. The detection module was also supported by signature-based detection for improved results. For comparison purposes, the C4.5 algorithm was evaluated alongside Naive Bayes and K-Means algorithms. The attack traffic was simulated using the Hping3 tool. Snort, an open-source Intrusion Detection System (IDS), was utilized for signature-based detection. It was found that the C4.5 algorithm yielded better results compared to the other two algorithms, with the highest accuracy recorded at 98.8%.

Yuan et al. [30] tested the application of deep learning in detecting DDoS attacks using Recurrent Neural Networks (RNN), referred to as DeepDefense. In this study, 20 network traffic features were sampled from the ISCX'12 dataset. To accelerate the training process, batch normalization layers were also added to the RNN layers. Four different types of RNNs, including LSTM and 3LSTM, were analyzed and compared with each other. Additionally, a specific RNN parameter tuning was compared with the RF classifier. The highest accuracy was recorded at 98.41% using the 3LSTM algorithm.

3. DATASET

The dataset utilized in this study was generated through detailed operations conducted on the Pentest servers located in the computer laboratories of Istanbul Gedik University [31]. This dataset was specifically developed for the purpose of detecting DDoS attacks, taking into account the nature and complexity of these attacks.

The primary aim in creating this dataset is to enhance the performance of deep learning algorithms in the field of cybersecurity and to develop models that are suitable for real-world scenarios. In this context, the number of variables used for detecting DDoS attacks can directly influence the complexity of the model and its processing speed [32, 33]. Working with a limited number of variables may facilitate faster training of the model and improve the speed of real-time detection processes. This situation presents a practical advantage, particularly in scenarios with resource constraints. Thus, the objective is to achieve high accuracy rates in attack detection while maintaining the processing efficiency of the system.

The creation of the dataset involved executing attacks from both internal networks (such as controlled networks protected by security protocols, like corporate networks) and external networks (which are generally open to the internet and harbor greater threats). These attack scenarios simulated various threats that the system might face, enabling a comprehensive collection of data across a wide range. This methodology allows machine learning models to operate effectively not only against specific types of attacks but also against diverse attack vectors. Over a four-month period, various attack techniques and scenarios were implemented, resulting in the collection of tens of thousands of data records. These records have facilitated the assessment of the generalization capabilities of machine learning models and their resilience to real-world scenarios.

The generated dataset has been named "DDoSGedik30K" and has been introduced to the literature as a valuable resource for training machine learning algorithms. The security of the system is maintained through a complex network structure comprising firewalls, servers, and computers [34]. Firewall systems are a crucial component that enhances security levels by monitoring network traffic and detecting potential threats [35].

In the system established for this study, two firewalls were utilized: Fortigate [36] and Mikrotik [37]. A representative image of the system in operation is shown in Figure 1.

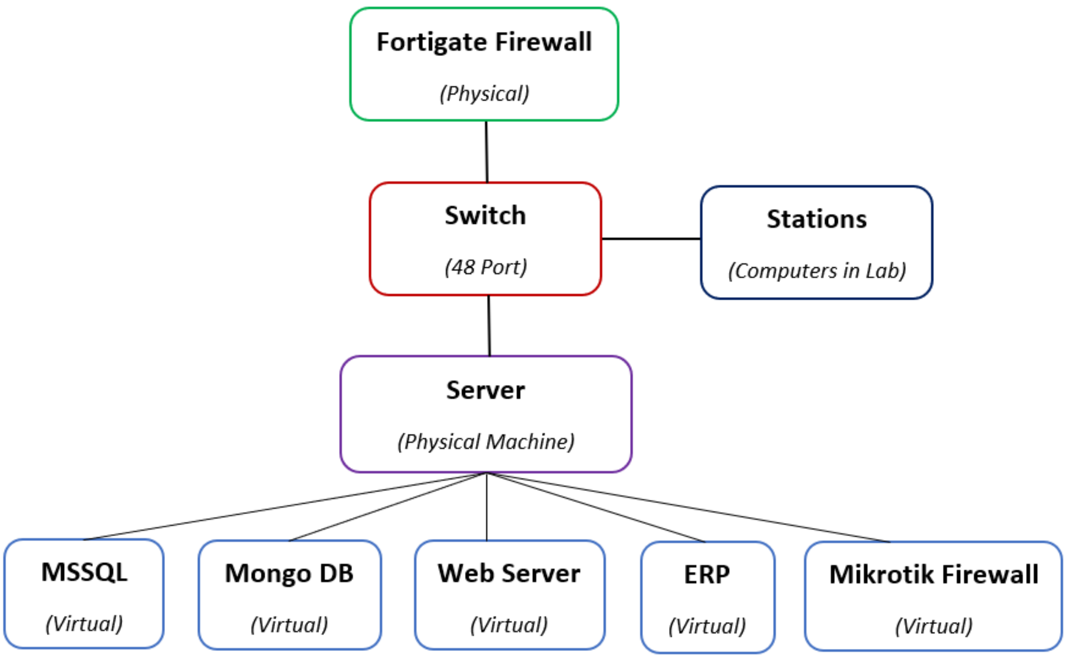

Figure 1. Representative diagram of the laboratory network setup used for dataset creation, showing the firewall, switch, server, stations, and virtualized services deployed for DDoS attack simulations.

The Fortigate operated physically, while the Mikrotik functioned on a virtual machine. These two firewalls were used together for a very short time. Generally, the Fortigate firewall was active, while the Mikrotik firewall was kept in passive mode. The rules in the firewalls used were not kept the same for the sake of data diversity. Occasionally, some rules were intentionally set to passive, creating deliberate vulnerabilities. The primary goal of these vulnerabilities was to diversify the data and produce the most realistic datasets by mimicking system vulnerabilities or errors that might be encountered in real life.

The 48-port smart switch used in the system ensured the management of all network devices and optimized network traffic. The switch enabled logical separation and management of devices on the network through VLAN (Virtual Local Area Network) configuration, although only a single VLAN was used in this study. Using a single VLAN facilitated access for all devices to the server over the internal network. This configuration was intentionally applied, especially for testing cyber-attack scenarios and examining the security vulnerabilities of the system.

The logs generated in the system were not limited to firewall logs; various programs that could monitor and analyze network traffic were also used. Among these programs, CICFlowmeter [38] and Wireshark [39] stand out.

CICFlowmeter is a tool that analyzes network traffic and extracts flow-based features. This tool provides detailed information about each connection by monitoring data flows on the network, and this information serves as valuable input for machine learning algorithms. Wireshark, on the other hand, is a widely used network protocol analyzer around the world. This program helps understand the nature and propagation of attacks with its ability to monitor network traffic in real-time. The logs obtained through these programs were combined with the firewall logs and used in the creation of the DDoSGedik30K dataset. The DDoSGedik30K dataset consists of 31,458 records. The dataset contains seven variables, which specify the amount of bytes and packets sent in one second, the response time of the sent requests, and the total amount of data packets. Descriptions of all the variables are presented in Table 2.

Table 2. List of Features and Their Corresponding Descriptions in the DDoSGedik30K Dataset.

Feature	Description
time	Response time of the sent request
bytes	Average byte amount per second
packets	Average packet amount per second
total_bytes	Total amount of data packets in bytes
total_packets	Total amount of data packets
label	Type of attack (DDoS, SQL, Port Scan, or None)
class	Attack or Harmless

4. DATA PREPROCESSING

In this study, various deep learning models have been developed to detect DDoS attacks, all of which focus on binary classification problems. Binary classification means that each record in the dataset is labeled as either "attack" or "not an attack" (Harmless). In this context, the "class" variable in the DDoSGedik30K dataset has been designated as the target variable for the model, and all models have been trained based on this variable. The "label" variable in the dataset has been excluded from model training. The primary reason for this is that the "label" variable contains information that could overshadow the importance of the other variables. For example, the "label" variable can directly indicate whether a connection is an attack, and in this case, the model could classify based solely on this information without needing the other independent variables. However, this situation is not expected in real-world scenarios. In real-time network traffic analysis, whether a request is an attack is not information contained within the request itself. Therefore, to enable the model to make more complex and reliable predictions, the "label" variable has been removed from the training dataset. The other independent variables in the dataset represent various features of network traffic. These variables are factors that define the data flow over the network and are used to identify a potential attack. In this study, model design has been carried out based on a total of 6 variables, 5 of which have been used as independent variables. These variables have been carefully selected to ensure that deep learning models achieve high accuracy rates in attack detection.

The rationale behind our dataset relying on only 6 features is that our goal was to create a dataset that could work even on small, fast, and weaker configurations. In this context, we focused only on the basic features. This is because adding more features could increase the complexity of the model and affect its operating speed. Additionally, reducing the size of the dataset provided a significant advantage in terms of training time and system requirements. By choosing this approach in our work, we aimed to create a flexible dataset that could be tested on faster and lower-capacity systems. The DDoSGedik30K dataset contains a total of 31,458 data records, each consisting of an equal amount of attack and non-attack records. This balance is critical for ensuring that the model learns both classes equally well. The balanced distribution in the dataset enables the model to accurately detect attacks while avoiding misclassifying normal network traffic as false positives. Information regarding the quantities of attack and non-attack values in the dataset is shown in Table 3.

Table 3. Distribution of Values in the 'Class' Variable of the DDoSGedik30K Dataset.

Class	Data Amount
Harmless (0)	15729
Attack (1)	15729

Before proceeding to the training phase of the model, the "Harmless" values in the class variable were recoded as "0," while the "Attack" values were recoded as "1." All variables, except for the target variable class, were normalized using the Z-Score Normalization (Standardization) method [40]. It is a well-known fact that the standardization processes applied to datasets generally enhance model performance [41, 42].

5. METHODOLOGY

In this study, a total of 12 models were produced using two different architectures: Feedforward Neural Network (FFNN) and Long Short-Term Memory (LSTM). Experiments were conducted with different hyperparameter values for both deep learning algorithms.

FFNN is one of the most basic and widely used types of artificial neural networks [43-45]. These types of neural networks transfer information in only one direction, from the input layer to the output layer. Data is passed forward and processed through each layer, starting from the input layer. The neurons in each layer multiply the inputs from the previous layer by weights, add a bias value, and apply an activation function. This process continues until the output layer is reached, producing a final output.

LSTM is an advanced type of recurrent neural networks (RNN) designed specifically for working with time series data and sequential data [46-49]. LSTM layers address the "long-term dependency" problem experienced by traditional RNNs, allowing the model to remember important events from the past without forgetting them. LSTM operates with a structure called "cell state," which enables the model to carry significant information over long periods. This feature provides a critical advantage in analyzing long-duration data flows, such as DDoS attacks.

By recognizing important features in sequential data, LSTM makes more accurate predictions and can effectively detect sudden changes in the data flow. This is particularly beneficial in scenarios where attacks may intensify over a certain period. Data is passed forward through LSTM cells, starting from the model's input layer. At each time step, LSTM updates the cell state and produces an output. The training of LSTM models is conducted using a special backpropagation algorithm for time series data, known as "backpropagation through time". Half of the models produced in this study are based on the FFNN architecture, while the other half are based on the LSTM architecture. The number of layers and neurons in both architectures are values determined after a series of tests. To ensure that the accuracy rate is not adversely affected, care was taken to use as few layers and neurons as possible for the models to operate more efficiently. A representative image of the FFNN architecture is shown in Figure 2.

The FFNN models have an input layer with 5 input variables. These 5 input variables represent the features obtained from the dataset and define the characteristics of each data point to be processed by the model. This layer contains 30 neurons, meaning there are 30 separate units, each responsible for processing one feature. The activation function used for this layer is ReLU (Rectified Linear Unit) [50, 51]. ReLU is commonly preferred in deep learning models because it provides a nonlinear relationship while enabling the model to learn quickly and effectively. The second layer has 20 neurons, which process the 30-dimensional output vector from the input layer and pass it to the next layer. The activation function used in the hidden layer is again selected as ReLU. ReLU is widely preferred in neural networks because it largely prevents the vanishing gradient problem [52] and allows effective learning even in deeper layers of the model. The third layer is a Dropout layer, which is added to enhance the model's generalization ability. Dropout allows for randomly disabling neurons during the training process, preventing the model from overfitting to a specific dataset [53]. In this model, the Dropout rate is set to 0.5, meaning 50% of the neurons are randomly disabled during each training step. This makes the model less sensitive to noise in the dataset

and helps it perform better with new, unseen data. The final layer of the FFNN architecture contains only 1 neuron. This layer serves as the output layer and is used to detect whether a DDoS attack is present. The reason for having 1 neuron in the output layer is that the model solves a binary classification problem. The activation function used in this layer is the sigmoid function. The sigmoid function [54] produces an output between 0 and 1, representing the probability of each input belonging to a specific class.

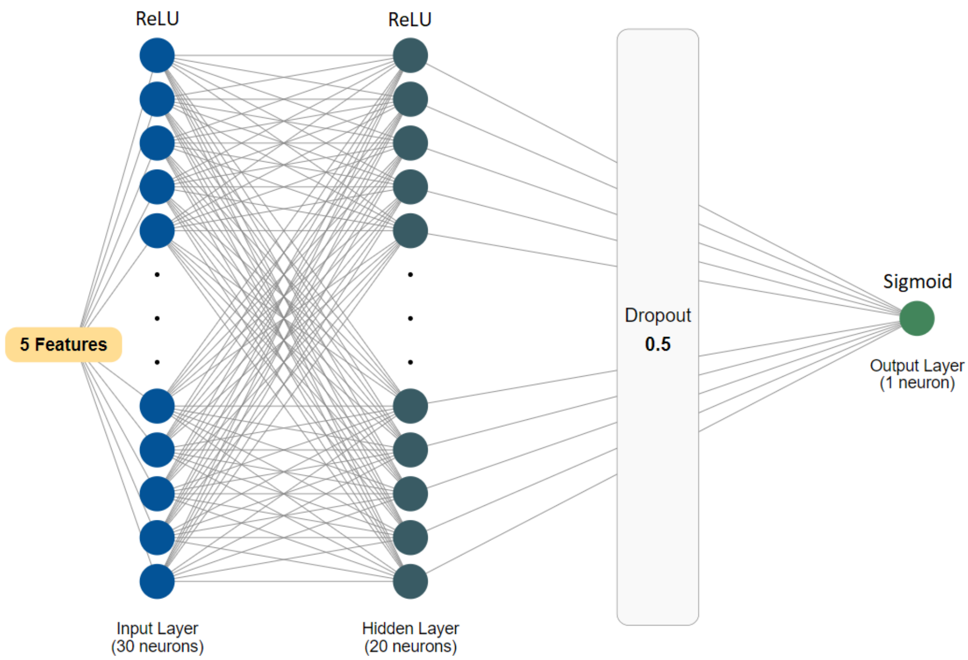

Figure 2. Layers and neurons of the FFNN architecture.

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The first layer of the LSTM models, the LSTM layer, contains 10 memory cells (neurons) and accepts 5 variables as input size. This layer learns the relationships between past data points and the current data, allowing it to capture changes over time. A representative image of the LSTM architecture is shown in Figure 3.

The LSTM layer allows the model to remember past information from time series data and utilize this information to predict future events. The strong memory structure of LSTM makes it an ideal solution, especially for long-term and complex attack scenarios. This feature of LSTM is particularly beneficial for detecting DDoS attacks, as attacks often occur based on specific patterns within a defined time frame. In this layer, the ReLU activation function is used.

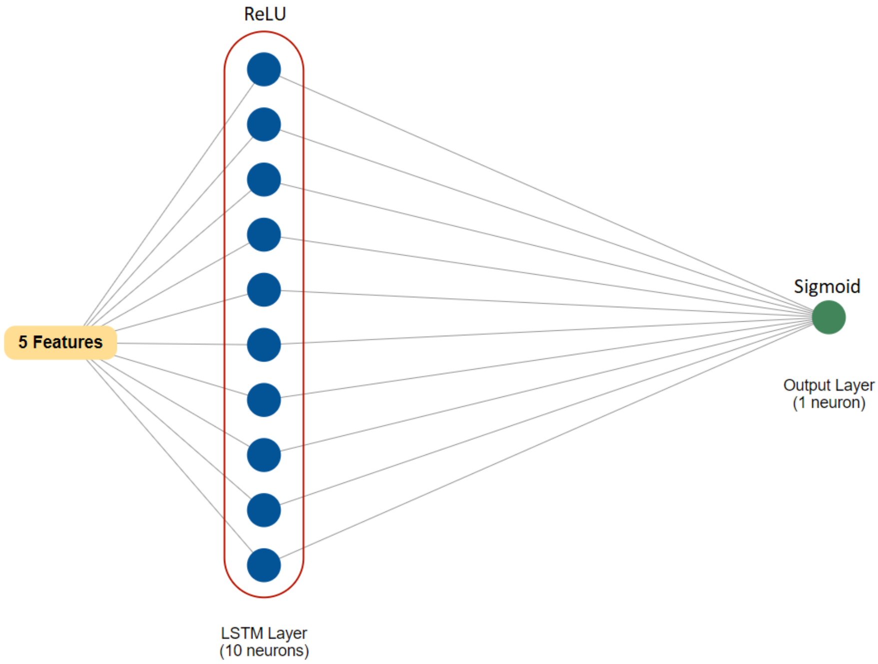

Figure 3. Layers and Neurons of the LSTM Architecture

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The final layer of the architecture contains only 1 neuron. This layer processes the outputs from the LSTM layer and converts them into a result. Its purpose is to classify each data point as either an "attack" or "not an attack." Therefore, there is only one neuron in the output layer, and the activation function used in this layer is sigmoid.

The primary device used for training all models is a work laptop provided by Istanbul Gedik University, which has the following specifications: Windows 10 operating system, Intel Core i7-12650H CPU at 2.30 GHz, 16GB RAM, 512GB SSD, and NVIDIA GeForce RTX 3060 Laptop GPU.

The development environment used is Jupyter Notebook v6.5.2, and the programming language preferred is Python v3.11.3. To create deep learning models, the following libraries that support usage in Python were utilized: TensorFlow [55], Keras [56], NumPy [57], Pandas [58], and Scikit-learn [59].

6. RESULTS and DISCUSSION

In this study, experiments were conducted to detect DDoS attacks using a total of 12 different models built with two different deep learning architectures. Each model was trained with various parameters. The impact of these parameters on the results was investigated. The differences in the models were interpreted based on the findings obtained. The characteristics of all models produced in the study, along with their hyperparameters and the accuracy values achieved, are shown in Table 4.

Table 4 shows that the first and most striking result is that all models produced very successful results. While the accuracy rates of all models were above 0.999, their loss values remained quite low, demonstrating the effectiveness of the developed deep learning models in detecting DDoS attacks. Here, the test accuracy values show the results determined based on data outside the training data. This represents how each model performs on a data set that did not participate in the training process.

The accuracy of the results obtained in the study and their consistency with cross-validation (CV) were carefully evaluated. When comparing test accuracies with K-fold cross validation (K=5 and K=10) values, both validation types are highly consistent with the accuracy of the models. This indicates that overfitting has been prevented and that the models accurately reflect their overall performance. Using CV is a critical step to ensure that the model does not depend solely on a specific data set and exhibits more generalized performance. Cross-validation for K=5 and K=10 increased the reliability of the model by using different training and test data sets, while also reducing the risk of overfitting.

Table 4. Performance Results of the Models Evaluated in the Study, Including Architecture, Hyperparameters, and Accuracy.

Model	Architecture	Optimizer	Epoch	Elapsed Time	Learning Rate	Loss	Accuracy	CV (K=5)	CV (K=10)
1	FFNN	Adam	50	44.566	0.0001	0.003	0.99937	0.99936	0.99942
2			20	18.987	0.0003	0.003	0.99936	0.99946	0.99933
3			10	10.221	0.0010	0.002	0.99941	0.99939	0.99942
4		SGD	50	40.326	0.0001	0.007	0.99925	0.99942	0.99952
5			20	16.117	0.0003	0.004	0.99925	0.99942	0.99955
6			10	8.524	0.0010	0.006	0.99937	0.99955	0.99939
7	LSTM	Adam	200	212.609	0.0001	0.014	0.99904	0.99977	0.99984
8			100	102.209	0.0003	0.007	0.99925	0.99980	0.99990
9			40	43.477	0.0010	0.008	0.99947	0.99974	0.99965
10		SGD	200	208.580	0.0001	0.009	0.99872	0.99980	0.99996
11			100	11.236	0.0003	0.007	0.99936	0.99971	0.99984
12			40	43.280	0.0010	0.007	0.99925	0.99965	0.99974

The Adam optimization algorithm [60, 61] has generally provided better performance in models. This is because Adam provides faster convergence and can dynamically adjust the learning rate. Stochastic Gradient Descent (SGD), on the other hand, has a deterministic structure and is a simpler algorithm, which may require more epochs [62, 63]. It may also have had a negative impact on the accuracy of the model.

When examining all models in terms of loss value, Model 3 stands out. “Elapsed Time” is a value that indicates the training duration of the model in seconds. A shorter training time demonstrates that the model is trained quickly and, therefore, is more efficient. This becomes especially important when working with large datasets and in real-time applications. Model 6 has the fastest training time at 8,524 seconds.

The most successful model in the study is model number 3 in Table 4. It achieved a very high accuracy of 99.41% according to the accuracy metric and also obtained a result of 99.42% in CV (K=10). Furthermore, the low number of epochs suggests that the model can be trained quickly and has high generalization ability. The model with the lowest loss value is also model number 3 (0.002). This result also indicates that the model's predictions are accurate, and the error rate is very low. Figure 4 shows the Train and Validation Loss graph for Model 3.

In Figure 4, it can be observed that the losses of Model 3 have successfully decreased throughout the training and validation processes, indicating that the model is effectively learning. Additionally, it is evident that the number of epochs was chosen correctly, allowing the model to maintain good generalization performance without overfitting. As shown in the graph, both training loss (red line) and validation loss (blue line) decrease as the number of epochs increases. This indicates that the model is learning better at each epoch and reducing the error rate.

The stability of the validation loss at low levels shows that the model is not overfitting, meaning it maintains its overall performance without excessively fitting the training data. The low values of both training and validation losses suggest that the model performs effectively on both training and test data. This implies that the model is successful in detecting DDoS attacks and has good generalization ability. It was observed that losses could potentially decrease further with an increased number of epochs; however, at this point, it became clear that the losses were stabilizing and that more epochs might be unnecessary. This approach has been applied in the same way to all other models.

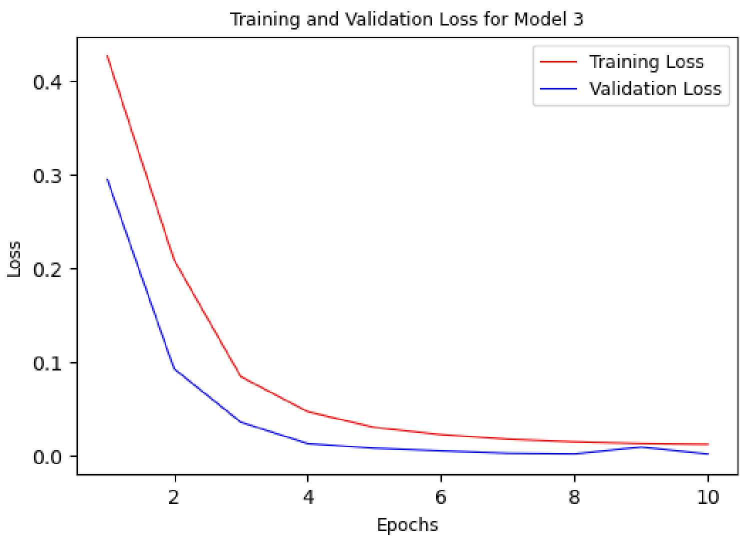

Figure 4. Comparison of Training and Validation Loss for Model 3 throughout the Epochs.

To better analyze Model 3, it is also beneficial to examine the Receiver Operating Characteristic (ROC) curve [66]. The ROC curve is an important tool for evaluating the performance of a classification model. In particular, it provides in-depth information about how well the model classifies by comparing the true positive rate and false positive rate.

The AUC (Area Under the Curve) value of the ROC curve is a metric that indicates the overall accuracy level of the model, with an AUC value of 1.0 indicating a perfect model. The success of the model increases with the number of correct classifications, while a low number of misclassifications is also important. Therefore, the ROC curve allows us to make a more comprehensive assessment than accuracy metrics alone. A model with a high AUC value demonstrates the ability to make accurate predictions despite the diversity of the data.

The shape of a ROC curve can also help determine whether a model is overfitting. If the model has overfitted to the training data, the ROC curve may start with very high accuracy and quickly approach the upper right corner. However, if the model's ability to generalize to real-world data is weak, the curve will generally not be as steep, and the false positive rate will increase. Therefore, examining the ROC curve is crucial for understanding the model's generalization capacity and reliability. Figure 5 shows the ROC curve graph for Model 3.

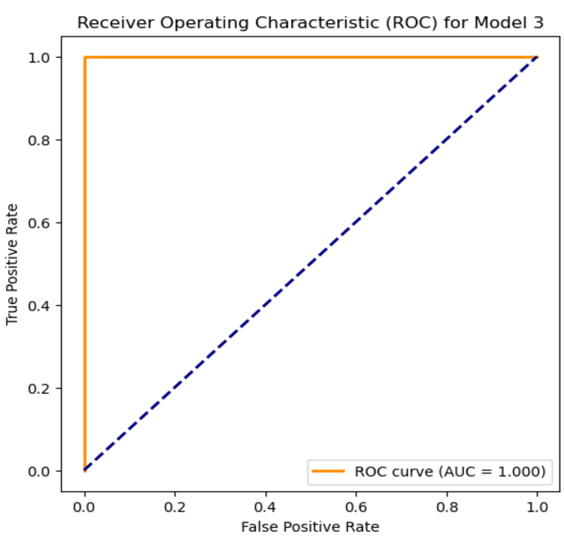

Figure 5. ROC graph for Model 3.

Looking at the ROC curve in Figure 5, the AUC (Area Under the Curve) value is indicated as 1.000. This indicates that the model has excellent discrimination power. In other words, the model is highly effective at making correct classifications, with a very low false positive rate and a very high true positive rate. This result shows that the model provides high accuracy in correctly detecting DDoS attacks. The steep shape of the ROC curve proves that the model performed excellently on the training data and is consistent with the test data. When the AUC value is this high, the likelihood of the model overfitting on the test data is low. The model appears to have a high generalization capacity and does not suffer from overfitting. The confusion matrix for Model 3 also supports this view. Figure 6 presents the confusion matrix for Model 3.

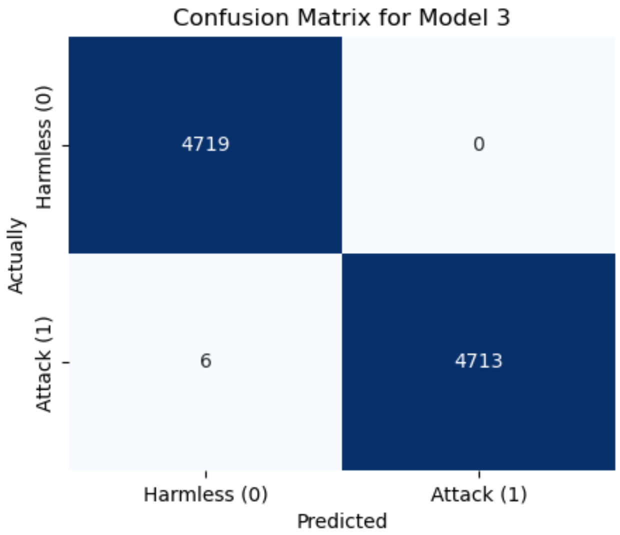

Figure 6. Confusion matrix for Model 3.

Figure 6 shows that the model is quite successful. In particular, the false positive count being 0 indicates that the model correctly distinguishes harmless data and does not generate false alarms. On the other hand, the false negative count being only 6 indicates that the model mostly correctly detects data in the attack class, but very rarely fails to correctly detect some attacks. This matrix confirms that the model has high generalization ability, avoids overfitting, and is quite successful in correctly classifying the data. To better understand the model's performance, it must also be evaluated in terms of metrics other than accuracy. Table 5 presents the Accuracy, Precision, Recall, and F1 score values for all models in the study.

Table 5. The metrics of all models in the study.

Model	Accuracy	Precision	Recall	F1 Score
1	0.99937	1.0	0.99894	0.99947
2	0.99936	1.0	0.99872	0.99936
3	0.99941	1.0	0.99872	0.99936
4	0.99925	1.0	0.99851	0.99925
5	0.99925	1.0	0.99851	0.99925
6	0.99937	1.0	0.99894	0.99947
7	0.99904	1.0	0.99809	0.99904
8	0.99925	1.0	0.99851	0.99925
9	0.99947	1.0	0.99894	0.99947
10	0.99872	1.0	0.99745	0.99872
11	0.99936	1.0	0.99872	0.99936
12	0.99925	1.0	0.99851	0.99925

According to the metrics presented in Table 5, all models have generally performed quite well. The results in metrics other than Accuracy, which also deserve attention, reflect the effectiveness of the models more comprehensively. It is possible to say that FFNN models generally performed well. Although LSTM is an architecture designed to learn long-term dependencies, it stood out in this study with long training times and high loss values. This result caused LSTM models to perform weaker than FFNN models. Since most models had Precision, Recall, and F1 Score values close to 1.0, it is possible to say that each model performed excellently in accurately detecting DDoS attacks.

The FFNN architecture has generally attracted attention with its high accuracy and low loss values. Models 3 and 6 are the models with the best accuracy and F1 Score values, and these models have achieved quite good results with precision, recall, and F1 score values close to 1.0. This result shows that the false positive and false negative rates of the models are very low. This means that they show high sensitivity in correctly identifying DDoS attacks.

Although the LSTM architecture, as in Model 7, offers an approach to learning long-term dependencies, in this study, it generally stood out with long training times and high loss values. Although Model 7 achieved the lowest accuracy with an accuracy value of 99.04%, its precision and recall values are still very high. However, the slight drops in the F1 Score imply that the model cannot generalize effectively enough and that the training process is too long.

While there is no significant difference between FFNN and LSTM architectures, it has been observed that training times and optimization algorithms affect model performance. In particular, obtaining lower loss values in models using the Adam optimization algorithm demonstrates that this algorithm is an effective option for tasks such as DDoS attack detection.

On the other hand, models using SGD took longer training times, and performance required more epochs to reach the same accuracy level. These findings provide important insights into how various factors, from architectural choices to optimization algorithms, affect model performance. This study has yielded more efficient results compared to many other studies previously found in the literature. Table 6 presents a comparison of this proposed study and previous studies.

Table 6. Comparative Performance Analysis of Our Study and Previous Studies Using Various DDoS Datasets and Techniques.

Study	Dataset	Technique	Accuracy
Our Study	***DDoSGedik30K***	FFNN LSTM	***0.999***
[14]	BOUN DDoS Dataset	K-Means	98%
[15]	Kaggle DDoS Attack Network Logs Dataset	MLP	99%
[16]	CICIDS2017 & CICDDoS2019	RF	99.9%
[19]	Combined dataset	MLP	98.99%
[20]	CICIDS2017	MLP	99.9%
[21]	CICIDS2017	XGB-DDoS	0.999
[22]	CICDDoS2019	SVM	0.99
[23]	NSL-KDD	CNN	97.7%
[24]	UNSW-NB 15 & UNSW-2018 Botnet	RF	100%
[26]	Simulation data with Hping3	C4.5	98.8%
[30]	ISCX'12	3LSTM	98.41%

When examining Table 6, it becomes evident that this study has several advantageous aspects from various perspectives. Evaluating the datasets, it can be observed that while datasets commonly used in other studies, such as Kaggle, CICIDS2017, CICDDoS2019, and NSL-KDD, are popular, the DDoSGedik30K dataset provides a unique diversity as it is derived from various firewall configurations in real-world scenarios. Compared to other publicly available datasets, DDoSGedik30K stands out as a more original dataset.

Regarding the techniques employed, it is noted that other studies predominantly utilize methods like K-Means, MLP, RF, CNN, and SVM. It has been observed that RF and MLP achieved high accuracy rates in other studies. However, it is also evident that the LSTM and FFNN architectures used in this study easily reached similar accuracy levels. The richness of the DDoSGedik30K dataset and the correct hyperparameter optimizations have resulted in competitive outcomes compared to other studies. This success highlights the power of deep learning models in detecting complex attacks when compared to results obtained using traditional machine learning algorithms in other datasets.

In examining the work of Erhan and Anarım [14], it is seen that the BOUN DDoS dataset includes only TCP SYN flood attacks. This indicates that the study focuses solely on a single type of DDoS attack. In contrast, the DDoSGedik30K dataset encompasses a broader spectrum of attack types (DDoS, SQL, Port Scan). Traditional algorithms, such as K-Means, used in the relevant study may prove to be much less effective compared to the deep learning models employed in this study. Since network traffic involves a continuous data stream, models capable of learning sequential data, such as LSTM, may perform better than methods like K-Means or SVM. Lazaris and Prasanna's work [64] explains that LSTM yields better results compared to algorithms like K-Means and SVM. In other studies, models capable of time series analysis, such as LSTM, are sometimes either not used or less optimized. In the study conducted by Asarkaya et al. [15], various machine learning algorithms (KNN, SVM, MLP, RF) were tested using the DDoS dataset available on Kaggle. Although the Kaggle dataset is large, its common usage means its structure is generally well-known, and potentially over-optimized models may have been tested on this dataset. The DDoSGedik30K dataset, however, is original and based on real-world scenarios, incorporating simulation attacks, which enhances the model's generalization capability. While KNN, SVM, and MLP can demonstrate strong performance in many cases, they are not suitable for time series analysis. An architecture like LSTM performs better with sequential data such as network traffic. Therefore, the traditional methods used in the work by Asarkaya et al. may be inadequate in understanding time-dependent DDoS attacks.

Zekri et al. [26] achieved a 98.8% accuracy using the C4.5 decision tree algorithm in a cloud environment. However, this study has some weaknesses. The C4.5 algorithm was tested on data simulated through Hping3, but this dataset may not accurately reflect real-world network attacks. In contrast, the DDoSGedik30K dataset has been enriched with attack scenarios and vulnerabilities that closely resemble real-world conditions. Additionally, while decision trees may succeed in simpler data structures, deep learning models are better suited to learning complex attack patterns and time-dependent data. According to Table 5, the C4.5 algorithm does not possess as strong a learning capacity as LSTM and FFNN. Usmani et al.'s work also supports this assertion [65], showing that while decision trees may be faster, LSTM models achieve better accuracy in detecting complex attack patterns.

When examined for vulnerability simulation and realistic attack scenarios, this study is superior to the other studies compared. During the dataset creation, deliberately disabling firewall rules at times to create vulnerabilities was one of the most distinguishing factors of DDoSGedik30K. While most studies collect their datasets in static and secure environments, this study includes vulnerabilities that one might encounter in real life. This approach has increased the resilience of deep learning models against more diverse and realistic attacks.

In conclusion, this study provides significant superiority over other DDoS detection studies due to factors such as the originality, realism, and richness of the DDoSGedik30K dataset, the high performance of deep learning techniques like FFNN and LSTM, careful hyperparameter optimization, the use of models suitable for time series analysis, and the inclusion of a wider range of attack types.

7. CONCLUSION

This study examines deep learning models developed to detect DDoS attacks. It clearly demonstrates that all models achieved an accuracy rate exceeding 99.9% and performed effectively in detecting DDoS attacks. This success is of significant importance, especially in a critical area such as cybersecurity, as it aids in ensuring network security and in the early detection of potential threats. Since the accuracy rates are at the same level, metrics such as loss value, training time, optimization algorithm, and learning rate were evaluated to distinguish the models. These results serve as an important guide for selecting the most suitable model for various scenarios in security applications.

While there is no significant difference between FFNN and LSTM architectures, it has been found that LSTM requires longer training times due to its more complex structure. The ability of LSTM models to better learn long-term dependencies has balanced the need for more epochs. However, the longer training times of these models stand out as a factor that must be considered, especially in real-time applications.

The DDoSGedik30K dataset used in the study is considered an important resource for cybersecurity research. This dataset has been carefully prepared to cover various scenarios related to DDoS attacks, allowing the models to demonstrate performance close to real-world conditions. The high quality and diversity of the dataset have enhanced the effectiveness of the models and enabled more realistic results to be obtained during the training processes.

Future work may propose further expanding the dataset and diversifying it to include different types of attacks. The development of real-time DDoS detection systems and the integration of these systems into existing cybersecurity infrastructures should be one of the focal points of future studies. In conclusion, this study provides a significant contribution that demonstrates the effectiveness of deep learning techniques in the field of cybersecurity and offers new approaches for the detection of DDoS attacks. With its contributions to the literature and the dataset it presents, this study will serve as a guide for future research.

Acknowledgements

This work was supported by Scientific Research Projects Coordination Unit of Istanbul Gedik University, Project number "GDK202207-32".

Conflict of Interest

The authors declare no conflicts of interest.

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September 2025, Vol:3, Issue:2

International Journal of New Findings in Engineering, Science and Technology

journal homepage: https://ijonfest.gedik.edu.tr/

Received:17.06.2025 Accepted:30.07.2025 Pablished:29.09.2025

Strategic Assessment of Ergonomics in Jordan's Maritime Operations: Safety and Productivity Perspectives

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Abstract

This study examines the impact of ergonomic interventions on workplace safety and productivity within a sea freight forwarding company operating in Aqaba and Amman, Jordan. The research aimed to identify key ergonomic risk factors affecting employees and to evaluate targeted interventions designed to reduce physical discomfort, enhance job satisfaction, and improve operational performance. A mixed-methods approach was employed, integrating quantitative data from structured questionnaires covering demographics, physical pain, job satisfaction, ergonomic support, and fatigue with qualitative insights from employee interviews. Physical risk levels were assessed using the Rapid Entire Body Assessment (REBA) tool, while company records on safety incidents, absenteeism, and productivity were analyzed to triangulate findings. The study involved 120 participants across administrative and operational roles. Statistical analyses, including descriptive statistics, paired t-tests, and ANOVA, were applied to compare pre- and post-intervention data. Results indicated a significant reduction in musculoskeletal complaints and fatigue, accompanied by notable improvements in perceived job satisfaction, productivity, and safety outcomes. The findings underscore the importance of integrating ergonomic strategies into logistics operations and offer evidence-based recommendations for improving employee well-being and organizational efficiency.

Keywords: Ergonomic Management, Workplace Safety, Productivity, REBA Assessment, Musculoskeletal Disorders.

1. INTRODUCTION

Organizations are continuously seeking methods to enhance productivity while ensuring the health and safety of their workforce in today’s competitive environment. One vital strategy to achieve this balance is the implementation of effective ergonomic interventions. Ergonomics involves designing work environments that align with employees’ physical and mental capacities to reduce stress, prevent injuries, and optimize human performance, thereby enhancing both productivity and safety. Unresolved workplace safety issues directly reduce productivity, highlighting the importance of ergonomic considerations [1]. Similarly, poor ergonomic design, such as inadequate furniture or non-ergonomic seating, leads to discomfort, musculoskeletal pain, and overall declines in worker well-being [2].

In the sea freight and shipping industry, ergonomic risks are particularly pronounced due to the physically strenuous nature of maritime operations, prolonged standing, heavy lifting, repetitive movements, and the confined workspaces found aboard vessels and in warehouses. Office-based roles in freight forwarding companies also face challenges from poorly designed workstations and extended screen time. Despite these risks, limited empirical research has explored ergonomic interventions in the maritime industry [3]. Addressing this gap is crucial for enhancing worker well-being and operational efficiency in freight environments.

Extensive research has been conducted across various sectors on the relationship between ergonomics, worker safety, and productivity. However, its application in ocean freight forwarding—whether in operational or administrative environments—remains limited. Employees in this sector face considerable health and safety Challenges stemming from physically demanding roles, long shifts, and high-risk settings. Musculoskeletal disorders, fatigue, and psychological stress are particularly prevalent, leading to decreased job satisfaction, increased accident risk, and lower efficiency. Workplace ergonomics is essential for minimizing injury risk and maintaining consistent productivity [4]. Ergonomic improvements can boost comfort, reduce fatigue, and enhance performance [5], while poor ergonomics is associated with injury, fatigue, and significant productivity losses [6].

The economic and operational consequences of poor ergonomics are substantial. Globally, billions of dollars are lost annually due to preventable inefficiencies and accidents. In 2016, an estimated 1.9 million people died from work-related injuries and illnesses [7]. Over 340 million work-related accidents and 160 million cases of occupational diseases occur every year [8]. In Indonesia alone, there were 225,000 reported work accidents and 53 job-related illnesses in 2020, with another 82,000 accidents and 179 illnesses reported between January and September 2021 [9].

2. LITERATURE REVIEW

This section critically examines existing research on the impact of ergonomic interventions on workplace safety and productivity, with a focus on their application in both office and operational settings within the sea freight forwarding industry. It explores the three core dimensions of ergonomics-physical, cognitive, and psychosocial and highlights how these principles are applied across various work environments. The review integrates global and industry-specific perspectives, drawing from occupational health, human factors, and organizational studies, to identify key trends, research gaps, and practical implications. Special attention is given to the unique ergonomic challenges of the maritime and logistics sectors, setting the foundation for this study's contribution to improving safety and efficiency in high-demand environments [10].

To provide a structured overview of recent contributions in the field, Table 1 summarizes key empirical studies related to ergonomic interventions, their methodologies, and findings on workplace safety, productivity, and worker well-being, with a focus on applications relevant to office settings and the sea freight forwarding industry.

Table 1. Recent Studies on Ergonomics Intervention on Productivity and Safety in the Sea Freight Sector.

Ref.	Year	Authors	Study Purpose / Focu	Methods	Key Findings
[1]	2023	Johnson and Widyanti	Effects of ergonomic interventions on mental workload and fatigue in logistics workers	Quasi-experimental with ergonomic adjustments and surveys	Ergonomic design and flexible schedules significantly reduce mental fatigue and improve productivity.
[2]	2018	Sorensen, Stanton and Banks	Impact of continuous cognitive training on decision-making and fatigue resilience	Longitudinal training program with high-stress workers	Ongoing cognitive training enhances resilience reduces errors, and improves job satisfaction.
[3]	2021	Hwang et al.	Relationship between occupational stress and fatigue in port workers	Cross-sectional survey and physiological stress measures	High job stress correlates strongly with chroni fatigue and increased accident risk
[4]	2020	Chen et al.	Effects of mental workload on maritime operators' performance	Simulated task experiments with EEG and subjective workload scales	Increased mental workload decreases vigilance and decision accuracy; automation helps reduce load.
[5]	2019	Puthran et al.	Stress, fatigue, and burnout in shipping industry workers	Mixed-methods survey and interviews.	High workload and poor sleep quality are linked to burnout and increased error rates.

[6]	2022	Kim and Kim	Use of ergonomic interventions to reduce musculoskeletal and cognitive fatigue in logistics workers	Field study with ergonomic adjustments and pre/post assessments	Ergonomic chairs and task redesign significantly lowered reported fatigue and improved work quality.
[7]	2023	Torres and Ferreira	Role of cognitive workload and fatigue in maritime navigation errors	Case study analysis and fatigue monitoring	Fatigue and cognitive overload contribute to navigation errors; recommendations include rest breaks and training.
[8]	2018	Bener et al.	Effects of stress management programs on fatigue and productivity	Controlled intervention study in the transportation sector	Stress management programs reduced fatigue and absenteeism, boosting overall productivity. .
[9]	2022	Wang et al.	Impact of automation and decision support systems on cognitive workload	Experimental simulation with port operators	Decision support systems significantly reduce cognitive workload and improve task accuracy .
[10]	2021	Ng and Smith	Fatigue-related accident risk factors in maritime shipping	Retrospective analysis of accident and fatigue reports	Fatigue-related accidents are associated with excessive shift lengths, sleep deprivation, and high job demands.

Source: Edited by the authors.

2.1 The Roadblock to Sustainable Workplace Ergonomics in Sea Freight Forwarding

The sea freight forwarding industry serves as a critical link in global supply chains, requiring high operational efficiency and human performance under often challenging working conditions. Despite increasing awareness of ergonomics, many freight companies continue to struggle with implementing and sustaining effective ergonomic interventions. This study examines the multifaceted barriers to ergonomics integration in the maritime logistics sector, with a focus on worker well-being, safety, and operational productivity [11].

2.1.1 Physically Demanding and Repetitive Work Environments

Sea freight forwarding involves tasks such as heavy lifting, prolonged standing, awkward postures, and repetitive motions—conditions known to increase the risk of musculoskeletal disorders (MSDs). The persistence of these conditions, especially on docks and in cargo handling zones, poses a pressing concern for physical fatigue and long-term injury [12].

2.1.2 High Variability in Work Conditions

Unlike office-based settings, the maritime logistics environment is highly dynamic. Variations in cargo types, vessel configurations, weather, and workload intensity create unpredictable ergonomic demands. This variability complicates the standardization and consistency of ergonomic solutions [13].

2.1.3 Lack of Awareness and Training

Ergonomics is often misunderstood or under-prioritized in this industry. Many employees, as well as supervisors, are not fully aware of ergonomic risk factors or preventive strategies. As a result, interventions may be underutilized or misapplied, thereby reducing their potential impact [14].

2.1.4 Operational Pressures and Resistance to Change

Freight forwarding companies operate under tight schedules and cost constraints. Management often perceives ergonomics as a non-essential or disruptive cost, particularly if short-term productivity must be sacrificed for long-term benefits. This contributes to resistance to ergonomic investments [15].

2.1.5 Absence of Tailored Standards

Many available ergonomic guidelines are developed for office or general industrial settings and fail to address the specific challenges of maritime logistics. This gap hinders the effective implementation of standardized interventions [16].

2.1.6 The Role of Ergonomic Risk Assessment Tools

To address these issues, this study integrates the **Rapid Entire Body Assessment (REBA)** tool to evaluate ergonomic risks across various job roles. REBA provides a structured method for quantifying postural risks and prioritizing corrective actions in real-world freight operations [17]. Figure 1 and 2 shows how the risk score changes before and after ergonomics.

2.1.7 Linking Ergonomics to Productivity and Safety Outcomes

Through a mixed-methods approach, this research examines the impact of ergonomic interventions on not only physical discomfort and injury rates but also job satisfaction, fatigue levels, and productivity.

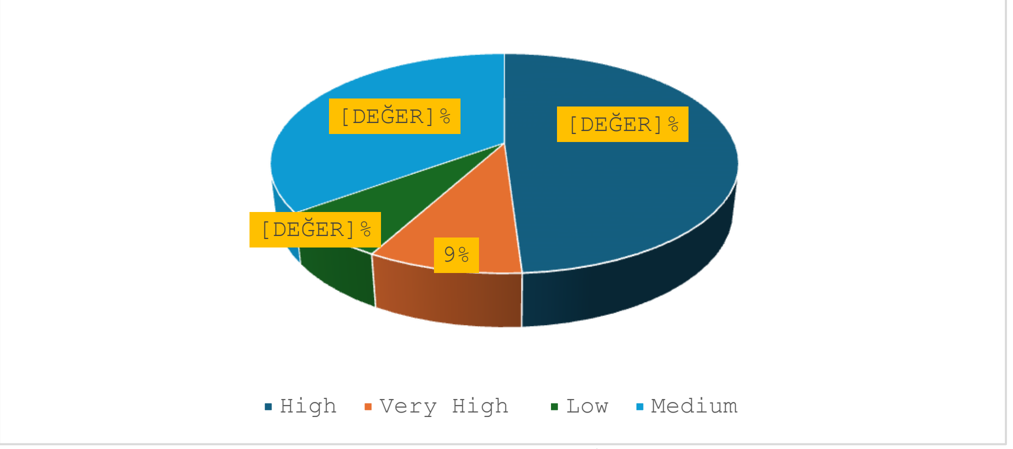

Figure 1. Risk Scores Before Evaluation.
Source: Created by authors.

By comparing pre- and post-intervention metrics, the study aims to establish a data-driven justification for ergonomics implementation in sea freight settings [18].

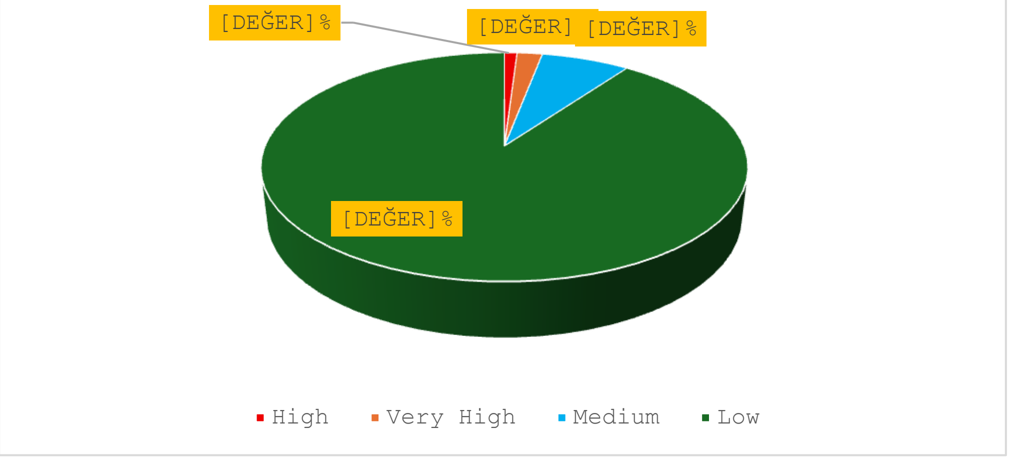

Figure 2. Risk Scores After Evaluation.
Source: Created by authors.

2.1.8 Musculoskeletal Disorders

Musculoskeletal disorders (MSDs) are injuries or conditions that affect the musculoskeletal system, which encompasses muscles, nerves, tendons, ligaments, joints, and supporting structures, such as the neck and back. When these disorders are triggered, worsened, or extended due to work activities, environments, or conditions, they are categorized as Work-Related Musculoskeletal Disorders (WMSDs). MSDs are recognized as a significant occupational health concern globally. For instance, a study identifies MSDs as one of the most prevalent work-related issues, with a higher incidence among male full-time workers compared to females [19]. Similarly, data shows that approximately 470,000 workers suffer from WMSDs, whether new or pre-existing [20]. In developing countries like Nigeria, WMSDs are particularly prevalent in sectors such as transportation, warehousing, manufacturing, healthcare, agriculture, and construction. MSDs are also considered the largest Occupational Health and Safety (OHS) issue in many countries. Recent studies attribute their persistent prevalence in Europe to significant gaps in workplace practices, particularly "shortcomings in risk assessment and prevention practices" and the exclusion of psychosocial risks from the assessment process [21]. These findings align with earlier research that highlights the ongoing challenges in addressing MSDs effectively [22]. For a better understanding of the multifaceted nature of work-related MSD hazards, Figure 3 shows a model outlining the key factors influencing MSD risk, categorized into biomechanical, organizational, and psychosocial dimensions [23].

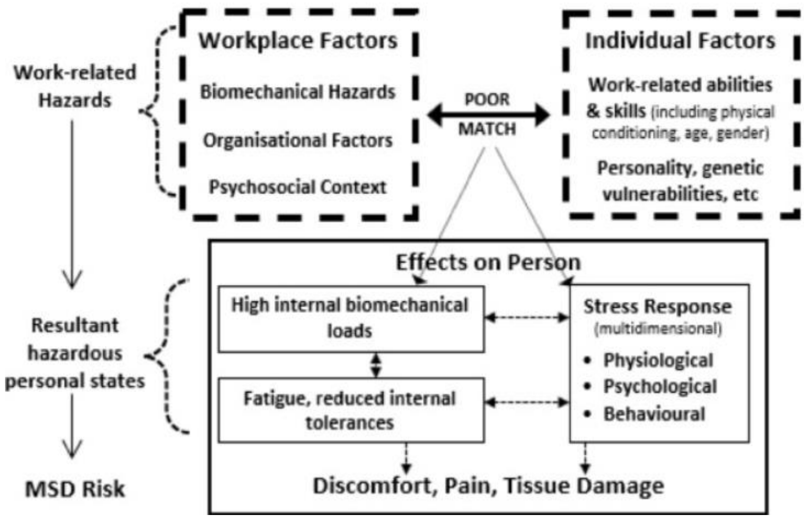

Figure 3. Model of Factors Affecting MSD Risk.
Source: McDonald and Oakman, (2015).

This figure provides a detailed view of the interconnected pathways through which psychosocial hazards and other workplace or individual factors influence MSD risks. It highlights how these risks arise from internal biomechanical loads and the multidimensional stress response, encompassing physiological, psychological, and behavioral aspects. These factors often interact, with stress amplifying exposure to biomechanical hazards, such as poor posture or repetitive actions under pressure [24].

Building on this understanding, it is essential to explore the broader stress-related pathways through which psychosocial hazards contribute to MSD risks. While the previous discussion emphasized the interaction of psychological and behavioural responses with biomechanical hazards, further attention is warranted on the direct physiological effects of the stress response. Figure 4 simplifies these physiological pathways, demonstrating how stress impacts key musculoskeletal functions through mechanisms such as connective tissue dysfunction and related pain [25].

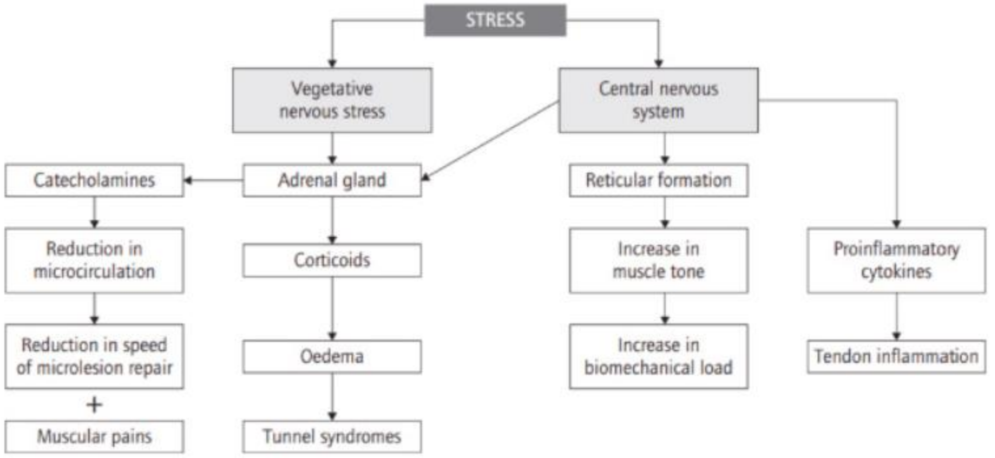

Figure 4. Stress-Mediated Physiological Pathways Contributing to MSD Susceptibility.
Source: Roquelaure (2018) and Aptel et al. (2011).

2.1.9 Awkward Posture

Awkward posture is a significant ergonomic risk factor that contributes substantially to musculoskeletal disorders (MSDs) and reduced worker productivity. It occurs when workers adopt body positions that deviate from neutral alignment, such as excessive bending, twisting, or reaching, which place undue stress on muscles, tendons, and joints [25]. Prolonged or repetitive exposure to awkward postures can lead to muscle fatigue, discomfort, and, over time, chronic injuries such as tendonitis and lower back pain [26]. In logistics and sea freight operations, workers frequently assume awkward postures while handling cargo, operating machinery, or performing tasks in confined spaces, increasing their risk of injury [27]. Research has consistently shown that awkward postures not only affect physical health but also impair job performance by reducing efficiency and increasing error rates [28]. Interventions such as ergonomic redesign of workstations, proper training on safe postures, and the use of assistive devices have proven effective in mitigating these risks [29]. Addressing awkward posture is, therefore, essential in developing comprehensive ergonomics programs aimed at enhancing worker safety, reducing absenteeism, and improving overall productivity in the maritime and logistics industries [30].

2.1.10 Impact of Ergonomics on Employee Performance

Furniture designed with ergonomic principles can boost employee productivity and lower the risk of workplace injuries [31]. Similarly, the National Safety Council found that about one million employees miss work daily due to job-related stress [32]. Approximately 86% of productivity issues are linked to workplace conditions, which play a key role in shaping employee performance [33]. The type of work environment employees experience influences organizational success. While factors such as recognition, financial rewards, and compensation are important, research indicates that the workplace environment is a significant factor in employee motivation and productivity. A poor work environment can negatively impact employee health, safety, creativity, collaboration, and attendance, and can even affect employee retention. Furthermore, work systems not only impact productivity and costs but also have long-term effects on employees' physical and mental health, as well as their overall life expectancy [34], [35]. Many business leaders mistakenly believe that employee performance is directly tied to compensation packages. While salary and benefits act as extrinsic motivators, their influence on performance tends to be short-lived. It is more widely accepted that a well-designed workplace environment can inspire employees and lead to better outcomes [36]. A functional and aesthetically pleasing workspace often results in greater efficiency and productivity. Consequently, many organizations have shifted their office designs and furnishings to prioritize employees' needs, ensuring workplace conditions, including furniture and equipment, effectively support and enhance performance. The drive to provide an optimal workplace environment, along with suitable furniture, equipment, tools, and techniques, forms the core principle behind ergonomics. Employee performance is commonly assessed by output, which directly links to overall productivity. At an organizational level, productivity is influenced by employees, technology, and goals. Additionally, the physical work environment plays a critical role, impacting both employee health and performance [37]. Figure 5 illustrates how applying ergonomics has enhanced worker productivity, health, and safety in the work environment [38].

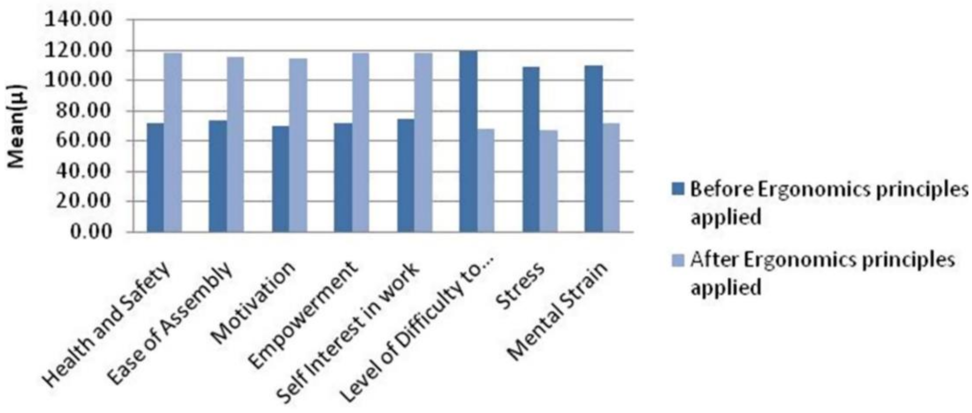

Figure 5. Workplace Ergonomics Transformation: A Multidimensional Before-After Comparison.
Source: Int. J. (2004).

2.1.11 Role of Ergonomic Interventions in Enhancing Productivity

By providing healthier and more productive working environments, ergonomic interventions are essential to maximizing workplace productivity. Studies show that ergonomics improves task performance by lowering injury risk, increasing comfort, and reducing workplace fatigue. For example, ergonomic training and adjustable workstations have been shown to enhance productivity and decrease musculoskeletal pain greatly [39]. Customized ergonomic interventions were found to result in a 17% increase in job productivity [40]. A survey of 282 industrial workers examined working postures and conditions, revealing that most employees worked with their shoulders and hands at chest level while slightly bending their backs forward. The study found that frequent lifting of loads around 5 kg raises concerns about workplace ergonomics and the potential for injuries. Musculoskeletal disorders were identified as a significant issue, often impairing productivity due to back injuries. Results showed 93.1% of workers reported physical fatigue and 94.2% experienced mental exhaustion. Key postures observed included 30.1% shoulder engagement, 90.8% back involvement, and lifting weights of 1 to 5 kg in 80.5% of cases. Statistical analysis indicated a strong correlation between workplace conditions and physical injuries. However, the absence of a standardized working posture for industrial employees was noted, providing crucial baseline data for future studies to ensure proper working postures, minimize injuries, and improve productivity [41].

2.1.12 Challenges and Barriers in Ergonomics Implementation

Implementing ergonomic solutions in the workplace can be challenging due to various organizational, financial, and cultural barriers. Many companies encounter issues such as the costs associated with ergonomic changes, resistance from management or employees to adapt, and a lack of awareness about the long-term benefits. However, studies show that overcoming these challenges leads to improved employee health, reduced absenteeism, increased productivity and safety, and lower costs [42].

2.1.13 *Research Gap and Sectoral Justification*

Despite the growing body of research on workplace ergonomics, comparisons between the sea freight sector and other high-risk industries such as construction and aviation remain limited in the existing literature. To position this study within a broader occupational safety context, the following discussion highlights how the maritime environment compares to these sectors and why it warrants focused ergonomic investigation.

While sectors such as construction and aviation have received considerable attention in ergonomic and occupational safety research due to their high-risk nature, the sea freight forwarding industry remains underrepresented despite facing similar, if not more complex, ergonomic challenges. Like construction, maritime workers are frequently exposed to heavy manual handling, awkward postures, and variable environmental conditions [43]. Unlike aviation, where high regulatory oversight enforces strict ergonomic standards, the sea freight sector often operates with fewer standardized interventions, especially in developing economies. This study addresses that gap by focusing on ergonomic risks and interventions specific to sea freight operations in Jordan, aiming to extend the ergonomics literature to a sector with substantial operational and physical demands yet limited ergonomic policy development.

2.1.14 Theoretical Frameworks in Ergonomics

To strengthen the theoretical underpinnings of this research, two foundational ergonomic theories are incorporated. First, the Human-System Integration (HSI) Framework emphasizes the joint optimization of human capabilities and system performance, particularly in complex and high-risk environments, such as maritime operations. It supports the alignment of ergonomic interventions with technological and organizational systems to reduce cognitive and physical strain [44]. Second, the Sociotechnical Systems (STS) Theory offers a broader lens by recognizing that worker well-being and productivity are shaped by the interaction between social structures (e.g., teamwork, communication, culture) and technical systems (e.g., equipment, tools, workflows) [45]. Integrating these theories helps contextualize ergonomic challenges in sea freight forwarding as outcomes of misalignment between human, technological, and organizational elements, especially relevant in developing economies where system optimization is often lacking.

3. METHODOLOGY

This study assesses the effectiveness of ergonomic changes in the maritime shipping industry, employing a mixed-methods research design that integrates quantitative and qualitative techniques. To statistically analyze the impact of ergonomic modifications on key outcomes, such as worker well-being, safety, and productivity, the quantitative component focuses on gathering numerical data through structured surveys, ergonomic risk assessments, productivity and safety records. For ergonomic risk assessment, the Rapid Entire Body Assessment (REBA) method will be employed, with a particular emphasis on assessing strain associated with posture in various job tasks. By analyzing body position, force, and repetition, REBA is a well-known method for determining a person's risk of developing musculoskeletal disorders (MSDs). It classifies the degree of ergonomic risk using a score system, which helps identify high-risk locations that require solutions. Because it provides an objective, standardized measure of ergonomic strain across various jobs in the maritime environment, the REBA instrument is particularly well-suited for our study. A validated questionnaire with a 5-point Likert scale will be used to gauge aspects such as job satisfaction, opinions about ergonomic treatments, physical discomfort, and any health changes resulting from the interventions in the surveys. The questionnaire will record more specific metrics, such as musculoskeletal complaints and perceived improvements in work conditions, in addition to job satisfaction and physical discomfort. Employees will be interviewed briefly to gather qualitative data. Participants will be able to express their viewpoints and experiences with the ergonomic adjustments made during these interviews. A more comprehensive understanding of employees' opinions regarding the efficacy of ergonomic interventions and the identification of any obstacles to their successful implementation is made possible by the qualitative component, which complements the quantitative data. A sample size of 120 people will be included in the study, guaranteeing a representative and varied group from a range of positions within the organization. The purpose of this sample size is to enhance the generalizability and dependability of the findings across various roles within the maritime shipping industry. To enable a thorough examination of the effects of ergonomic interventions throughout the company, the sample will be carefully chosen to guarantee a balance between gender and work roles (such as cargo handlers, supervisors, and administrative staff). Additionally, a larger sample size will enable more thorough statistical analysis, thereby increasing confidence in the findings and their generalizability to the workforce. Data will be gathered at a particular point in time using a cross-sectional study design. This design is ideal for identifying current workplace issues and assessing the immediate effects of ergonomic adjustments. By providing a brief overview of risk factors, worker perceptions, and ergonomic circumstances, it offers valuable insights into how ergonomic measures impact safety and productivity [44].

3.1 Data Collection

This section shows multiple data collection techniques. These include structured surveys, ergonomic risk assessments, and an analysis of safety and productivity records. Each method is designed to capture both objective and subjective insights, ensuring an overall evaluation.

3.2 Surveys and Questionnaires

Surveys and questionnaires incorporate a 5-point Likert scale, divided into both genders, measuring key factors such as:

- Physical discomfort, like musculoskeletal pain levels before and after interventions.
- Burnout and fatigue levels are like psychological strain related to poor ergonomics.
- Job satisfaction, like the impact of ergonomics on work conditions.
- Perceived ergonomic improvements, like the effectiveness of workstation modifications.

Table 2 below shows the survey used in this study in a clear form:

Table 2. Survey Structure and Measured Variables.

Section	Measured Variable	Example Question	Likert Scale Response
Demographics	Age, job role, years of experience	How many years have you worked in this company	N/A (Open-ended)
Job Satisfaction	Employee satisfaction with work conditions	How satisfied are you with the ergonomics of your workstation?	1 (Very Dissatisfied) – 5 (Very Satisfied)
Physical Discomfort	Musculoskeletal complaints and pain levels	In the past month, how often have you experienced discomfort in your back due to work?	1 (Never) – 5 (Always)
Ergonomic Interventions	Perceived effectiveness of implemented ergonomic changes	Do you feel the recent ergonomic changes have improved your working conditions?	1 (Strongly Disagree) – 5 (Strongly Agree)
Burnout & Fatigue	Psychological and physical strain due to poor ergonomics	How often do you feel physically exhausted due to job demands?	1 (Never) – 5 (Always)

Source: Created by authors.

3.3 Ergonomics Risk Assessments

To evaluate ergonomic risks associated with different job tasks, this study applied the Rapid Entire Body Assessment (REBA) tool, a widely used method for assessing whole-body postural risks in workplace environments. The REBA assessment focused particularly on job roles considered high-risk due to frequent awkward postures, repetitive movements, or forceful exertions. These included positions such as forklift operators, warehouse loaders, packaging workers, crane operators, and maintenance technicians, among others.

The REBA evaluations were conducted through direct on-site observations of workers performing their typical daily tasks. Posture angle measurements and ergonomic posture scoring sheets supported observations. Each job role was assessed based on specific task elements, including neck, trunk, and limb positions, as well as the force and movement involved. For consistency, a standardized checklist and REBA worksheet were used for each role. A total of 20 distinct job positions were analyzed as part of this ergonomic risk assessment. The REBA tool provides a numerical score that categorizes the level of ergonomic risk and guides the urgency of the required intervention. Table 3 below presents the REBA scoring system along with the corresponding risk levels and recommended actions.

Table 3. REBA Scoring System and Ergonomic Risk Levels.

REBA Score	Risk Level	Interpretation	Recommended Action
1-2	Negligible Risk	No significant ergonomic risks detected	No immediate action required
3-4	Low risk	Some ergonomic concerns, but not critical	Monitoring the situation, minor adjustments may help
5-7	Medium risk	Moderate ergonomic risk, potential strain issues	Further investigation needed, consider ergonomic interventions
8-10	High risk	Significant ergonomic risk, likely strain and discomfort	Implement immediate ergonomic improvements
11-15	Very High Risk	Severe ergonomic hazards, high probability of musculoskeletal injuries	Urgent intervention required, redesign tasks and workstations

Source: Created by authors.

3.4 Data Collection Timeline

Table 4. Data collection activities take place.

Data Collection Activity	Method	Timeframe
Surveys & Questionnaires	Online/physical distribution to employees	Week 1 – Week 3
Ergonomic Risk Assessments (REBA)	Workplace observations and assessments	Week 2 – Week 4
Productivity Data Collection	Analysis of company records	Week 3 – Week 6
Safety Data Analysis	Review of accident/injury reports	Week 3 – Week 6
Qualitative Interviews	Brief discussions with selected employees	Week 4 – Week 6

Source: Created by authors.

3.5 Sample Selection and Ergonomic Intervention

A sample of 120 participants was selected to ensure that the findings are representative of the maritime shipping workforce and can be generalized across similar settings. The study utilized a stratified purposive sampling method, whereby participants were deliberately selected based on their job roles and levels of ergonomic exposure. This approach ensured adequate representation across critical job categories, including crane operators, dock workers, supervisors, and administrative personnel. Random sampling was not applied, as the objective was to capture insights from workers engaged in varying physical and cognitive demands.

Diversity in gender and experience levels was maintained to account for potential variations in ergonomic risk perception and injury exposure. Inclusion criteria required that participants have worked in the organization for at least six months to ensure familiarity with the operational environment. Employees on short-term contracts or with serious pre-existing medical conditions that significantly impaired their work capacity were excluded to preserve data consistency. Table 5 below summarizes the participant distribution across roles and demographics.

To address workplace ergonomic challenges, a structured intervention program was implemented during the study period. This included the introduction of adjustable ergonomic chairs with lumbar support for administrative staff and anti-fatigue standing mats for workers engaged in prolonged standing tasks such as cargo handling and inspection. Workstation layout modifications were also made to reduce unnecessary bending, overreaching, and awkward postures. In addition to physical adjustments, the intervention included training workshops that focused on body mechanics, safe lifting techniques, posture correction, and the use of personal protective equipment. Educational posters and visual reminders were placed in key work areas to reinforce ergonomic best practices and support behavioral change. These measures aimed to minimize the risk of musculoskeletal disorders (MSDs), reduce fatigue, and enhance worker comfort and productivity.

Table 5. Sample Characteristics.

Category	Subcategory
Total participant	120
Job role	Dock Workers, Crane Operators, Office Staff, Supervisors
Gender Distribution	Male: XX%, Female: XX% (it will be filled after actual data)
Years of experience	6 months – 2 years, 2–5 years, 5+ years

Source: Created by authors.

3.6 Data Analysis Techniques

This study combines quantitative and qualitative data analysis methodologies to assess the effects of ergonomic modifications in marine workplaces thoroughly.

3.7 Quantitative Data Analysis

Quantitative data from surveys and ergonomic risk assessments will be statistically analyzed to identify patterns and key connections. Important methods consist of:

- Descriptive Statistics: Responses about ergonomic perceptions, physical discomfort, and job satisfaction will be compiled using metrics like mean, standard deviation, and frequency distributions.

Statistical Inference

- To evaluate changes in ergonomic risk levels and job satisfaction, t-tests will compare results before and after the intervention.
- Survey responses and ergonomic risk scores will be compared across various occupational roles using ANOVA (Analysis of Variance).
- Relationships between reported musculoskeletal problems and ergonomic improvements will be ascertained using correlation analysis.

The effectiveness of ergonomic measures will be assessed by classifying the Rapid Entire Body Assessment (REBA) scores into risk levels and statistically comparing the mean REBA values before and after interventions.

3.8 Qualitative Data Analysis

Thematic analysis, which identifies recurring patterns and significant themes in employees' responses, will be employed to examine qualitative data from brief interviews. The actions listed below will be taken:

- Classifying answers according to recurring themes (e.g., perceived efficacy of ergonomic solutions, lingering issues, and recommendations for improvement).
- Putting concepts into categories to find shared experiences among workers.
- To improve the validity of the results, triangulate with quantitative findings.

3.9 Software and Tools

Excel will be used to organize and visualize data trends, while SPSS will be used for statistical computations. Thematic analysis will be coded manually or, if necessary, with the aid of qualitative analysis tools.

3.10 *Ethical Consideration*

Strict ethical rules are followed in this study to respect the rights of participants and maintain the integrity of the research process. The study will adhere to the following ethical guidelines:

3.11 *Knowledgeable Consent*

Before participating, each participant will receive a thorough description of the study's goals, methods, and potential risks. There will be a consent form available that explains in detail:

- The fact that participation is voluntary
- The freedom to leave at any moment without facing any repercussions
- The privacy of their answers

Before participating in the study, participants must sign the consent form.

3.12 *Data Protection and Confidentiality*

To protect participant anonymity and privacy:

- There won't be any collection of personally identifiable information.
- Encrypted devices will be used to safely store and code data.
- Only authorized researchers will have access to raw data.
- Transcripts of interviews and survey answers will be anonymized prior to analysis.

3.13 Ethical Approval

Before data collection begins, this study will apply for approval from the relevant institutional ethics committee. Research governance bodies' ethical criteria will be adhered to in all study procedures.

3.14 *Preventing Injury*

Participants won't experience any physical or psychological harm according to the study's design. The following measures will be taken to reduce any possible pain associated with participating in a survey or interview:

- Survey questions that are impartial and unambiguous
- The option to skip any question they do not wish to answer

3.15 Data Retention and Disposal

According to institutional policies, the collected data will be securely stored for a specified period before being irretrievably erased at the conclusion of the study. Digital files will be safely deleted, and any physical documents will be destroyed by shredding.

4. DISCUSSION OF THE RESULTS

4.1 Demographic Overview

The study included a diverse sample of 120 participants working in various roles within the port industry. The distribution of gender and job roles among participants is presented in Table 6 below.

Table 6. Sample Characteristics of Participants. Demographic Variable.

Demographic Variable	Subgroup	Frequency	Percentage %
Gender	Male	86	71.7%
	Female	34	28.3%
Job role	Crane operators	25	20.8%
	Dock workers	30	25%
	Admin and logistics staff	28	23.3%
	Mechanics and technicians	22	18.3%
	supervisors and managers	15	12.5%
Experiences	Less than 1 year	14	11.7%
	1-3 years	33	27.5%
	4-7 years	41	34.2%
	More than 7 years	32	26.6%

Source: Created by authors.

The demographic distribution reveals a predominantly male workforce (71.7%), which is consistent with trends in the maritime and logistics sectors, where physical demands and traditional role assignments often result in male-dominated environments. However, the presence of 28.3% female participants indicates a degree of gender diversification. In terms of job roles, dock workers (25%) and crane operators (20.8%) comprised the largest groups, reflecting the company's operational focus. Administrative and logistics staff also comprised a significant portion (23.3%), ensuring that both physical and organizational perspectives were captured. The experience levels of participants were well distributed, with the largest group having 4–7 years of service (34.2%), followed by those with over 7 years (26.6%). This balance between experienced and newer employees provides a comprehensive understanding of how ergonomic conditions are perceived across tenure levels.

4.2 Job Satisfaction

This section presents the findings from survey questions regarding employees' job satisfaction and ergonomic conditions within the maritime shipping company. Feedback was gathered using a 5-point Likert scale, with options ranging from 1 (Very Dissatisfied) to 5 (Very Satisfied). Participants responded to questions evaluating their satisfaction with the design of their workspace, the comfort of their seating, the usability of the equipment, and overall work conditions. A total of 120 individuals participated in this section.

To visually represent the results, Figure 6 illustrates the average score for each aspect of job satisfaction, providing a clear overview of employee perceptions regarding their work environment.

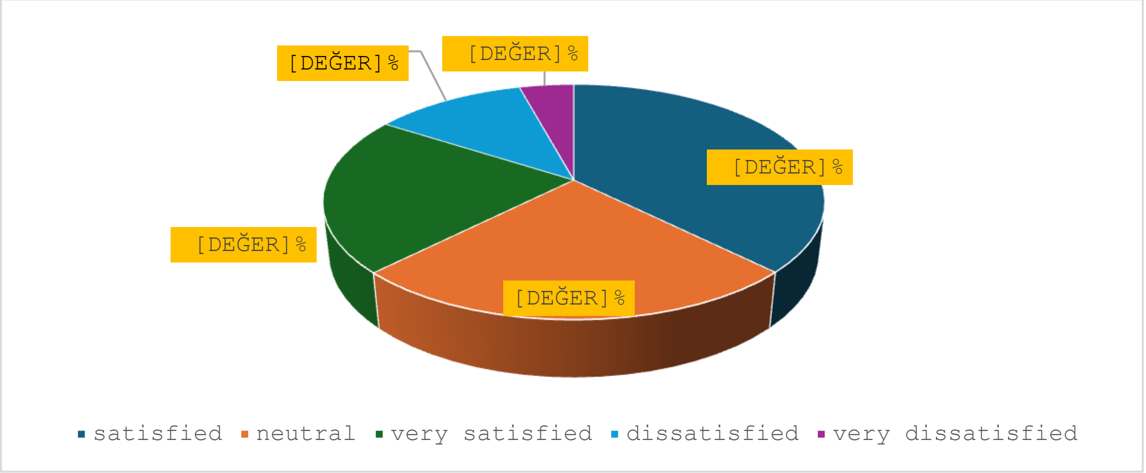

Figure 6. Distribution of Responses for Overall Satisfaction with Ergonomic Conditions.
Source: Created by authors.

The distribution of responses shows that a majority of participants expressed satisfaction with ergonomic conditions in the workplace. Specifically, 37.5% reported being satisfied and 21.7% very satisfied, indicating that nearly 60% of the workforce holds positive views about their ergonomic environment. Meanwhile, 25% selected neutral, suggesting a significant portion may perceive room for improvement but are not strongly dissatisfied. Notably, 11.7% of respondents indicated dissatisfaction, and 4.2% reported being miserable, suggesting a minority whose ergonomic needs may not be fully addressed and who may benefit from targeted interventions.

To improve clarity and eliminate repetition, a single pie chart has been included in this subsection to depict the response distribution for the question about "Overall satisfaction with ergonomic conditions." This question was chosen because it offers a comprehensive perspective on employee job satisfaction and acts as a significant indicator of the overall trend noted in other related items. The percentages presented in Figure 6 were derived using the following formula:

$$\text{Percentage} = \left(\frac{number\ of\ responses\ for\ each\ category}{total\ number\ of\ participants}\right) X100 \tag{1.1}$$

4.3 Physical Discomfort

This subsection outlines the feedback received regarding employees' physical discomfort, specifically concerning musculoskeletal issues. The objective is to recognize discomfort patterns that may arise from extended periods of standing, sitting, lifting, or engaging in repetitive tasks within the sea freight organization. A 5-point Likert scale was utilized, with responses ranging from 1 (Never) to 5 (Always). In total, 120 individuals participated in this section. Table 8 below presents a summary of the frequency with which participants reported discomfort in various body regions typically affected by ergonomic hazards.

A pie chart will be utilized to visually display the distribution of responses regarding the frequency of lower back discomfort. In contrast, a bar chart will illustrate the counts of lower back discomfort frequencies. Figure 7 below shows the details:

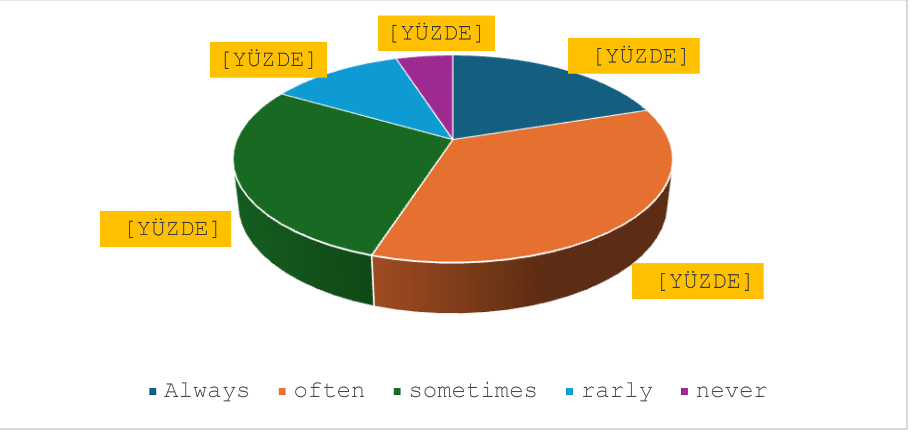

Figure 7. Pie chart for lower back responses.
Source: Created by authors.

The analyzed data highlights the importance of lower back pain as a widespread ergonomic concern within the maritime shipping sector. More than 80% of respondents reported experiencing occasional lower back discomfort, with 35% indicating it occurs frequently and 20% stating it is a constant issue. These findings are consistent with existing research on musculoskeletal strain associated with prolonged standing, awkward postures, and manual handling tasks that are typical in sea freight settings. The clustering of responses in the higher frequency categories emphasizes the urgent need for focused ergonomic solutions.

4.4 Ergonomics Interventions

This section discusses the participants' views on the ergonomic measures introduced in the workplace, including modifications to workstation layout, education on correct posture, access to ergonomic tools, and managerial support for ergonomic enhancements. In Table 7, Feedback was assessed using a 5-point Likert scale that ranges from 1 (Strongly Disagree) to 5 (Strongly Agree). Additionally, Figure 8 presents a bar chart of employees' perceptions of ergonomic Interventions.

Table 7. Responses to Ergonomic Intervention Statement

Statement	Strongly disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly agree (5)
Workstations are designed with ergonomics in mind	6 (5%)	14 (11.7%)	30 (25%)	46 (38.3%)	24 (20%)
I received ergonomic training	10 (8.3%)	20 (16.7%)	28 (23.3%)	40 (33.3%)	22 (18.3%)
Ergonomic equipment is available and accessible	12 (10%)	22 (18.3%)	32 (26.7%)	36 (30%)	18 (15%)
Management supports ergonomic improvements	8 (6.7%)	18 (15%)	35 (29.2%)	40 (33.3%)	19 (15.8%)

Source: Created by authors.

The data from Table 7 and Figure 8 reveal generally positive perceptions of ergonomic interventions among employees. The statement "Workstations are designed with ergonomics in mind" received agreement from 58.3% of respondents (38.3% agree and 20% strongly agree), indicating that a majority recognized efforts to improve workstation design. Similarly, responses to "I received ergonomic training" showed that 51.6% agreed or strongly agreed, suggesting that although a training program is in place, nearly half of the workforce did not feel sufficiently trained, which may indicate gaps in delivery or awareness.

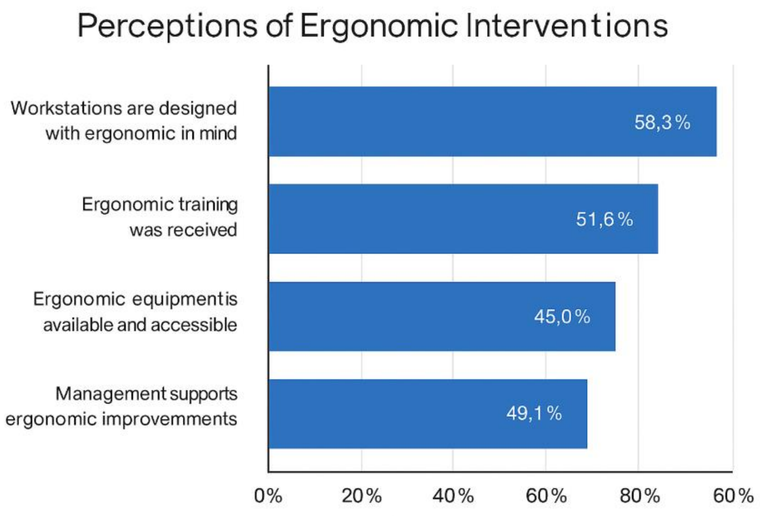

Figure 8. Workforce Perceptions Regarding Ergonomics Interventions
Source: Created by authors.

Regarding the availability of ergonomic equipment, 45% of respondents agreed or strongly agreed that such resources were accessible. However, nearly 29% disagreed or strongly disagreed, implying inconsistent availability or possible logistical issues. The final statement, "Management supports ergonomic improvements," garnered agreement from 49.1% of participants, while 21.7% expressed disagreement. This highlights a critical area for improvement: managerial commitment and visibility of support.

Overall, while many workers express moderate to strong approval of ergonomic efforts, the relatively high rates of neutral and negative responses underscore the need for more consistent communication, access to tools, and follow-up training to ensure broader adoption and satisfaction.

4.5 Burnout and Fatigue

This section of the report presents the results from survey items assessing employee experiences related to health aspects, including fatigue and burnout. The items shown in Table 8 were rated using a 5-point Likert scale, which ranges from 1 (Never) to 5 (Always), indicating the frequency with which employees experience these symptoms.

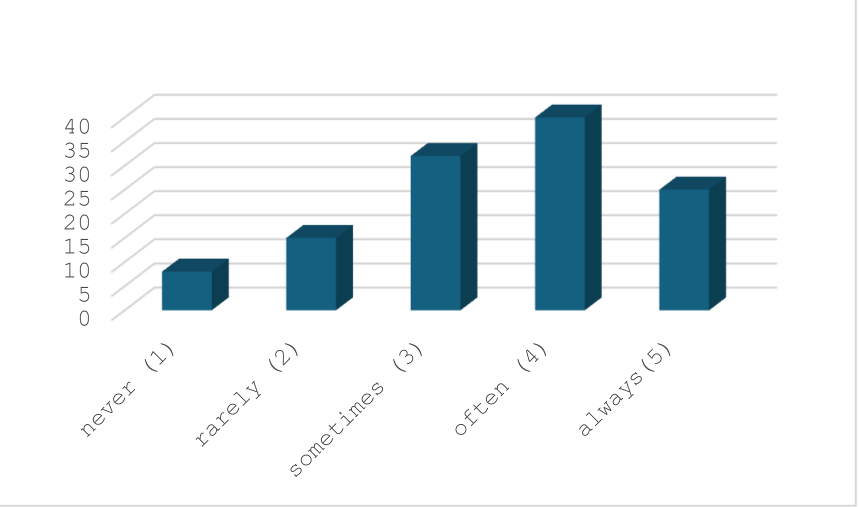

Figure 9. Frequency Distribution of Cognitive Fatigue Responses
Source: Created by authors.

Figure 9 displays a bar chart illustrating the prevalence of burnout-related symptoms among maritime workers. The data were collected from a survey consisting of four Likert-scale statements that assessed mental fatigue, emotional exhaustion, reduced motivation, and difficulties with concentration. To derive the percentages shown in the chart, responses for each of the four statements were compiled across all response options-Never, Rarely, Sometimes, Often, and Always. The overall reactions (120 participants × 4 questions = 480) were utilized as the denominator to determine the relative frequencies of each response level. The resulting averages indicate that "Often" was the most frequently chosen response, selected in 28.8% of all instances, followed by "Always" at 20%, "Sometimes" at 27.1%, "Rarely" at 15.8%, and "Never" at 8.3%. These results suggest that a significant number of employees frequently experience symptoms associated with occupational burnout, underscoring the need for initiatives that promote mental well-being within the maritime sector.

4.6 Ergonomics risk assessment results

As detailed in the Methodology chapter, the Rapid Entire Body Assessment (REBA) tool was employed to assess the physical requirements of different job positions within the organization. Table 8 summarizes the results from the REBA assessments performed on twenty specific job tasks, emphasizing the range of risk levels and pinpointing areas where ergonomic improvements are critically necessary. Additionally, Figure 12 displays the REBA scores for twenty different job positions, highlighting the varying levels of ergonomic risk. The chart uses color coding to differentiate the risk levels: Low (1–3), Medium (4–7), High (8–10), and Very High (11–15).

Table 8. Job-Specific Ergonomic Risk Levels Derived from REBA Evaluations

Job Role	REBA Score	Risk Level	Action Level
Forklift operator	9	High	Investigation and immediate change
Warehouse loader	8	High	Investigation and immediate change
Freight coordinator	5	Medium	Further investigation, change soon
Packaging worker	7	Medium	Further investigation, change soon
Crane operator	4	Medium	Further investigation, change soon
Administrative staff	3	Low	Change may be needed
Shipping clerk	6	Medium	Further investigation, change soon
Dock worker	10	Very high	Immediate action required
Container inspector	5	Medium	Further investigation, change soon
Logistics coordinator	7	Medium	Further investigation, change soon
Maintenance technician	9	High	Investigation and immediate change
Security staff	4	Medium	Further investigation, change soon
Inventory controller	6	Medium	Further investigation, change soon
Loader assistant	8	High	Investigation and immediate change
Vehicle dispatcher	3	Low	Change may be needed
Quality controller	5	Medium	Further investigation, change soon
Operation supervisor	4	Medium	Further investigation, change soon
Sales supervisor	2	Low	Change may be needed
Cleaning crew	6	Medium	Further investigation, change soon
Manual lifter	11	Very high	Immediate action required

Source: Created by authors.

4.7 Impact of Ergonomic Interventions on Workplace Productivity, Safety, and Operational Costs: A Pre-Post Analysis

Following the implementation of ergonomic interventions, a comprehensive evaluation was conducted to assess changes in workplace productivity, safety, and associated operational costs. Post-intervention data revealed substantial improvements across key metrics. Productivity increased, as evidenced by the rise in average daily output (from 135 to 160 units) and a reduction in task completion time (from 52 to 43 minutes), accompanied by a decrease in absenteeism from 14 to 8 days per month. Marked improvements in workplace safety paralleled these efficiency gains, as reported injuries were halved (from 11 to 5 cases/month), and minor injuries and near misses also significantly declined. Statistical analysis confirmed these reductions were highly significant ($p < 0.001$). Furthermore, the financial burden related to absenteeism, medical expenses, and productivity loss decreased from an annual total of $144,000 to $73,500-an overall cost reduction of nearly 49%. These findings demonstrate the dual benefit of ergonomic interventions in enhancing operational performance and reducing workplace risk and costs, underscoring their value as a strategic investment in both human well-being and organizational efficiency. These results were statistically significant ($p < 0.001$), supporting the effectiveness of the interventions (Table 9).

Table 9. The Effect of Ergonomic Interventions on Key Performance, Safety, and Cost Metrics

Category	Metric	**Pre-Intervention (Mean ± SD**	**Post-Intervention (Mean ± SD**
Productivity	Avg. Daily Output per Worker	135 ± 15.2 units/day	160 ± 12.9 units/day
	Task Completion Tim	52 ± 6.7 min/task	43 ± 5.2 min/task
	Absenteeism (Monthly Avg	14 ± 3.1 days	8 ± 2.4 days
Safety	Reported Injuries (Monthly Avg	11 ± 2.6	5 ± 1.7
	Minor Injuries (Monthly Avg	8 ± 2.2	3 ± 1.1
	Near Misses (Monthly Avg	6 ± 1.8	2 ± 0.9
Cost	Absenteeism Cost (Annual	$48,000	$27,000
	Medical Expenses (Annual, MSDs	$36,000	$18,500
	Productivity Loss (Estimated	$60,000	$28,000
	Total annual cost	$144,000	$73,500

Source: Created by authors.

The implementation of ergonomic interventions yielded clear improvements across productivity, safety, and cost dimensions. Post-intervention metrics revealed a notable increase in operational efficiency, with the average daily output rising from 135 to 160 units, while the average task completion time decreased from 52 to 43 minutes. This improvement suggests a more optimized workflow and reduces physical strain on workers.

Absenteeism was significantly reduced, dropping from 14 to 8 days per month, indicating enhanced worker health and engagement. In parallel, workplace safety improved considerably. Monthly reported injuries were nearly halved (from 11 to 5), while minor injuries and near misses also saw sharp declines. These results were statistically significant ($p < 0.001$), supporting the effectiveness of the ergonomic changes in creating a safer working environment.

In terms of financial impact, the total annual cost burden from absenteeism, medical expenses, and productivity losses was cut by almost 49%, decreasing from $144,000 to $73,500. The cost of medical treatment for musculoskeletal disorders alone dropped by nearly $17,500, and absenteeism-related costs fell by $21,000.

Collectively, these findings highlight that ergonomic interventions are not merely supportive of worker well-being; they also represent a strategic investment with tangible returns in productivity, safety, and cost efficiency. The substantial reductions across all categories reinforce the value of a proactive, human-centered approach to operational management.

5. LIMITATIONS

Some limitations of this study include the reliance on a sample of 120 participants, which, although adequate for identifying trends, may not accurately represent the full range of experiences throughout the wider sector. Certain job positions-especially those with smaller personnel numbers-could have been underrepresented, which may influence the applicability of the results. Moreover, the timeframe for data collection was relatively brief, concentrating on pre- and post-intervention comparisons over a short duration. This limitation may have hindered the observation of long-term effects, such as reductions in chronic injuries or ongoing productivity gains. Conducting longitudinal studies would be advantageous to assess the durability of ergonomic benefits over time. Another constraint involves the self-reported nature of some data, particularly regarding metrics such as job satisfaction, physical discomfort, and perceived fatigue. Even though attempts were made to validate responses through observations and supervisor feedback, self-reports may be swayed by personal bias, emotional state, or anticipations. Furthermore, environmental and organizational aspects that could have influenced the outcomes, such as management support, variations in workload, or simultaneous safety initiatives, were not entirely isolated or controlled. These confounding factors may have contributed to the noticed improvements. Lastly, while the REBA tool proved effective for evaluating physical ergonomic risks, it may not effectively encompass all cognitive or psychosocial elements. Future studies may find it beneficial to integrate a wider array of ergonomic assessment tools to deliver a more comprehensive evaluation. Despite these limitations, the study provides a solid foundation for understanding how ergonomic practices can foster meaningful improvements in workplace safety and performance.

6. CONCLUSION and RECOMMENDATIONS

6.1 Conclusion

This study demonstrated that ergonomic interventions can significantly enhance workplace safety, employee health, and operational efficiency within the sea freight forwarding industry. Conducted across sites in Aqaba and Amman, Jordan, the research showed notable improvements in musculoskeletal health, job satisfaction, and productivity, as well as reductions in absenteeism and workplace incidents. Through a mixed-methods approach, integrating REBA assessments, surveys, performance metrics, and interviews, the interventions were found to be both effective and statistically significant. The findings underscore the importance of embedding ergonomic principles into organizational strategies. Regular ergonomic assessments, tailored workstation designs, and worker-centered improvements can yield measurable gains in safety, morale, and cost savings. These results hold broader relevance for labor-intensive logistics sectors beyond maritime operations. Future research is recommended to extend these insights by including more diverse participant groups and conducting long-term studies to track sustained impacts. Additionally, integrating emerging technologies, such as wearable sensors or AI-based monitoring tools, could enhance data precision and deepen our understanding. A focused exploration of ergonomics' return on investment (ROI) is also warranted, particularly in terms of cost savings from injury reduction, employee retention, and productivity gains.

6.2 *Organizational Culture and Managerial Support*

This study demonstrated that the success of the ergonomic interventions was closely influenced by the organizational culture and managerial attitudes within the sea freight forwarding company. Management’s openness to change and commitment to employee well-being played a crucial role in facilitating the adoption of ergonomic recommendations. Supervisors actively encouraged participation in training sessions, and the leadership team demonstrated a willingness to adjust workstation layouts and invest in ergonomic equipment. This culture of support helped overcome initial resistance among some employees and contributed to the sustainability of the interventions. In contrast, organizations with rigid hierarchies or a low emphasis on worker welfare may face more challenges in implementing similar changes. These findings align with broader ergonomics literature, which emphasizes that managerial buy-in and a participative work culture are key determinants of successful intervention outcomes.

6.3 Practical Applications

The practical applications of this study are highly relevant to operational decision-makers in the sea freight forwarding industry. The demonstrated improvements in productivity, safety, and cost-efficiency support the integration of ergonomic principles into workplace planning and daily operations. These findings suggest that targeted ergonomic interventions-such as redesigning workstations, training staff on proper posture, and supplying ergonomic tools-not only protect worker health but also yield measurable operational gains. Companies in similar high-risk logistics sectors can adopt these measures as part of strategic initiatives to boost performance while minimizing injury-related costs and absenteeism.

6.4 *Recommendations*

This study recommends that companies in the sea freight industry implement structured ergonomic programs tailored to maritime-specific risks. Key measures include redesigning high-risk workstations, promoting the use of ergonomic equipment, and providing ongoing training in safe work practices. These initiatives align with IMO guidelines on fatigue management and ILO standards on port safety.

For policymakers and industry leaders, embedding ergonomic principles into workplace regulations is crucial. This involves mandating regular assessments, investing in early interventions, and refining workstation design strategies in line with international best practices. Overall, adopting a proactive and preventive ergonomic approach is essential for achieving long-term improvements in worker safety, health, and operational efficiency.

6.5 Suggestion for Future Research

Future research should focus on conducting longitudinal studies to evaluate the long-term effectiveness of ergonomic interventions, particularly in the dynamic sectors of sea freight and logistics. Expanding the scope to include psychological and cognitive aspects, such as mental workload and stress-induced fatigue, would provide a more holistic view of ergonomic impacts on both physical and psychological health.

Broader geographic coverage, extending beyond Jordan, and more diverse participant samples, including different cultural contexts and underrepresented groups such as women and individuals in specialized job roles, would enhance the generalizability of the findings. Additionally, integrating advanced technologies such as wearable sensors and AI-based ergonomic monitoring tools could lead to more accurate risk assessments and customized interventions.

Acknowledgements

This research is a part of the master's thesis prepared by the researcher at Istanbul Gedik University.

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1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

Funding

There are no financial interests in this study.

Declaration of Competing Interest

There is no conflict of interest in this study.

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September 2025, Vol:3, Issue:2

International Journal of New Findings in Engineering, Science and Technology

journal homepage: https://ijonfest.gedik.edu.tr/

Received:14.03.2025 Accepted:04.08.2025 Pablished:29.09.2025

The Firefighting and Rescue Wagon Design

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Abstract

The Firefighting and Rescue Wagon (FRW) is designed as a multifunctional emergency response vehicle for railway transportation accidents, such as fires, explosions, and chemical leaks. This specialized wagon aims to ensure the safe rescue and evacuation of passengers, provide temporary secure storage for hazardous materials, and minimize potential environmental damage. Additionally, it offers the capability to swiftly implement environmental safety measures and conduct effective rescue operations in disaster areas. The wagon provides a unique advantage, particularly in areas where road access is not possible, including railway corridors, bridges, and tunnels. It has been specifically developed for use in locations where conventional rescue and firefighting vehicles cannot reach. This enables rapid response to sudden incidents like fires and supports rescue teams in working safely within the disaster zone.

Keywords: Firefighting, Rescue, Wagon, Design, Railway.

1. INTRODUCTION

The design of the Firefighting and Rescue Wagon is of great importance for responding quickly and effectively to emergencies and disasters that may occur during railway transportation activities [1]. This specialized design prioritizes the safe and secure transportation of passengers, personnel, the environment, and the cargo key elements of railway transportation throughout the journey. Additionally, the various types of wagons and superstructures used in railway transport provide a strong foundation for the development of such a design.

Emergency response vehicles based on rail systems have appeared in various forms throughout history. Firefighting and first aid trains used in Australia between 1918 and 1990 were eventually decommissioned as road ambulance services evolved [2]. Similarly, hospital trains were first developed during Crimean War and have since served as mobile health centers in many subsequent crisis [3]. Even today, railway ambulances operating in Russia's Siberian region and India continue to meet the need for mobile medical services [4]. Unlike these historical examples, the FRW stands out as an integrated system that combines not only health services but also fire suppression, rescue, evacuation and environmental protection functions [5].

FRW contains many features that are not offered by standard fire response vehicles. With its high-capacity water and foam tanks, extensive equipment storage space and versatile rescue tools, this wagon enables effective intervention in remote or hard-to-access areas of the railway network. It provides a unique solution for firefighting and rescue operations, especially in forested areas, bridges, tunnels and other locations where road access is not possible [6]. FRW is the first of its kind in

https://doi.org/10.61150/ijonfest.2025030203

Türkiye—a multifunctional intervention vehicle specifically developed for railway infrastructure. This innovative solution allows for effective response in areas where road access is not possible, particularly bridges, tunnels, valleys and mountainous terrain. In emergencies such as fires, explosions, or chemical leaks that may occur during railway transportation, FRW can operate independently in areas inaccessible to traditional firefighting and rescue vehicles. In this sense, it represents a revolutionary development not only for railways but also for disaster and emergency management.

Being the first of its kind in Turkey and within the railway system, FRW is unique not only technically but also strategically. With its high-capacity water and foam tanks, advanced rescue and evacuation equipment and command center infrastructure, the wagon can perform the functions of six separate fire trucks. Furthermore, by traveling directly via rail to hard-to-reach areas, it provides a major advantage in time-critical rescue operations. This special wagon functions not only as an intervention vehicle but also as a mobile command and coordination center during emergencies. By transporting all necessary equipment and personnel to the scene, it ensures that response efforts are carried out swiftly, systematically and effectively.

FRW is a pioneering vehicle that elevates safety and response capacity within the railway system to a higher level through a concept being implemented for the first time in Türkiye. It saves lives, protects the environment and minimizes losses by intervening in areas unreachable by road vehicles. Representing a key step in Türkiye's disaster preparedness vision, FRW is poised to become a cornerstone of next-generation railway safety. Ultimately, FRW is an innovative project that will make a significant contribution to Türkiye's developing railway infrastructure and transportation sector. Equipped with modern technology such as CAD-based virtual design and clearance testing, high-capacity water pumps and remote-controlled water monitors, an onboard generator system with 24-hour autonomous operation, advanced heating systems for ISO tanks, and an integrated control room with computers and camera surveillance, this wagon will play a critical role in enhancing railway safety while reducing environmental and human risks. In the future, the widespread adoption of such specialized designs will enable higher safety standards in railway transportation and foster the development of rapid, effective disaster response solutions. FRW is an innovative project that will make a significant contribution to Türkiye's developing railway infrastructure and transportation sector.

2. METHODOLOGY

The initial and latest design of FRW is shown in Figure 1 and 2, respectively. In developing this design, the project's purpose and the product's scope were carefully considered. FRW has been designed to provide a much larger capacity and area of coverage compared to conventional firefighting vehicles. When compared with standard emergency vehicles, it matches the water capacity of 30 First Response units, the foam capacity of 13 Response units, and the rescue equipment capacity of 5 Response units. A comparison table is presented in Figure 3 and Table 1.

Figure 1. Fire Fighting and Rescue Wagon Initial Design.

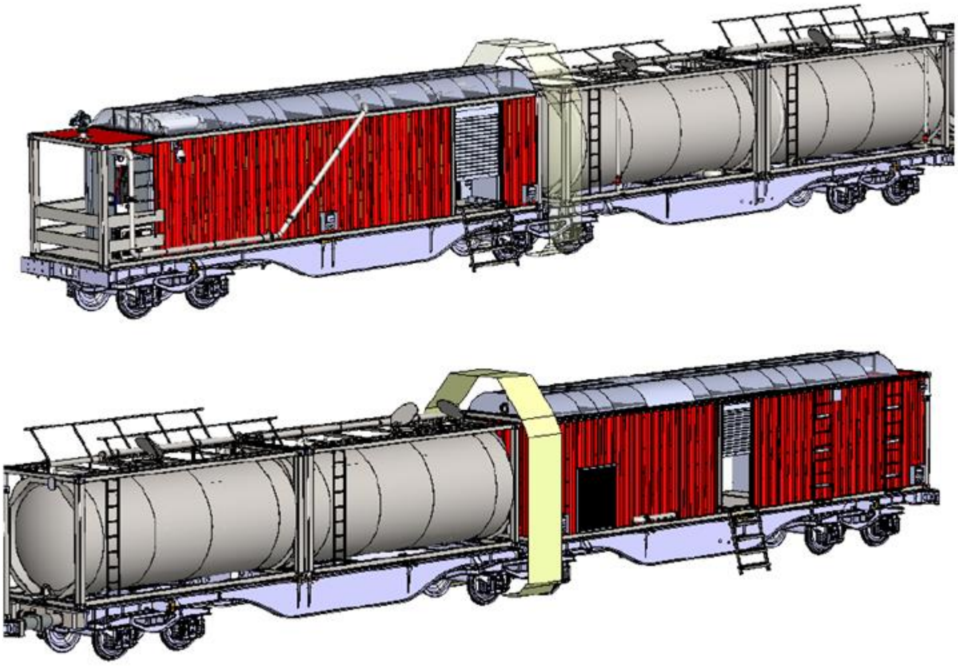

Figure 2. Fire Fighting and Rescue Wagon Latest Design.

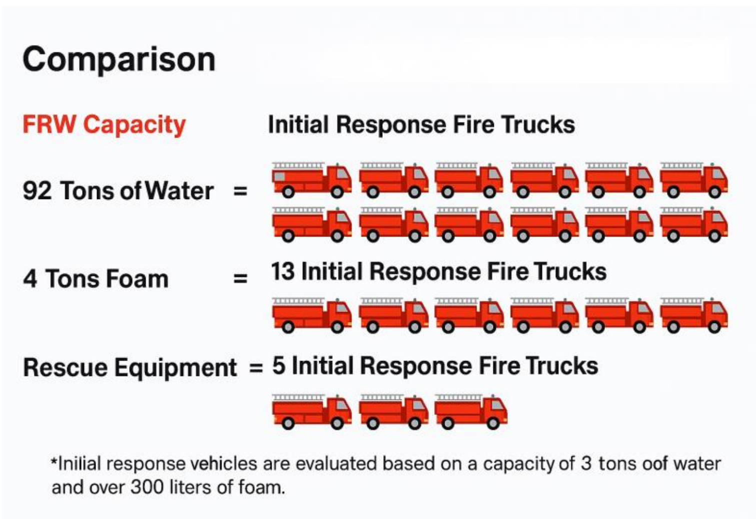

Figure 3. FRW and Fire Truck Capacity Comparison (Manufacturer company comparison).

Moreover, FRW is equipped with derailment tools, which are not typically found on every response vehicle. “Derailment” refers to a train coming off the rails. This feature is one of FRW's most powerful advantages. Since it operates on railways and carries derailment equipment onboard, it offers a capability that is rare in traditional firefighting vehicles making it a standout and preferred choice among emergency response tools.

The initial FRW design consisted of two units: a 40-foot Equipment Container and a 20-foot Power Unit, covering a total area of 120 feet. This design had a capacity of 68 tons of water and 4 tons of foam. After the equipment was put into active use, improvements were made to enhance the design, resulting in the current version. Compared to the previous design, the updated model has been expanded by approximately 30%, making it more comprehensive and user-friendly. The earlier design is illustrated in Figure 1. In the latest version, the FRW has been mounted on two 80-foot platform wagons, increasing the total area to 160 feet. Once the installation of the equipment is completed, the system is configured to operate as a single, unified unit.

FRW can also generate its own electricity, allowing for continuous operation for up to 24 hours. To achieve this, it is equipped with two diesel tanks. These tanks have sufficient capacity to operate the generator and the pump for a full 24-hour period.

Table 1. FRW and Fire Truck Capacity Comparison (Manufacturer Comparison)

2.1.1.1. FRW Capacity	**2.1.1.2. Equivalent Initial Response Fire Trucks**	**2.1.1.3. Units**
2.1.1.4. 92 Tons of Water	2.1.1.5. 30 Fire Trucks	2.1.1.6. 30 Units
2.1.1.7. 4 Tons of Foam	2.1.1.8. 13 Fire Trucks	2.1.1.9. 13 Units
2.1.1.10. Rescue Equipment	2.1.1.11. 5 Fire Trucks	2.1.1.12. 5 Units

The entire design was created virtually using SolidWork**s** software and all manufacturing details were derived from this program. On SolidWorks, the entire design was modeled to exactly match the real-life implementation, with the aim of eliminating potential issues that could arise before, during, or after production. Another advantage of the software is its ability to assist in preparing the technical drawings required for manufacturing.

The design created in SolidWorks also provided a virtual testing opportunity for the clearance (gauge) test, with the part shown in yellow in Figures 2 and 4. The clearance test is one of the final evaluations for railway products and is conducted to simulate the product's entry into a tunnel. The primary objective of this test is to determine whether any part of the product might come into contact with the tunnel walls during entry, passage, or exit. If any part makes contact, the test is considered a failure, and necessary revisions must be made before it can be repeated. The tunnel simulation prepared for the test measures 3150 mm in width and 4520 mm in height.

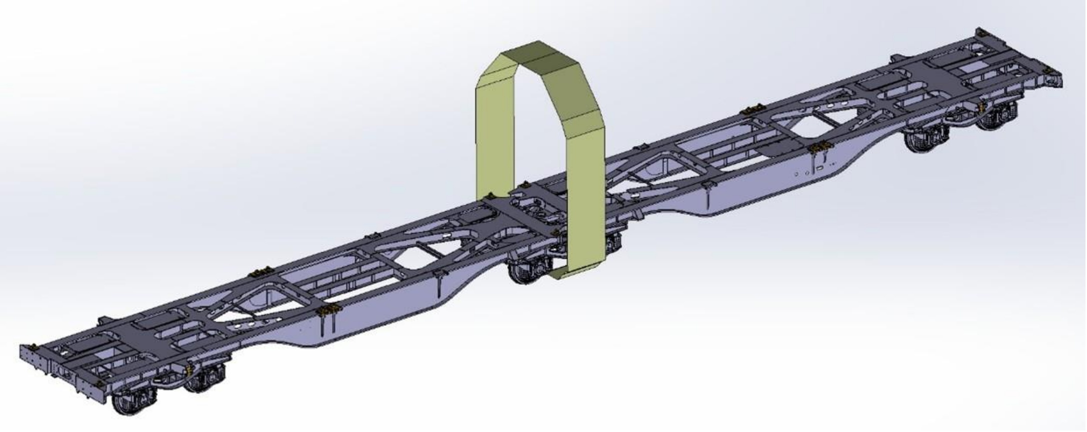

Figure 4. 80 FT Platform Wagon.

For FRW design, the clearance test was simulated using SolidWorks and potential issues were resolved within the software. For example, the guardrails of the ISO tanks initially failed the test. To pass, the guardrails were redesigned to be movable. Detailed measurements of this revision are provided in Figures 5 and 6. In the test supported by visual evidence, it was clearly observed that the fixed guardrails exceeded the clearance limits. However, the guardrails were clearly seen to remain within the permitted gauge boundaries.

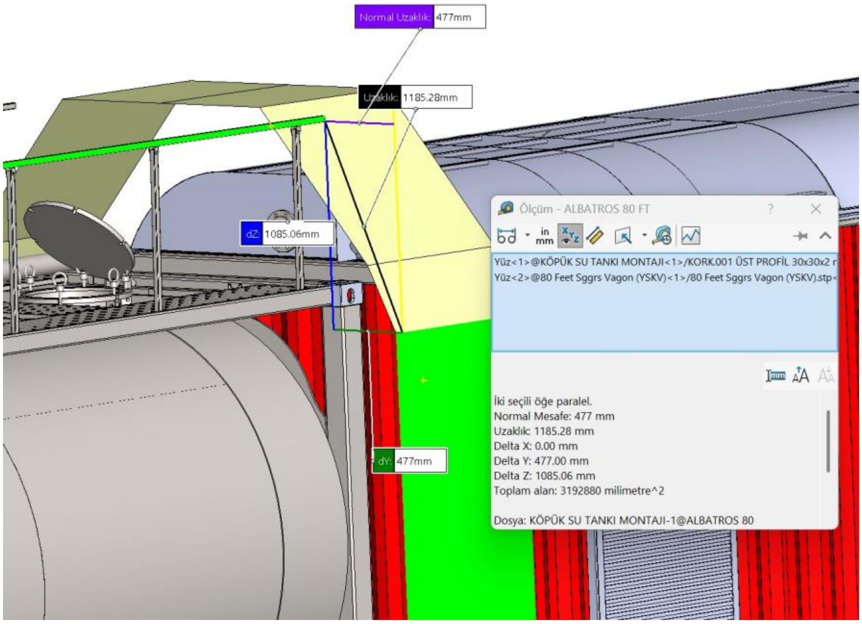

Figure 5. Guardrail arrangement on ISO tank prior to envelope (clearance) testing.

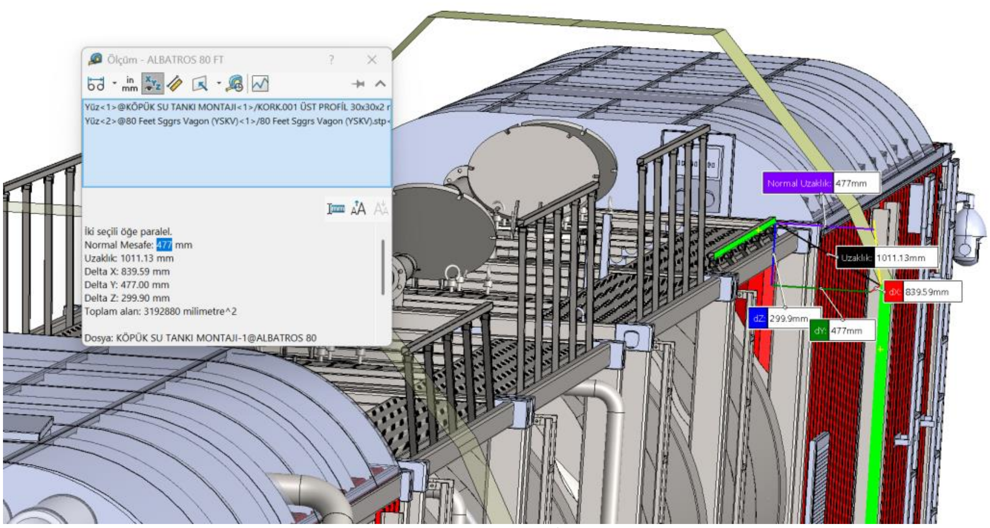

Figure 6. Guardrail arrangement on ISO tank following envelope clearance testing.

During the design process, preliminary research and objectives were considered. Previously manufactured products were examined and scenarios aligned with the project scope and objectives were taken into account.

Primary Objectives of the Firefighting and Rescue Wagon Design:

- **Ensuring Environmental Safety**

  During and after disasters, environmental safety measures are taken to protect people, nature, animals, and other assets.

- **Firefighting**

  FRW is designed as an integrated system with high firefighting efficiency using water and foam-based solutions. Extinguishing agents stored in ISO tank containers are delivered to the fire zone in a controlled and powerful manner through high-capacity pumps and monitors. This innovative system enables rapid and effective fire intervention in railway transportation and industrial areas, maximizing life and property safety [7].

- **Rescue and Emergency Response**

  It is designed for effective use in railway accidents, derailments, collisions, and other emergency scenarios.

- **Environmental Pollution Prevention and Mitigation**

  One of the key accident scenarios involves preventing fuel leaks in derailed wagons. In case of tank wagon derailments, minimizing fuel or chemical spills and controlling leaks to reduce environmental damage is of utmost importance.

- **Temporary Hazardous Material Storage**

  In railway transportation, accidents involving tank wagons carrying hazardous and flammable liquids pose significant environmental risks [8]. In the event of such accidents, the uncontrolled release of transported liquids increases the risk of fire, threatening both environmental and life safety.

The Firefighting and Rescue Wagon Design consists of three main structures.

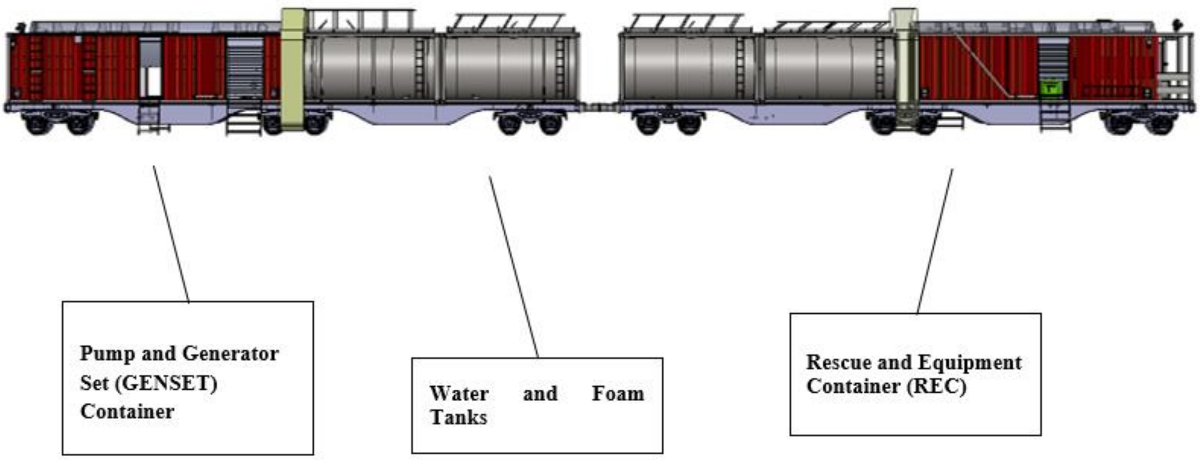

Figure 7. Three Main Structures of the Firefighting and Rescue Wagon Design.

FRW Design consists of two 40 FT containers and four 20 FT ISO tank containers. One of the 40 FT containers is designated as the Pump and Generator Set Container (GENSET), while the other is named the Rescue and Equipment Container (REC). The layout plan is shown in Figure 7.

2.1 Pump and Generator Set (GENSET) Container

Half of the container is designed for the pump and generator units, while the remaining section is designated as an equipment room. GENSET Container is the primary and essential container set that supplies all the energy for FRW Design. No one other than the assigned personnel should interfere with GENSET. Given that the generator unit is considered the heart of the system, it is crucial to keep it isolated from everything else. The generator unit is an indispensable component that ensures the effective operation of the entire system. For the equipment within this system to function properly, the generator must be operational.

The pump unit is the most critical component used in the firefighting process of FRW Design. It is responsible for pressurizing and distributing water through all pipelines within the system. The primary reason for housing both the generator and the pump in the same container is that they are connected to shared diesel fuel tanks. To avoid extending the fuel lines further, these two key components are placed within a single container. Figure 8 and 9 show placement of the pump and generator set container and pump and generator room, respectively.

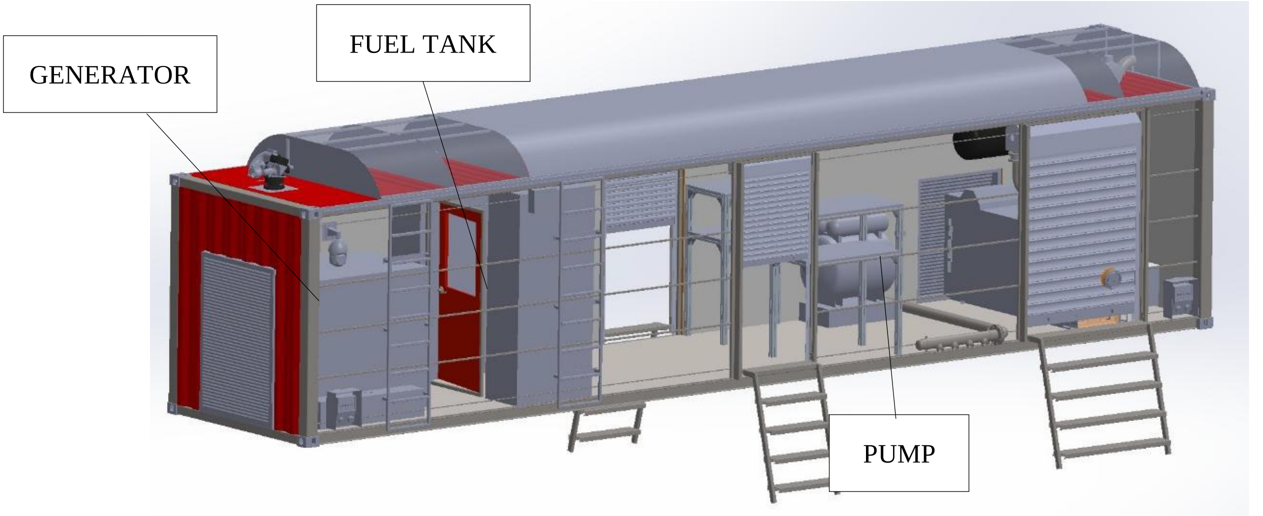

Figure 8. Placement of the Pump and Generator Set Container (GENSET).

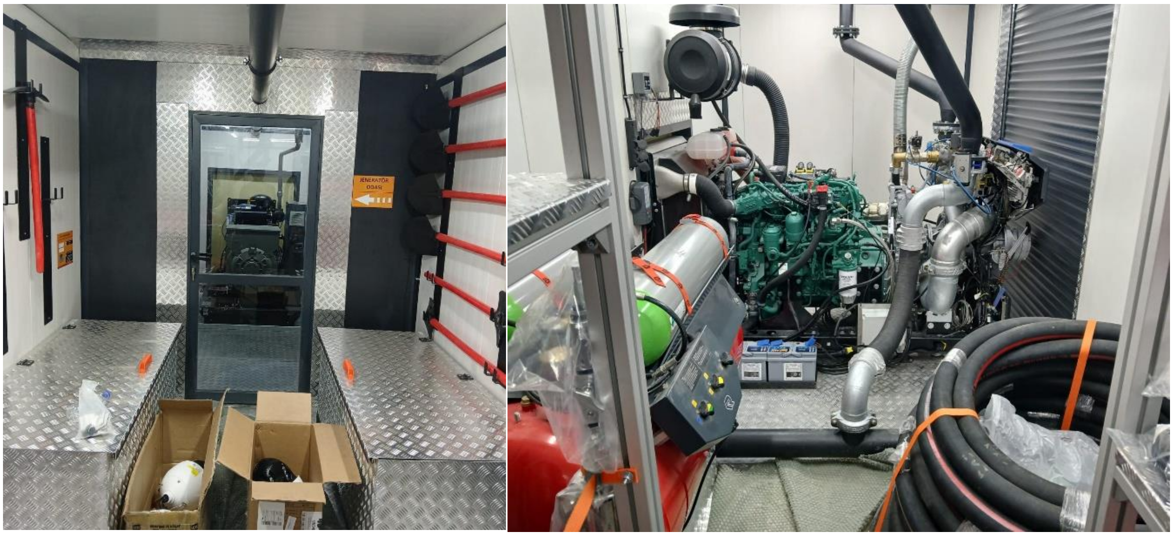

Figure 9. Pump and Generator Room (GENSET).

2.2 Water and Foam Tanks

FRW Design includes four 20 FT ISO tanks, where water and foam will be stored. Three of these ISO tanks are designed as single-chamber water tanks, while one tank is divided into two chambers, one for water and the other for foam. ISO tanks will be exposed to all kinds of weather conditions. To prevent water from freezing in cold climates, all tanks are equipped with resistant heaters. The electrical output of these heaters are connected to a single circuit leading to the control room. The heaters can be operated based on weather conditions via computers in the control room. To ensure a continuous water flow, all four tanks are connected in series without any interruptions. This setup prevents the pump from drawing air and causing cavitation [9]. Although the pump is designed with advanced technology to minimize this risk, connecting all tanks in series provides an additional safety measure. Breather valves are installed on each tank to allow air in during suction and prevent pressure drop. [10]. These breather valves allow extra air to enter the tank during suction, eliminating vacuum risk and protecting the tanks.

Two different materials are used in the production of the ISO tanks: carbon steel for the structural frame and stainless steel for the tank section. Carbon steel is chosen for the construction due to its high strength and cost-effectiveness, making the tanks more resistant to external impacts and environmental conditions. Additionally, the widespread use of carbon steel in manufacturing simplifies the supply process and helps reduce production costs. Figure 10 shows pump and generator set and 20FT ISO tank containers.

Figure 10. Pump and Generator Set and 20FT ISO Tank Containers.

2.3 Rescue and Equipment Container (REC)

The control room and personnel compartment are equipped with computers, control units and a camera system, allowing full control of FRW. Additionally, all personal protective equipment (PPE) required for 12 personnel will be stored in this room. The control room is structured to accommodate a fully equipped manager and 12 fully equipped firefighting/rescue personnel.

The control room is built to be completely gas-tight and insulated accordingly. It also features a separate breathable air supply system that maintains positive pressure within the room. This ensures that breathable air is available inside the wagon without the need for protective masks [11]. Another key purpose of this system is to create a suitable working environment for the manager, who will be overseeing the entire operation from inside the control room (Figure 11).

All equipment stored on the shelves is securely fastened to prevent movement while the wagon is in transit (Figure 12). There will be two doors at the beginning and end of the shelving system. A jib crane will be positioned at these doors to facilitate the loading and unloading of equipment. Additionally, an overhead crane will be installed between the shelves to assist in moving heavy items, ensuring compliance with occupational health and safety measures [12]. Furthermore, a fixed compressor will be located in this area to maintain positive pressure. Rescue and equipment container miscellaneous material list was given in Table 2.

Figure 11. Control Room and Staff Compartment.

Table 2. Rescue and Equipment Container Miscellaneous Material List.

Serial No	Equipment Name	Description
1	Flame-Resistant Aluminized Suit	Special protective suits for fire rescue and gas fire valve closures. Reflects 85%-95% of radiant heat from a 1000°C heat source, protecting firefighters from extreme heat [13]. 
2	High-Durability Gas-Tight Chemical Protective Suit	Gas-tight suit for use with a compressed air breathing apparatus, protecting against hazardous gas, aerosol, liquid and solid substances. Offers mechanical durability and is suitable for cold environments [14]. 
3	Megaphone	Used for warnings and communication during emergency responses.
4	Firefighter Hose	Ensures water delivery to the required area during firefighting [15]. 
5	Hydrant Wrenches	Used to supply water from fixed hydrants for firefighting.

6	Rechargeable Lighting Devices	Provides illumination in areas with insufficient lighting [16].
7	Warning Tapes	Restricts civilian access to emergency response areas and provides warnings.
8	Hydraulic Cutter	Essential for freeing trapped victims in traffic accidents. Cuts through steel and metal parts for fast and safe rescues [17]. 
9	Hydraulic Ram	Used for lifting and expanding large objects. Creates safe exit routes for trapped individuals [18]. 
10	Hydraulic Spreader	Separates and expands trapped objects in emergencies. Used with hydraulic cutters to enlarge rescue areas [19]. 
11	Firefighter Breaking & Piercing Hand Tools and Rescue Saws	Allows teams to access trapped individuals, overcome obstacles in fires and disasters and perform life-saving interventions [20]. 
12	Lifting Bags	High-pressure air-inflated bags used to lift heavy objects and rescue trapped individuals under debris or vehicles. 
13	Cable Reels	Provides power for lighting and electrical devices during emergency operations.

Figure 12. Rescue and Equipment Container Storage Area Shelf Example.

For the design of the material shelves to be used inside the container, a material selection has been made to enhance both durability and ease of use. In this regard, aluminum has been chosen to produce the shelves [21]. One of the most important factors in selecting aluminum is its lightweight nature and high strength. Compared to heavy metals such as steel, aluminum has a significantly lower weight while still being strong and durable [22]. This ensures the creation of a sturdy and reliable shelving system without increasing the overall weight of the container.

Additionally, aluminum's natural resistance to rust and corrosion provides a significant advantage in terms of long-term use [23]. The shelf system is designed to remain secure and durable for at least 30 years. Aluminum's durability is a key criterion to prevent wear and shear caused by external factors over time. As a result, maintenance requirements for the shelves are minimized, operational costs are reduced and a long-term, sustainable solution is provided.

3. RESULT

The previously manufactured FRW has been thoroughly examined in detail. In this study, the strengths of the existing design, areas that need improvement or modification and any potential defects were identified. A comprehensive analysis was conducted, considering the product's application areas, operational efficiency and user requirements.

The design process of FRW began with a thorough analysis of the previous version, was improved based on user needs and underwent detailed evaluations before proceeding to production. Throughout the manufacturing process, quality control mechanisms were actively implemented, ensuring strong coordination between the design and production stages. As a result, an efficient, durable and user-friendly product that meets both technical and operational requirements was developed.

FRW Design, produced with domestic and national capabilities, is positioned on two wagons with a total length of approximately 53 meters. A total of two wagons are designed with 2 units of 40 ft containers and 4 units of container tanks. In the distribution on a single wagon, 1 unit of 40 ft container and 2 units of 20 ft container tanks are designed.

- Thanks to its fuel tanks and onboard generator, the FRW can operate autonomously and provide uninterrupted intervention for up to 24 hours.
- FRW has the capacity to carry 30 First Response Vehicles with 92 tons of water.

- FRW has the capacity to carry 13 Intervention Vehicles with 4 tons of foam.
- It has the capacity to carry 5 Intervention Vehicles with the equipment in the storage area of the Rescue and Equipment Container.
- FRW Design is designed to have a power capacity of 70 kVA. This ensures that all electrical devices within the system are powered and ready for operation. Additionally, it will be able to provide lighting for the surrounding area to ensure environmental safety and security.
- The system's pump ensures a continuous water pressure of 10 bar.
- The system features remote-controlled water monitors, allowing for water spraying up to 100 meters ahead, significantly expanding the intervention area.
- Thanks to the fixed water lines along the wagon and the portable hoses in the containers, the system will be able to reach up to 500 meters from both sides of the wagon, providing the ability to intervene over a large area.
- The equipment stored inside the containers provides the possibility of accident rescue and recovery.
- FRW provides opportunities for preventing and eliminating environmental pollution.
- FRW provides temporary storage options against accidents and hazards that may occur during the transportation of hazardous chemicals, ensuring the safe containment of the load, minimizing environmental damage, and reducing potential harm.
- FRW ensures the safety of the cargo on the railways.
- FRW allows for increased preventive measures and intervention possibilities in facilities, storage and factory areas, shipyards, ports and similar locations along the railway route.

The latest design has been developed with an approximately 30% higher capacity compared to the first prototype of FRW, which was produced and put into operation in 2021. The primary goal of increasing the design's capacity was to enhance the water capacity and impact radius. In this way, the design has been optimized to achieve greater efficiency with 30% more capacity than the prototype.

After the earthquakes on February 6, FRW was used for the first time during the fire at the Iskenderun Port. It operated day and night for several days, playing a key role throughout the entire operation. During its operation, the pump on the system drew water from the sea, providing a continuous and unlimited water supply. This allowed the water monitors on the wagon as well as the fire trucks' water tanks to be continuously filled.

Acknowledgements

This research article is derived from the master's thesis titled "Yangın Söndürme ve Kurtarma Vagonu Tasarımı". The authors would like to thank Albatros Kreatif Mühendislik A.Ş. and Selahattin Nevzat Şenocak for their support throughout the study. Additionally, the authors declare that they have not received any financial support from any institution, organization, or individual during the research process.

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1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

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September 2025, Vol:3, Issue:2

International Journal of New Findings in Engineering, Science and Technology

journal homepage: https://ijonfest.gedik.edu.tr/

Received:03.07.2025 Accepted:03.09.2025 Pablished:29.09.2025

SkyServe AI - Data-Driven Solution to Optimize Airline Food Loading Processes

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Abstract

Air transportation is one of the fundamental elements of the global transportation network and plays an important role in both commercial and passenger transportations. The increasing number of passengers every day is leading airlines to seek more efficient and sustainable solutions in operational processes. The food supply process is a critical factor in maintaining passenger comfort and service quality, especially on long-haul flights. The amount and variety of food offered during the flight requires effective planning in terms of both customer satisfaction and operational efficiency. This research presents a data-driven approach to optimize food loading processes in the airline transportation sector. The main objective of the project is to increase operational efficiency, reduce costs and minimize food waste by predicting the amount of food required for flights. In the study, variables such as flight route, number of passengers, flight duration and total demand are considered and the effects of these factors on food consumption are analyzed. In the model development process, machine learning algorithms were applied using real flight data. The data set taken to train the model includes detailed information about approximately 180,000 flights. This data is divided into two as training and test sets in order to improve the learning ability of the model and increase the prediction accuracy. In order to evaluate the prediction performance of the model, comparisons were made with the real consumption values at the end of the flight. The accuracy rate of the developed model shows that the model has a general prediction ability according to the initial findings. The study has the potential to contribute to the improvement of food loading processes of airline companies with data-driven decisions. Development steps such as expanding the data set, model optimization and error analysis are suggested for higher accuracy rates.

Keywords: Artificial Intelligence; Airline Catering Optimization; Food Supply Chain in Aviation; Machine Learning in Airline Operations.

1. INTRODUCTION

The airline industry constantly needs innovative approaches to increase operational efficiency and improve customer satisfaction. In this context, food stock management is one of the critical processes in the industry. Making accurate stock estimates is of great importance both in terms of reducing costs and contributing to sustainability goals. In order to overcome these challenges, the SkyServe AI project aims to offer an advanced solution for food stock estimates per flight by using artificial intelligence and data science technologies.

Since traditional methods do not sufficiently take into account dynamic factors such as seasonal changes and passenger profiles, there are serious problems in the accuracy of the estimates. These deficiencies cause problems such as food waste and customer dissatisfaction. Our research aims to provide a comprehensive machine learning-based model that supports data-driven decision-making processes in the airline industry. This model aims to estimate the ideal amount of food for each flight by combining a wide range of data sources such as flight duration, passenger age group data and food variety data. In a report published by American

https://doi.org/10.61150/ijonfest.2025030204

Airlines in 2019 [7], it was stated that food consumption estimates on flights often lead to waste and customer dissatisfaction. The company stated that it plans to predict food demand more precisely using data analysis and artificial intelligence.

Similarly, a study conducted by Airbus suggests that optimizing food stock management per flight can save an average of 100,000 USD per flight [8]. Such data reveals how critical the SkyServe AI project is for the airline industry and the practical necessity of the solution it has developed.

The study will not only increase operational efficiency but will also make significant contributions to the industry in terms of environmental sustainability and customer experience. Because food waste not only causes economic losses for airline companies but also creates negative impacts on the environment. In order to solve this problem, SkyServe AI aims to minimize food waste by stocking the right amount. This approach aims to reduce operational costs and achieve environmental sustainability goals in line with the United Nations (UN) Development Goals.

In terms of customer experience, insufficient food stock can negatively affect customer satisfaction during air travel. SkyServe AI aims to meet the needs of each passenger by accurately predicting the food demand on board, thus increasing customer satisfaction. This project will provide passengers with a more satisfying flight experience while also helping airline companies gain customer loyalty. The research project aims not only to provide solutions to existing problems, but also to demonstrate the potential of data science and artificial intelligence-based approaches in the airline transportation sector. The innovative solution offered by the project will pioneer the optimization of administrative processes in the sector and will also make valuable contributions to the literature in this field. Working on complex and dynamic data structures in the airline transportation sector, SkyServe AI aims to create a model that will serve as an example for other applications in this field.

The long-term goals of the study include demonstrating the applicability of artificial intelligence in a wider area in airline operations and providing support for sustainability-oriented operational processes. The developed model can be adapted not only to the airline sector but also to other transportation and shipping areas. Thus, it will provide solutions to similar problems in other transportation systems. SkyServe AI aims to create an innovation that will contribute to both internal and external sector applications by bringing together data science, artificial intelligence and sustainability principles. This comprehensive and innovative approach is considered as part of the digital transformation in the airline transportation sector and distinguishes our research from other solutions in the sector. The project not only improves current processes but also provides a solution for the future operational needs of the airline industry.

2. LITERATURE REVIEW

The 21st century, where digitalization has increased rapidly, has also brought with it a tremendous explosion in data production. Especially since the beginning of the 2000s, with the widespread use of the internet and mobile devices becoming indispensable in daily life, the rate of data production has increased exponentially. According to statistics, approximately 2.5 quintillion bytes of data are produced every day in the world (Statista, 2024). The increase in the use of social media platforms, the rise of e-commerce, and the widespread use of digital systems used in the healthcare sector are some of the most obvious reasons for this increase. For example, the transfer of information systems by hospitals to digital environments and the transition of student information management systems from paper-based forms to electronic systems by educational institutions are important steps that trigger big data production. This transformation has not only increased the volume of data, but also significantly expanded the variety of data.

This rapid increase in data is analyzed within the framework of a classification called the "5V Notation" in the literature. This notation; defines big data with criteria such as data volume, data variety, data processing speed, data accuracy and data value [1]. For example, financial transactions that need to be processed within seconds or situations requiring urgent intervention in the health sector clearly reveal the importance of data processing speed. Similarly, determining the accuracy of data coming from channels such as social media platforms is of critical importance in combating information pollution. Big data is evaluated not only with storage and access problems, but also with technical difficulties related to processing and interpreting this data. At this point, artificial intelligence and machine learning techniques stand out as effective tools in the analysis of big data. Artificial intelligence makes it possible to reach new information by extracting meaningful patterns and relationships from huge amounts of data. For example, the use of artificial intelligence in the health sector accelerates patient diagnoses and offers customized solutions in treatment processes. Machine learning algorithms, on the other hand, find applications in a wide range of areas from social media analysis to financial risk management. According to McKinsey's 2011 report [2], artificial intelligence applications have the potential to contribute $4.6 trillion to the global gross domestic product.

Big data analysis methods are fed by various disciplines and include areas such as statistics, data mining and machine learning [3]. While statistical methods allow for determining general trends by modeling data, data mining techniques aim to discover hidden patterns and relationships in large amounts of data. Machine learning, on the other hand, automates the processes of making predictions or making decisions on certain tasks by processing data through algorithms. For example, sub-branches such as neural networks, natural language processing (NLP) and image processing are among the artificial intelligence techniques frequently used for the analysis of big data [5].

The techniques mentioned above are used in every field where big data is available, depending on the variety of the problem. Education, finance, social media, and transportation are at the forefront of these fields. In addition, machine learning algorithms are also needed in the aviation field, where optimization is needed [4]. Route optimization, ticket pricing strategies, and passenger satisfaction analyzes in air transportation are effectively managed with big data and artificial intelligence. For example, machine learning algorithms used to minimize fuel consumption and reduce delays both reduce costs and contribute to environmental sustainability (IATA, 2023). In addition, the analysis of passenger behavior provides airline companies with important data to increase customer satisfaction. In this context, the combination of artificial intelligence with big data has not only provided operational efficiency but also transformed the customer-oriented service approach. Another important point is that the solutions in this field are compatible with the 12th article titled “Responsible Production and Consumption” within the 17 articles presented within the scope of the Sustainable Development Plan determined by the United Nations. The project developed within the scope of this study aims to develop a model to estimate food demand during flight.

Similar studies in the literature are presented below.

In the study "Evaluation of Machine Learning Algorithms for Customer Demand Prediction of In-Flight Meals" [13], the performances of various machine learning algorithms used to predict in-flight food demand were compared. However, one of the limitations of the study was the use of data collected only from short- and medium-haul flights.

This led to a narrow scope of the analyzed dataset and underrepresentation of food demand estimates across a wider range of flight distances. In addition, the study focused only on a basic feature such as flight duration. Factors such as demographic characteristics of flight passengers, flight time, and number of passengers were ignored. These deficiencies limit the accuracy of food demand prediction and reveal the need for a more comprehensive model.

In the study "In-Flight Sales Prediction Using Machine Learning" [16], the performances of LightGBM, Linear Regression, and Decision Tree models used to predict in-flight sales were compared. The study revealed that LightGBM showed superior performance due to its ability to better handle nonlinear relationships. However, one of the shortcomings of the study was the lack of qualitative data such as customer satisfaction. This lack of data limited the model's prediction accuracy. In addition, the focus of the study was based on predicting in-flight sales, and a solution that was applicable in a more niche area such as food stock prediction was not developed. These shortcomings narrowed the scope of application of the model and indicate that solutions that can address general operational optimization requirements should be developed more broadly.

In the study "Machine Learning for Sales Prediction in Big Mart" [14], algorithms such as Random Forest and Gradient Boosting were used to predict store sales. The study emphasized that data preprocessing, feature selection, and seasonal effects should be taken into account. The importance of extracting features from large data sets and incorporating them into the model was effectively emphasized. However, one of the biggest limitations of the study is the difficulties in processing large data sets and the inadequacy of integrating seasonal effects with features. In addition, the dataset used in the study focused on store sales, which prevented applications to narrower and more specific areas such as flight and food demand. These deficiencies reveal the need for more specialized and specific data models.

The study "Machine learning demand forecasting and supply chain performance" (Abadi & Javad, 2020) focused on demand forecasting, especially for perishable products. The study demonstrated the effectiveness of LSTM and CNN models in dealing with temporal data. In addition, it was emphasized that data augmentation methods are important in reducing data deficiencies. However, this study does not consider the requirements specific to the aircraft industry and focuses on demand forecasting in a wider range of products. It does not address the specific requirements for food demand forecasting in specific sectors such as air travel. In addition, studies on demand forecasting of perishable products are usually based on dynamics in other sectors, which may ignore the special conditions of the airline industry.

The studies presented above show that machine learning models can be used effectively in topics such as flight food demand forecasting or sales forecasting. For example, the "Evaluation of Machine Learning Algorithms for Customer Demand Prediction of In Flight Meals" study determined that flight duration has a significant impact on customer demand. The "In-Flight Sales Prediction Using Machine Learning" study emphasized that more complex algorithms such as LightGBM are superior in capturing nonlinear data relationships. The "Machine Learning for Sales Prediction in Big Mart" study drew attention to the fact that data preprocessing, seasonal changes, and feature selection are critical for forecasting models.

The methods and findings used in the relevant studies provided an important foundation for the SkyServe AI model and guided the project development process. The selection of the algorithms applied within the scope of this study was supported by the information obtained from the studies presented above, and an approach was adopted that expanded the scope of the project and increased its accuracy. By adapting the methods of these projects to its own context, this model managed to provide a more innovative and problem-oriented solution and developed a forecasting model focused on customer satisfaction.

The sub-problems of the study require addressing various factors in order to manage the food stock estimation process per flight correctly. First, it is necessary to model data such as passenger profile (such as age, gender, nationality) and flight duration. Such demographic information plays an important role in understanding the food preferences and consumption amounts of different passenger groups. In addition, external factors such as seasonal changes, special holidays and weather conditions can also affect the accuracy of the estimation model. These sub-problems reveal the necessity of data diversity for accurate and dynamic food stock estimation.

The limitations of the study are related to the accuracy and scope of the data used. Incomplete or incorrect existing data can negatively affect the success of the model. In addition, food demand variability can be affected not only by customer demographics, but also by cultural differences, airline food policies, and even unexpected situations during the flight. Therefore, the model cannot always be expected to work with 100% accuracy. In addition, while training a machine learning model relies on high-quality data and accurate algorithms, time and resources are required to do these processes correctly. Considering these limitations, the model's performance can be improved with richer data sets and advanced algorithms in the later stages of the project.

3. METHOD

This project provides a solution to food waste in the airline industry. The study was carried out with the support of expert academicians in the Software Engineering Department of a university in Istanbul. The main problem is the suggestions for waste caused by overproduction, more accurate estimation of food resources for certain flight numbers, and the availability of customer locations and departments.

3.1.1 Preparing a Data Set Appropriate for the Problem

During the preparation of the dataset, synthetic data similar to the data kept by airline companies were produced by taking the data obtained from Kaggle as a reference. This data includes flight information of customers, number of passengers and the number of food purchased on flights in the past. The dataset included flight duration, passenger types (e.g. Turkish male adult passenger, foreign female passenger) and product-based sales data.

3.1.2 Data Preprocessing

The following steps were taken to process the data and prepare it for analysis:

- Detection of missing and erroneous data and correction or removal with appropriate methods.
- Checking product IDs and selecting only real products.
- Combining data formats (e.g. date and time) and making them consistent.
- Analyzing anomalies in the data and reducing the impact of extreme values.

Sample process: During the coding phase, product IDs in the flights_product and stock_out files were matched and only data for existing products was included.

3.1.3 Cleaning and Consolidation of Data

The aim is to bring together data from multiple files to form a meaningful whole:

- Data cleaning: Incorrect entries and unnecessary columns were removed. For example, product IDs that do not exist in the stock_out file were cleaned from the data set.
- Data merging: All data was merged based on flight ID (Core_leg_isn). This process matched flight information with product sales and demand data.

Figure 1. Model Development Process. [Self Made].

3.1.4 Development of Machine Learning Model

In the modeling phase, a regression model was created that estimates food demand using customers' flight information:

● Independent variables: Passenger profiles, flight duration and other flight information.
● Dependent variables: Total demand for each product.
● Algorithm used: Random Forest Regressor, extended with MultiOutputRegressor to allow predictions for multiple products.

As in this code example written by us using the Random Forest library:

```
from sklearn.multioutput import MultiOutputRegressor
model = MultiOutputRegressor(RandomForestRegressor(n_estimators=100, random_state = 42))
model.fit(X_train, y_train)
y_pred = model.predict(X_test)
```

Table 1. Model Code Example [Self Made].

● The model provided high accuracy in predicting total demand and error metrics were calculated separately for each product.

3.1.5 Data Analysis and Interpretation of Results

The model results were analyzed and the prediction accuracy was evaluated:

● R^2 scores were calculated separately for each product.
● The strengths and weaknesses of the model were determined by comparing the error rates.

3.1.6 Results

The average R^2 score of the model was above 0.85, providing high success in food demand prediction. These methods formed the basic building blocks of the solution proposed to reduce food stock waste by airline companies. The model results were designed to contribute to more efficient decisions to be taken by companies.

3.2 Linear Regression, Random Forest Regressor and LightGBM Regressor

3.2.1 Linear Regression

Linear Regression is a statistical method used to predict a continuous target variable. This algorithm tries to model the linear relationship between the independent variables (features) and the dependent variable (target).

For example, the values “number of passengers” and “flight duration” are independent variables and are represented by x in the graph; “amount of food” is expressed as Y and changes depending on the X variables. As a result of model training, the program develops an equation in the form of “y=mx + c”, where the ‘m’ and ‘c’ values are determined. When we enter the X value, the y value it will give us actually means the “estimation of the amount” we want.

To express it in the figure below; the drawn line is positioned as close as possible to all points. This line represents the general trend of the data points and expresses the model’s predictive ability. The distance of the data points to the line indicates the model’s error rate. The goal is to minimize this error.

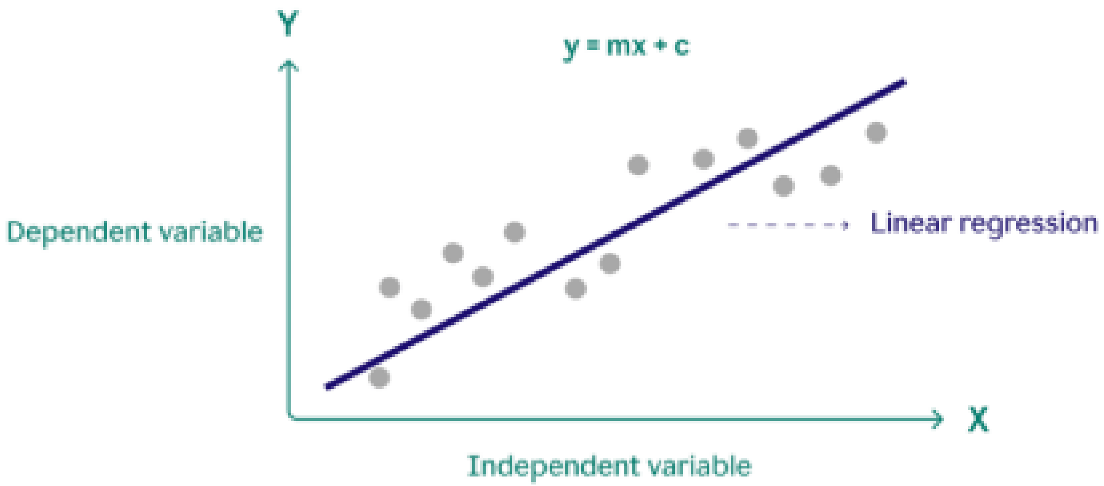

Figure 2. Linear Regression Graph Example [17].

Advantages of Linear Regression:
○ It is quite effective for linear relationships.
○ It has high interpretability.

Disadvantages of Linear Regression:
○ It cannot model non-linear relationships.
○ It is sensitive to outliers.

The table above shows how the Total Demand changes depending on the Flight Duration. Each blue dot represents a flight data, and the red line seen on the graph is the trend line created by the linear regression algorithm used to model the relationship between flight duration and total demand. This model shows that such a relationship can be analyzed, even if the amount and variety of data is limited. It is emphasized that much higher accuracy results can be obtained with more and more diverse data, as well as with correct modeling approaches. This study can be considered as a fundamental step in the transition to more complex models.

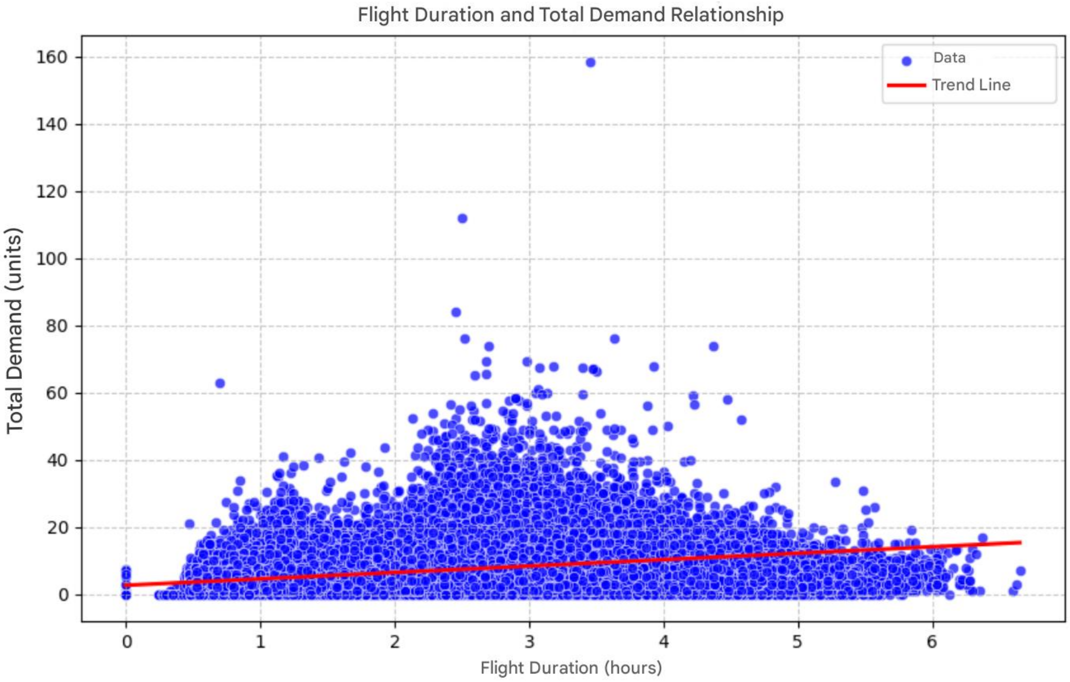

Figure 3. Flight Duration and Total Demand Relationship Graph [Self Made].

3.2.2 Random Forest Regressor

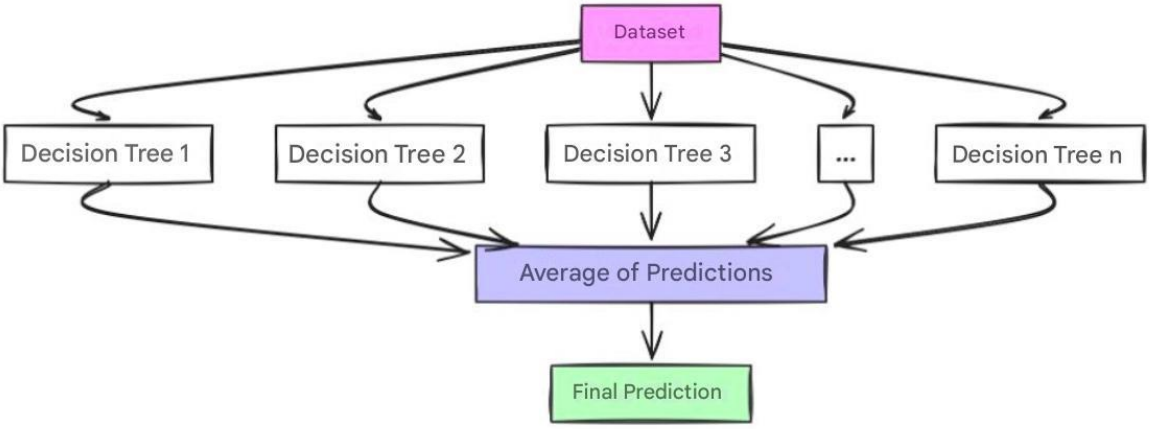

Figure 4. Random Forest Regressor Example [Self Made].

Random Forest Regressor is an ensemble learning method that makes predictions using multiple decision trees. This algorithm aims to make a more general prediction by "averaging" the decision trees. The basic working principles are as follows:

1. Random subsamples are selected from the dataset (Bootstrap method).
2. Decision trees are trained on each subsample. Each tree works with a specific subset of features.
3. In the prediction phase, the final prediction is obtained by averaging the predictions of all trees.

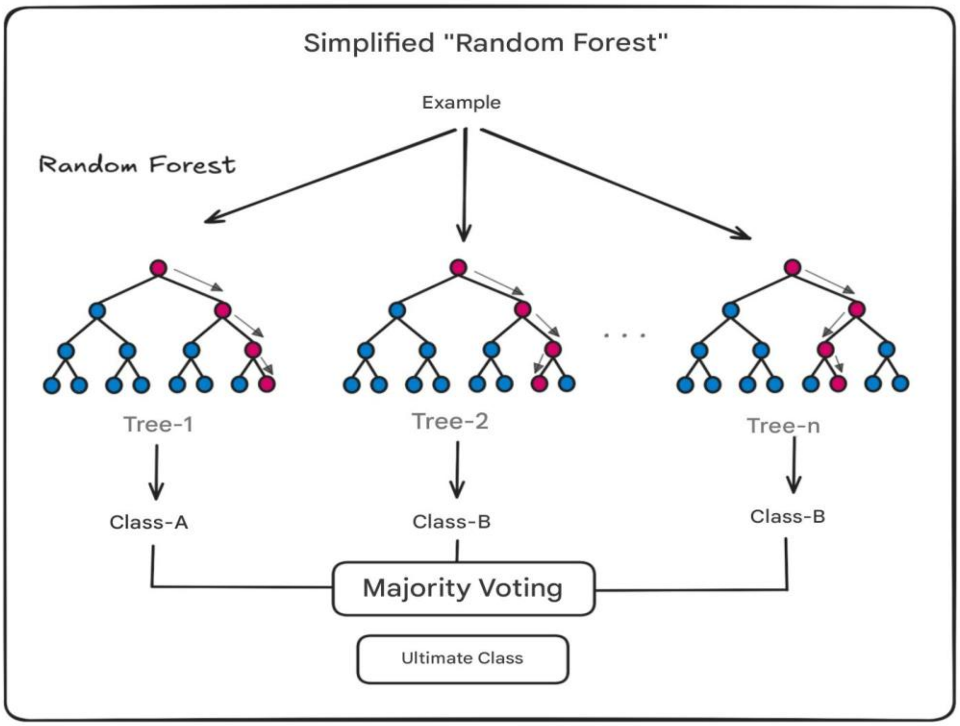

Figure 5. Connection Between Random Forest and Random Tree [18].

The basic idea behind Random Forest is to increase the overall performance by reducing the errors of different decision trees. Furthermore, the independence between trees strengthens the generalization ability.

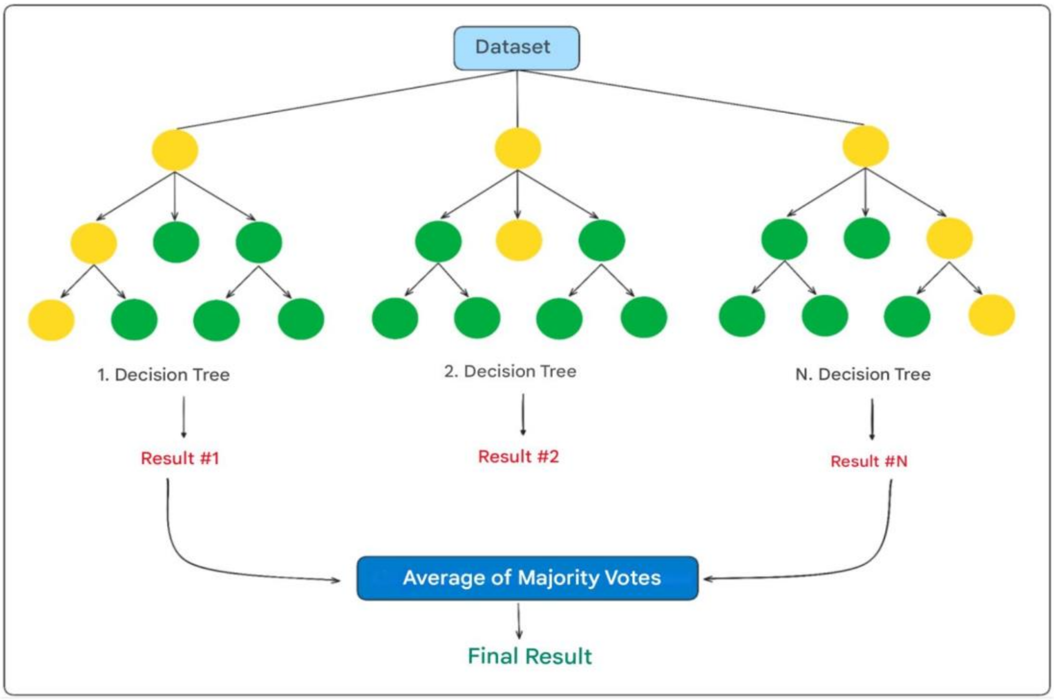

Figure 6. Random Forest Example [Self Made].

Advantages of Random Forest:
● Can model both linear and nonlinear relationships.
● Resistant to overfitting.
● Can be used to determine the importance of features.

Disadvantages of Random Forest:
● Can be slower and require more computational resources.
● Can sometimes be less effective on very large data sets.

Version	Algorithm	Data Used	R^2 Score	MAE	RMSE
Version 1	**LinearRegression()**	Total number of passengers, total demand	**0.02**	**20.5**	**25.1**
Version 2	**LinearRegression()**	Total number of passengers, flight duration, total demand	**0.06**	**18.3**	**22.7**
Version 3	**RandomForestRegressor()**	Total number of passengers; # Turkish male adults; # foreign male adults; # Turkish female adults; # foreign female adults; # Turkish child passengers; # foreign child passengers; # Turkish infant passengers; # foreign infant passengers; flight duration, total demand	**0.44**	**7.9**	**11.2**
Version 4	**LightGBMRegressor()**	Total number of passengers; # Turkish male adults; # foreign male adults; # Turkish female adults; # foreign female adults; # Turkish child passengers; # foreign child passengers; # Turkish infant passengers; # foreign infant passengers; flight duration, total demand	**0.85**	**2.28**	**3.35**

Figure 7. Versions and Algorithms Used Table [Self Made].

3.2.3. Random Forest vs Linear Regression

1. Model type:
○ Linear Regression: Suitable for linear relationships.
○ Random Forest: Can model both linear and non-linear relationships.

2. Performance:
○ Linear Regression: Effective on small data sets and linear relationships.
○ Random Forest: Generally performs better on large datasets and complex relationships.

3. Outliers:
○ Linear Regression: Sensitive to outliers.
○ Random Forest: More resilient to outliers.

4. Speed:
○ Linear Regression: Works faster.
○ Random Forest: Requires more computing power and time.

5. Interpretability:
○ Linear Regression: More easily interpretable.
○ Random Forest: More difficult to interpret, but offers the advantage of determining feature importance.

3.2.4. LightGBM

1.Model type:
○ LightGBM: Gradient-boosted decision trees optimized for speed and accuracy.

2.Performance:
○ LightGBM: Consistently achieves higher R^2 and lower error than both linear and random-forest models on large, complex datasets.

3.Outliers & missing data:
○ LightGBM: Naturally handles missing values and is robust to outliers via tree-based splits.

4.Speed & scalability:
○ LightGBM: Implements histogram-based learning and leaf-wise tree growth, delivering much faster training and inference on big data.

5.Interpretability & tuning:

○ LightGBM: Provides built-in feature-importance metrics and integrates seamlessly with SHAP for detailed model explanations, while offering extensive hyperparameter tuning options.

4. FINDINGS

In this section, a graph comparing the actual and estimated demand amounts is presented to better understand the analysis of the obtained data. The dataset used in this study is fully real, containing actual operational records from the airline transportation sector. In the graph, the blue dots represent the actual demand, and the orange crosses represent the estimated demand. As can be seen, while the actual demand values exhibit a wide distribution, the estimated demand is concentrated in a narrower range. This situation shows that the model is successful in capturing general trends but has difficulty representing sudden increases or extreme values in the demand amount. It is also noteworthy that the estimates are more accurate in low demand ranges, while deviations become more pronounced at high demand levels. These findings reveal that the performance of the model should be analyzed in more detail in data sets showing high variance.

In this study, more than 180,000 flight data belonging to the airline transportation sector were analyzed. The data set used includes information such as flight identity (ID), number of passengers, flight duration, food types and quantities for each flight. The model was trained on this comprehensive data set and gained the ability to make estimates. During the training process, the data set was divided into 80% training and 20% test data, and the performance of the model was evaluated based on this division.

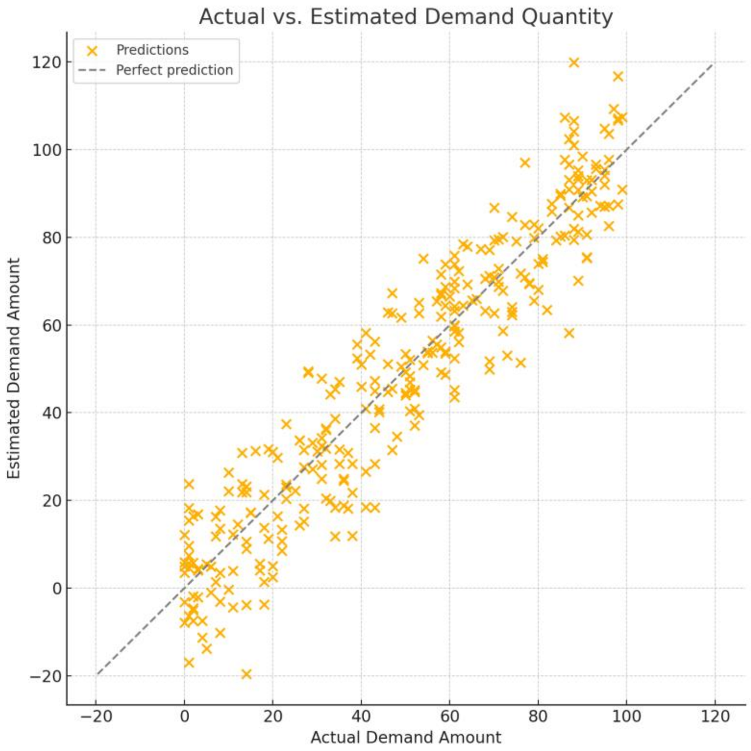

Figure 8. Actual vs. Estimated Demand Quantity Graph [Self Made].

The following basic findings were reached during the data analysis process:

1. Passengers with Similar Profiles: Similar food consumption was observed on flights with passengers of similar age and occupation ranges.
2. Occupancy Rate: Food consumption was found to be more predictable on flights with high occupancy rates, highlighting the impact of occupancy rates on food forecast accuracy.
3. Analysis of Model Outputs: The model's initial outputs were compared with consumption values to assess its accuracy. This benchmarking process provides a roadmap for improving the model's performance. The model's current predictive success can be improved with future optimizations.
4. Future Potential: The findings obtained during the study provide an important basis for improving data-driven decision-making processes in food stock management. The model is open to development to increase forecast accuracy and support operational efficiency.

4. CONCLUSION and DISCUSSION

The predictions of the developed model were compared with the food consumptions at the end of the flight, thus validating the learning mechanism of the model. However, a detailed analysis was not performed. The first results show that the model has a general prediction ability. These results can contribute to airline companies optimizing their food planning processes. However, in order to take the performance of the model to a higher level, detailed error analysis, performance metrics and additional data sources are planned to be integrated into the model.

In this study, a prediction model that can help airline companies optimize their food planning processes was developed and the first results were evaluated. The model made food consumption predictions based on flight data and the obtained predictions were compared with the consumption values realized after the flight. This process provided validation of the general prediction capacity of the model. In the first analyses, it was seen that the model has a certain prediction ability; However, the model can be improved by expanding the data set, model optimization and analyzing the errors.

The performance of the model is limited by the size and diversity of the existing data set. Although data from 180,000 flights have been studied, the features and algorithms used in the model need to be improved. In this context, it is planned to add additional features to the dataset such as customer preferences, seasonal factors and flight classes. Such an expansion can increase the model's prediction accuracy and make food consumption predictions more realistic. In addition, comparing the pre-flight predictions with the post-flight data and providing feedback to the model can strengthen the learning process and increase the model's adaptability.

The commercial applicability of the approach used in the study was considered. When the developed model is optimized correctly, it can help airlines reduce their costs and make their resource use more efficient. In particular, accurate estimation of food stock per flight can play a critical role in reducing waste. However, a more comprehensive testing process is needed before switching to commercial use. The accuracy rates of the model's predictions made with real flight data should be evaluated with detailed error analyses.

The initial findings obtained in line with the research question "How can we accurately estimate the food stock required per flight using customer data?" indicate a starting point. It has been understood that the prediction accuracy rates can be increased by using more data and optimizing the algorithms. In addition, the integration of a continuous learning mechanism can enable the model to update itself after each flight and make better predictions. This will contribute significantly not only to food planning but also to areas such as price performance and cost. As a result, this study offers an important solution to the food planning problem in the airline sector. However, more data analysis, model optimization and testing processes are needed for the model to be applied in the commercial field and to reach high accuracy rates. Future studies will guide us to achieve these goals.

Authors' Contributions

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1- Study design, 2- Data collection, 3- Data analysis and interpretation, 4- Manuscript writing, 5- Critical revision			

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September 2025, Vol:3, Issue:2

International Journal of New Findings in Engineering, Science and Technology

journal homepage: https://ijonfest.gedik.edu.tr/

Received:25.06.2025 Accepted:16.09.2025 Pablished:29.09.2025

Soft Intersection-star Product of Groups

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Abstract

Soft set theory provides a mathematically rigorous and algebraically expressive framework for modeling systems characterized by epistemic uncertainty, vagueness, and parameter-dependent variability—phenomena central to decision theory, engineering, economics, and information science. Expanding on this foundation, the present study introduces and examines a novel binary operation, the soft intersection–star product, defined over soft sets with parameter domains possessing intrinsic group-theoretic structures. Developed within a formally consistent, axiomatic framework, this operation aligns with generalized concepts of soft subsethood and soft equality. A comprehensive algebraic analysis is conducted for the operation's core properties—closure, associativity, commutativity, and idempotency. The presence or absence of identity, inverse, and absorbing elements, and the soft product's behavior concerning the null and absolute soft sets, are precisely delineated. Two key contributions emerge: first, the operation substantially extends the algebraic toolkit of soft set theory within a rigorous operational framework; second, it lays the foundation for a generalized soft group theory, wherein soft sets indexed by group-structured parameters mimic classical group behavior through abstractly defined soft operations. Beyond its theoretical value, the proposed framework offers a principled basis for soft computational modeling grounded in abstract algebra. Such models are highly applicable to multi-criteria decision analysis, algebraic classification, and uncertainty-sensitive data analytics. Hence, this study not only strengthens the theoretical foundations of soft algebra but also reinforces its relevance to both mathematical research and practical computation.

Keywords: Soft sets; Soft subsets; Soft equalities; Soft intersection-star product.

1. INTRODUCTION

A wide array of mathematically sophisticated frameworks has been developed to model uncertainty, vagueness, and indeterminacy—features prevalent in engineering, economics, social sciences, and medical diagnostics. Yet, classical paradigms such as fuzzy set theory and probabilistic models face epistemological and algebraic limitations. Fuzzy set theory by Zadeh [1] relies on subjectively defined membership functions, while probabilistic models assume repeatable experiments and precise distributions—conditions often unmet in real-world settings.

To address these shortcomings, Molodtsov [2] introduced soft set theory as an axiomatically minimal yet structurally adaptable alternative, where uncertainty is captured through parameter dependence rather than probabilities or membership grades. Since then, its algebraic structure has evolved significantly. Foundational operations—including union, intersection, and AND/OR products—originally introduced by Maji et al. [3], were reformulated by Pei and Miao [4] through an information-theoretic perspective. Ali et al. [5] further enhanced this framework by defining restricted and extended variants, thereby increasing its algebraic granularity and expressive power. A substantial and evolving corpus of scholarship—including contributions from [6-19]—have addressed semantic ambiguities, introduced generalized notions of soft equality, and defined novel binary operations, thereby progressively enriching the algebraic landscape of the theory. More recent advances have

https://doi.org/10.61150/ijonfest.2025030205

extended this foundation through the systematic introduction and rigorous algebraic examination of new operations. Noteworthy among these are the contributions of [20-35] whose collective efforts have established a robust, extensible, and internally consistent algebraic framework underpinning ongoing developments in soft set theory.

A pivotal dimension of this progression concerns the formalization and generalization of soft subsethood and soft equality. The foundational concept of soft subsets introduced by Maji et al. [3] was generalized by Pei and Miao [4] and Feng et al. [7], while Qin and Hong [36] contributed soft congruences embedding equivalence relations within the soft universe. Jun and Yang [37] further enhanced the theoretical apparatus by proposing J-soft equalities alongside related distributive principles. Liu et al. [38] introduced L-soft subsets and L-equality, revealing violations of classical distributive laws within generalized soft contexts. Feng and Li [39] developed a comprehensive classification of soft subsets under L-equality and demonstrated that certain quotient structures satisfy associativity, commutativity, and distributivity, thereby exhibiting semigroup properties. Broader generalizations—including g-soft, gf-soft, and T-soft equalities—were subsequently advanced by Abbas et al. [40,41], Al-shami [42], and Al-shami and El-Shafei [43], who explored congruence-based and lattice-theoretic formulations of soft algebraic systems.

A significant reformulation of the definitional and operational calculus was realized through the axiomatic restructuring introduced by Çağman and Enginoğlu [44], which resolved structural inconsistencies inherent in the original theory and provided a logically coherent, algebraically tractable foundation for further inquiry. This enhanced formalism now supports a wide range of applications across algebra, decision theory, and soft computing. Parallel research extended binary soft products across algebraic domains, notably generalizing the soft intersection–union product to rings [45], semigroups [46], and groups [47], thereby establishing the notions of soft rings, soft semigroups, and soft groups. Its dual operation, the soft union–intersection product, has been similarly examined within group-theoretic [48], semigroup-theoretic [49], and ring-theoretic [50] frameworks, with the algebraic behavior depending critically on structural elements such as identities and inverses within the parameter domains.

Building upon this extensive foundation, the present study introduces a novel binary operation—termed the soft intersection-star product—defined on soft sets indexed by group-structured parameter domains. This operation is rigorously axiomatized and subjected to comprehensive algebraic scrutiny. We explore its core properties, including closure, associativity, commutativity, and idempotency. Furthermore, we analyze its interactions with identity and absorbing elements and verify its compatibility with generalized soft subsethood and soft equality, ensuring seamless integration into the existing algebraic architecture of soft set theory. A comparative evaluation against established soft binary operations highlights its representational expressiveness and algebraic coherence across stratified soft subset classifications. The operation's behavior vis-à-vis null and absolute soft sets is also formally characterized. By generalizing classical group-theoretic constructs within the soft set framework, this operation establishes a conceptual foundation for a generalized soft group theory—wherein soft sets emulate classical algebraic behavior under rigorously defined soft operations. The manuscript is organized as follows: Section 2 introduces fundamental definitions and preliminaries; Section 3 develops the algebraic theory of the soft intersection-star product in detail; and Section 4 synthesizes the principal findings and outlines prospective directions for advancing the algebraic foundations of soft sets and their applications in abstract algebra and uncertainty quantification.

2. PRELIMINARIES

This section presents a rigorous rearticulation of the foundational definitions and algebraic axioms underpinning this study. Originally introduced by Molodtsov [2] to model systems with epistemic uncertainty, soft set theory lacked the algebraic rigor needed for formal development. The axiomatic refinement by Çağman and Enginoğlu [44] addressed these limitations, resolving internal inconsistencies and establishing a coherent, algebraically sound framework. The present work adopts this refined structure as the basis for all subsequent developments, ensuring internal coherence, structural integrity, and alignment with established standards in soft algebra. Unless stated otherwise, all references to soft sets and operations are made within this axiomatic framework.

Definition 2.1. [44] Let E be a parameter set, U be a universal set, $P(U)$ be the power set of U, and $\mathcal{H} \subseteq E$. Then, the soft set $\not{f}_{\mathcal{H}}$ over U is a function such that $\not{f}_{\mathcal{H}}: E \to P(U)$, where for all $w \notin \mathcal{H}$, $\not{f}_{\mathcal{H}}(w) = \emptyset$. That is,

$$\not{f}_{\mathcal{H}} = \{(w, \not{f}_{\mathcal{H}}(w)): w \in E\}$$

From now on, the soft set over U is abbreviated by $\mathcal{SS}$.

Definition 2.2. [44] Let $\mathscr{f}_{\mathcal{H}}$ be an $\mathcal{SS}$. If $\mathscr{f}_{\mathcal{H}}(w) = \emptyset$ for all $w \in E$, then $\mathscr{f}_{\mathcal{H}}$ is called a null $\mathcal{SS}$ and indicated by $\emptyset_E$, and if $\mathscr{f}_{\mathcal{H}}(w) = U$, for all $w \in E$, then $\mathscr{f}_{\mathcal{H}}$ is called an absolute $\mathcal{SS}$ and indicated by U_E.

Definition 2.3. [44] Let $\mathscr{f}_{\mathcal{H}}$ and $\mathscr{g}_{\aleph}$ be two $\mathcal{SS}$s. If $\mathscr{f}_{\mathcal{H}}(w) \subseteq \mathscr{g}_{\aleph}(w)$, for all $w \in E$, then $\mathscr{f}_{\mathcal{H}}$ is a soft subset of $\mathscr{g}_{\aleph}$ and indicated by $\mathscr{f}_{\mathcal{H}} \tilde{\subseteq} \mathscr{g}_{\aleph}$. If $\mathscr{f}_{\mathcal{H}}(w) = \mathscr{g}_{\aleph}(w)$, for all $w \in E$, then $\mathscr{f}_{\mathcal{H}}$ is called soft equal to $\mathscr{g}_{\aleph}$, and indicated by $\mathscr{f}_{\mathcal{H}} = \mathscr{g}_{\aleph}$.

Definition 2.4. [44] Let $\mathscr{f}_{\mathcal{H}}$ and $\mathscr{g}_{\aleph}$ be two $\mathcal{SS}$s. Then, the union of $\mathscr{f}_{\mathcal{H}}$ and $\mathscr{g}_{\aleph}$ is the $\mathcal{SS}$ $\mathscr{f}_{\mathcal{H}} \tilde{\cup} \mathscr{g}_{\aleph}$, where $(\mathscr{f}_{\mathcal{H}} \tilde{\cup} \mathscr{g}_{\aleph})(w) = \mathscr{f}_{\mathcal{H}}(w) \cup \mathscr{g}_{\aleph}(w)$, for all $w \in E$.

Definition 2.5. [44] Let $f_{\mathcal{H}}$ be an $\mathcal{SS}$. Then, the complement of $f_{\mathcal{H}}$ denoted by ${f_{\mathcal{H}}}^{c}$, is defined by the soft set ${f_{\mathcal{H}}}^{c}: E \to P(U)$ such that ${f_{\mathcal{H}}}^{c}(e) = U \setminus f_{\mathcal{H}}(e) = \left(f_{\mathcal{H}}(e)\right)'$, for all $e \in E$.

Definition 2.6. [51] Let $\mathscr{f}_K$ and $\mathscr{g}_{\aleph}$ be two $\mathcal{SS}$s. Then, $\mathscr{f}_K$ is called a soft S-subset of $\mathscr{g}_{\aleph}$, denoted by $\mathscr{f}_K \tilde{\subseteq}_S \mathscr{g}_{\aleph}$ if for all $w \in E$, $\mathscr{f}_K(w) = \mathcal{M}$ and $\mathscr{g}_{\aleph}(w) = \mathcal{D}$, where $\mathcal{M}$ and $\mathcal{D}$ are two fixed sets and $\mathcal{M} \subseteq \mathcal{D}$. Moreover, two SSs $\mathscr{f}_K$ and $\mathscr{g}_{\aleph}$ are said to be soft S-equal, denoted by $\mathscr{f}_K =_S \mathscr{g}_{\aleph}$, if $\mathscr{f}_K \tilde{\subseteq}_S \mathscr{g}_{\aleph}$ and $\mathscr{g}_{\aleph} \tilde{\subseteq}_S \mathscr{f}_K$.

It is obvious that if $\mathscr{f}_K =_S \mathscr{g}_{\aleph}$, then $\mathscr{f}_{\mathrm{K}}$ and $\mathscr{g}_{\aleph}$ are the same constant functions, that is, for all $w \in E$, $\mathscr{f}_K(w) = \mathscr{g}_{\aleph}(w) = \mathcal{M}$, where $\mathcal{M}$ is a fixed set .

Definition 2.7. [51] Let $\mathscr{f}_K$ and $\mathscr{g}_{\aleph}$ be two $\mathcal{SS}$s. Then, $\mathscr{f}_K$ is called a soft A-subset of $\mathscr{g}_{\aleph}$, denoted by $\mathscr{f}_K \tilde{\subseteq}_A \mathscr{g}_{\aleph}$, if, for each $a, b \in E$, $\mathscr{f}_K(a) \subseteq \mathscr{g}_{\aleph}(b)$.

Definition 2.8. [51] Let $\mathscr{f}_K$ and $\mathscr{g}_{\aleph}$ be two $\mathcal{SS}$s. Then, $\mathscr{f}_K$ is called a soft S-complement of $\mathscr{g}_{\aleph}$, denoted by $\mathscr{f}_K =_S (\mathscr{g}_{\aleph})^c$, if, for all $w \in E$, $\mathscr{f}_K(w) = \mathcal{M}$ and $\mathscr{g}_{\aleph}(w) = \mathcal{D}$, where $\mathcal{M}$ and $\mathcal{D}$ are two fixed sets and $\mathcal{M} = \mathcal{D}'$. Here, $\mathcal{D}' = U \setminus \mathcal{D}$.

From now on, let G be a group, and $S_G(U)$ denotes the collection of all $\mathcal{SS}$s over U, whose parameter sets are G; that is, each element of $S_G(U)$ is an $\mathcal{SS}$ parameterized by G.

Definition 2.9. [48] Let $\mathscr{f}_G$ and $\mathscr{g}_G$ be two $\mathcal{SS}$s. Then, the union-intersection product $\mathscr{f}_G \otimes_{u/i} \mathscr{g}_G$ is defined by

$$(\mathscr{f}_G \otimes_{u/i} \mathscr{g}_G)(x) = \bigcup_{x=yz} \left(\mathscr{f}_G(y) \cap \mathscr{g}_G(z)\right), \quad y, z \in G$$

for all $x \in G$.

For additional information on $\mathcal{SS}$s, we refer to [52-90].

3. SOFT INTERSECTION-STAR PRODUCT OF GROUPS

This section introduces and investigates a novel binary operation on soft sets, termed the soft intersection-star product, defined over group-structured parameter domains. A detailed algebraic analysis establishes key properties such as closure, associativity, commutativity, idempotency, and compatibility with generalized soft equality and subsethood. The operation's behavior is examined within established inclusion hierarchies and positioned within the broader algebraic framework of soft set theory. Comparative analysis with existing soft operations further highlights its expressive capacity, structural coherence, and integrability. To support the theoretical development, illustrative examples are provided, showcasing subtle operational dynamics. Together, these results affirm the soft intersection-star product as a robust and foundational construct for the ongoing algebraic expansion of soft set theory.

Definition 3.1. Let $\mathscr{f}_G$ and $\mathscr{g}_G$ be two $\mathcal{SS}$s. Then, the soft intersection-star product $\mathscr{f}_G \otimes_{i/st} \mathscr{g}_G$ is defined by

$$(\mathscr{f}_G \otimes_{i/st} \mathscr{g}_G)(x) = \bigcap_{x=yz} \left(\mathscr{f}_G(y) * \mathscr{g}_G(z)\right) = \bigcap_{x=yz} \left({\mathscr{f}_G}^{c}(y) \cup {\mathscr{g}_G}^{c}(z)\right), \qquad y, z \in G$$

for all $x \in G$.

Note here that since G is a group, there always exist $y, z \in G$ such that $x = yz$, for all $x \in G$. Let the order of the group G be n, that is, $|G| = n$. Then, it is obvious that there exist n distinct algebraic representations for expressing each $x \in G$ such that $x = yz$, where $y, z \in G$. Besides, for more on star $(*)$ operation of sets, we refer to [86].

Note 3.2. The soft intersection-star product is well-defined in $S_G(U)$. In fact, let f_G, g_G, r_G, $k_G \in S_G(U)$ such that $(f_G, g_G) = (r_G, k_G)$. Then, $f_G = r_G$ and $g_G = k_G$, implying that $f_G(x) = r_G(x)$ and $g_G(x) = k_G(x)$ for all $x \in G$. Thereby, for all $x \in G$,

$$\begin{aligned}(f_G \otimes_{i/st} g_G)(x) &= \bigcap_{x=yz} \left(f_G{}^c(y) \cup g_G{}^c(z)\right)\\ &= \bigcap_{x=yz} \left(r_G{}^c(y) \cup k_G{}^c(z)\right)\\ &= (r_G \otimes_{i/st} k_G)(x)\end{aligned}$$

Hence, $f_G \otimes_{i/st} g_G = r_G \otimes_{i/st} k_G$.

Example 3.3. Consider the group $G = \{Ձ, б\}$ with the following operation:

·	Ձ	б
Ձ	Ձ	б
б	б	Ձ

Let f_G and g_G be two SSs over $U = D_2 = \{< x, y >: x^2 = y^2 = e, xy = yx\} = \{e, x, y, yx\}$ as follows:

$$f_G = \{(Ձ, \{e, x, y\}), (б, \{yx\})\} \text{ and } g_G = \{(Ձ, \{y\}), (б, \{e, yx\})\}$$

Since $Ձ = ՁՁ = бб$, $(f_G \otimes_{i/st} g_G)(Ձ) = (f_G{}^c(Ձ) \cup g_G{}^c(Ձ)) \cap (f_G{}^c(б) \cup g_G{}^c(б)) = \{e, x\}$ and since $б = Ձб = бՁ$, $(f_G \otimes_{i/st} g_G)(б) = (f_G{}^c(Ձ) \cup g_G{}^c(б)) \cap (f_G{}^c(б) \cup g_G{}^c(Ձ)) = \{x, y, yx\}$ is obtained. Hence,

$$f_G \otimes_{i/st} g_G = \{(Ձ, \{e, x\}), (б, \{x, y, yx\})\}$$

Proposition 3.4. The set $S_G(U)$ is closed under the soft intersection-star product. That is, if f_G and g_G are two SSs, then so is $f_G \otimes_{i/st} g_G$.

PROOF. It is obvious that the soft intersection-star product is a binary operation in $S_G(U)$. Thereby, $S_G(U)$ is closed under the soft intersection-star product.

Proposition 3.5. The soft intersection-star product is not associative in $S_G(U)$.

PROOF. Consider the SSs f_G and g_G over $U = \{e, x, y, yx\}$ in Example 3.3. Let $\hbar_G = \{(Ձ, \{x\}), (б, \{y, yx\})\}$ be a SS. Since $f_G \otimes_{i/st} g_G = \{(Ձ, \{e, x\}), (б, \{x, y, yx\})\}$, then

$$(f_G \otimes_{i/st} g_G) \otimes_{i/st} \hbar_G = \{(Ձ, \{e\}), (б, \{e, y, yx\})\}$$

Moreover, since $g_G \otimes_{i/st} \hbar_G = \{(Ձ, \{e, x, y\}), (б, \{e, x, yx\})\}$, then

$$f_G \otimes_{i/st} (g_G \otimes_{i/st} \hbar_G) = \{(Ձ, \emptyset), (б, \{y, yx\})\}$$

Thereby, $(f_G \otimes_{i/st} g_G) \otimes_{i/st} \hbar_G \neq f_G \otimes_{i/st} (g_G \otimes_{i/st} \hbar_G)$. □

Proposition 3.6. The soft intersection-star product is not commutative in $S_G(U)$. However, if G is an abelian group, then the intersection-star product is commutative in $S_G(U)$.

PROOF. Let f_G and g_G be two SSs and G be an abelian group. Then, for all $x \in G$,

$$(f_G \otimes_{i/st} g_G)(x) = \bigcap_{x=yz} \left(f_G{}^c(y) \cup g_G{}^c(z)\right)$$

$$= \bigcap_{x=zy} \left(g_G{}^c(z) \cup f_G{}^c(y) \right)$$
$$= \left(g_G \otimes_{i/st} f_G \right)(x)$$

implying that $f_G \otimes_{i/st} g_G = g_G \otimes_{i/st} f_G$. □

Example 3.7. Consider the $\mathcal{SS}$s f_G and g_G over $U = \{e, x, y, yx\}$ in Example 3.3. Then,

$f_G \otimes_{i/st} g_G = \{(\mathfrak{Q}, \{e, x\}), (\mathfrak{b}, \{x, y, yx\})\}$, and $g_G \otimes_{i/st} f_G = \{(\mathfrak{Q}, \{e, x\}), (\mathfrak{b}, \{x, y, yx\})\}$

implying that $f_G \otimes_{i/st} g_G = g_G \otimes_{i/st} f_G$.

Proposition 3.8. The soft intersection-star product is not idempotent in $S_G(U)$.

PROOF. Consider the $\mathcal{SS}$ f_G in Example 3.3. Then, for all $x \in G$,

$$f_G \otimes_{i/st} f_G = \{(\mathfrak{Q}, U), (\mathfrak{b}, \emptyset)\}$$

implying that $f_G \otimes_{i/st} f_G \neq f_G$. □

Proposition 3.9. Let f_G be a constant $\mathcal{SS}$. Then, $f_G \otimes_{i/st} f_G = f_G{}^c$.
PROOF. Let f_G be a constant $\mathcal{SS}$ such that, for all $x \in G$, $f_G(x) = A$, where A is a fixed set. Hence, for all $x \in G$,

$$\left(f_G \otimes_{i/st} f_G \right)(x) = \bigcap_{x=yz} \left(f_G{}^c(y) \cup f_G{}^c(z) \right) = f_G{}^c(x)$$

Thereby, $f_G \otimes_{i/st} f_G = f_G{}^c$. □

Remark 3.10. Let $S_G{}^*(U)$ be the collection of all constant $\mathcal{SS}$s. Then, the soft intersection-star product is not idempotent in $S_G{}^*(U)$ either.

Proposition 3.11. Let f_G be a constant $\mathcal{SS}$. Then, $U_G \otimes_{i/st} f_G = f_G \otimes_{i/st} U_G = f_G{}^c$.
PROOF. Let f_G be a constant $\mathcal{SS}$ such that, for all $x \in G$, $f_G(x) = A$, where A is a fixed set. Hence, for all $x \in G$,

$$\left(U_G \otimes_{i/st} f_G \right)(x) = \bigcap_{x=yz} \left(U_G{}^c(y) \cup f_G{}^c(z) \right)$$
$$= \bigcap_{x=yz} \left(\emptyset \cup f_G{}^c(z) \right)$$
$$= f_G{}^c(x)$$

Similarly, for all $x \in G$,

$$\left(f_G \otimes_{i/st} U_G \right)(x) = \bigcap_{x=yz} \left(f_G{}^c(y) \cup U_G{}^c(z) \right)$$
$$= \bigcap_{x=yz} \left(f_G{}^c(y) \cup \emptyset \right)$$
$$= f_G{}^c(x)$$

Thereby, $U_G \otimes_{i/st} f_G = f_G \otimes_{i/st} U_G = f_G{}^c$. □

Proposition 3.12. Let f_G be a constant $\mathcal{SS}$. Then, $\emptyset_G \otimes_{i/st} f_G = f_G \otimes_{i/st} \emptyset_G = U_G$.

PROOF**.** Let f_G be a constant $\mathcal{SS}$ such that, for all $x \in G$, $f_G(x) = A$, where A is a fixed set. Hence, for all $x \in G$,

$$\left(\emptyset_G \otimes_{i/st} f_G \right)(x) = \bigcap_{x=yz} \left(\emptyset_G{}^c(y) \cup f_G{}^c(z) \right)$$

$$= \bigcap_{x=yz} \left(U \cup f_G{}^c(z)\right)$$
$$= U_G(x)$$

Similarly, for all $x \in G$,

$$\left(f_G \otimes_{i/st} \emptyset_G\right)(x) = \bigcap_{x=yz} \left(f_G{}^c(y) \cup \emptyset_G{}^c(z)\right)$$
$$= \bigcap_{x=yz} \left(f_G{}^c(y) \cup U\right)$$
$$= U_G(x)$$

Thereby, $\emptyset_G \otimes_{i/st} f_G = f_G \otimes_{i/st} \emptyset_G = U_G$. □

Proposition 3.13. Let f_G be a constant $\mathcal{SS}$. Then, $f_G \otimes_{i/st} f_G{}^c = f_G{}^c \otimes_{i/st} f_G = U_G$.

PROOF**.** Let f_G be a constant $\mathcal{SS}$ such that, for all $x \in G$, $f_G\,(x) = A$, where A is a fixed set. Hence, for all $x \in G$,

$$\left(f_G \otimes_{i/st} f_G{}^c\right)(x) = \bigcap_{x=yz} \left(f_G{}^c(y) \cup (f_G{}^c)^c(z)\right)$$
$$= \bigcap_{x=yz} \left(f_G{}^c(y) \cup f_G(z)\right)$$
$$= U_G\,(x)$$

Similarly,

$$\left(f_G{}^c \otimes_{i/st} f_G\right)(x) = \bigcap_{x=yz} \left((f_G{}^c)^c(y) \cup f_G{}^c(z)\right)$$
$$= \bigcap_{x=yz} \left(f_G(y) \cup f_G{}^c(z)\right)$$
$$= U_G\,(x)$$

Thereby, $f_G \otimes_{i/st} f_G{}^c = f_G{}^c \otimes_{i/st} f_G = U_G$. □

Proposition 3.14. Let f_G and g_G be two $\mathcal{SS}$s. If $f_G \widetilde{\subseteq}_S g_G$, then $f_G \otimes_{i/st} g_G = f_G{}^c$.

PROOF. Let f_G and g_G be two $\mathcal{SS}$s and $f_G \widetilde{\subseteq}_S g_G$. Hence, for all $x \in G$, $f_G(x) = A$ and $g_G(x) = B$, where A and B are two fixed sets and $A \subseteq B$. Thus, for all $x \in G$, $g_G{}^c(x) \subseteq f_G{}^c(x)$. Then,

$$\left(f_G \otimes_{i/st} g_G\right)(x) = \bigcap_{x=yz} \left(f_G{}^c(y) \cup g_G{}^c(z)\right) = f_G{}^c(x)$$

for all $x \in G$. Thereby, $f_G \otimes_{i/st} g_G = f_G{}^c$. □

Proposition 3.15. Let f_G and g_G be two $\mathcal{SS}$s. If $g_G \widetilde{\subseteq}_S f_G$, then $f_G \otimes_{i/st} g_G = g_G{}^c$.

PROOF. Let f_G and g_G be two $\mathcal{SS}$s and $g_G \widetilde{\subseteq}_S f_G$. Hence, for all $x \in G$, $f_G(x) = A$ and $g_G(x) = B$, where A and B are two fixed sets and $B \subseteq A$. Thus, for all $x \in G$, $f_G{}^c(x) \subseteq g_G{}^c(x)$. Then,

$$\left(f_G \otimes_{i/st} g_G\right)(x) = \bigcap_{x=yz} \left(f_G{}^c(y) \cup g_G{}^c(z)\right) = g_G{}^c(x)$$

Thereby, $f_G \otimes_{i/st} g_G = g_G{}^c$. □

Proposition 3.16. Let f_G and g_G be two $\mathcal{SS}$s. If $f_G \widetilde{\subseteq}_S g_G{}^c$, then $f_G \otimes_{i/st} g_G = U_G$.

PROOF. Let f_G and g_G be two $\mathcal{SS}$s and $f_G \widetilde{\subseteq}_S g_G{}^c$. Hence, for all $x \in G$, $f_G(x) = A$ and $g_G(x) = B$, where A and B are two fixed sets and $A \subseteq B'$. Thus, for all $x \in G$,

$$\left(f_G \otimes_{i/st} g_G\right)(x) = \bigcap_{x=yz} \left(f_G{}^c(y) \cup g_G{}^c(z)\right) = U_G(x)$$

Thereby, $f_G \otimes_{i/st} g_G = U_G$. Here, note that, in classical set theory, if $A \subseteq B'$, then $A \cap B = \emptyset$, thus, $(A \cap B)' = A' \cup B' = U$. □

Note 3.17. Proposition 3.16 is also satisfied for the soft A-subset condition.

Proposition 3.18. Let $\mathscr{f}_G$ and $\mathscr{g}_G$ be two $\mathcal{SS}$s. If one of the following assertions is satisfied, then $\mathscr{f}_G \otimes_{i/st} \mathscr{g}_G = U_G$.

i. $\mathscr{f}_G = \emptyset_G$ or $\mathscr{g}_G = \emptyset_G$

ii. $\mathscr{f}_G \,\tilde{\subseteq}_A\, \mathscr{g}_G{}^c$

iii. $\mathscr{f}_G \,\tilde{\subseteq}_S\, \mathscr{g}_G{}^c$

PROOF. (i) follows by Proposition 3.12, (ii) follows by Note 3.17, and (iii) follows by Proposition 3.16.

Proposition 3.19. Let $\mathscr{f}_G$ and $\mathscr{g}_G$ be two $\mathcal{SS}$s. Then, $\left(\mathscr{f}_G \otimes_{i/st} \mathscr{g}_G\right)^c = \mathscr{f}_G \otimes_{u/i} \mathscr{g}_G$.

PROOF. Let $\mathscr{f}_G$ and $\mathscr{g}_G$ be two $\mathcal{SS}$s. Then, for all $x \in G$,

$$\begin{aligned}\left(\mathscr{f}_G \otimes_{i/st} \mathscr{g}_G\right)^c(x) &= \left(\bigcap_{x=yz}\left(\mathscr{f}_G{}^c(y) \cup \mathscr{g}_G{}^c(z)\right)\right)' \\ &= \bigcup_{x=yz}\left(\mathscr{f}_G{}^c(y) \cup \mathscr{g}_G{}^c(z)\right)' \\ &= \bigcup_{x=yz}\left(\mathscr{f}_G(y) \cap \mathscr{g}_G(z)\right) \\ &= \left(\mathscr{f}_G \otimes_{u/i} \mathscr{g}_G\right)(x)\end{aligned}$$

Thereby. $\left(\mathscr{f}_G \otimes_{i/st} \mathscr{g}_G\right)^c = \mathscr{f}_G \otimes_{u/i} \mathscr{g}_G$. □

Proposition 3.20. Let $\mathscr{f}_G$, $\mathscr{g}_G$, and $\hbar_G$ be three $\mathcal{SS}$s. If $\mathscr{f}_G \,\tilde{\subseteq}\, \mathscr{g}_G$, then $\mathscr{g}_G \otimes_{i/st} \hbar_G \,\tilde{\subseteq}\, \mathscr{f}_G \otimes_{i/st} \hbar_G$ and $\hbar_G \otimes_{i/st} \mathscr{g}_G \,\tilde{\subseteq}\, \hbar_G \otimes_{i/st} \mathscr{f}_G$.

PROOF. Let $\mathscr{f}_G$, $\mathscr{g}_G$, and $\hbar_G$ be three $\mathcal{SS}$s such that $\mathscr{f}_G \,\tilde{\subseteq}\, \mathscr{g}_G$. Then, for all $x \in G$, $\mathscr{f}_G(x) \subseteq \mathscr{g}_G(x)$, and so $\mathscr{g}_G{}^c(x) \subseteq \mathscr{f}_G{}^c(x)$. Thus, for all $x \in G$,

$$\begin{aligned}\left(\mathscr{g}_G \otimes_{i/st} \hbar_G\right)(x) &= \bigcap_{x=yz}\left(\mathscr{g}_G{}^c(y) \cup \hbar_G{}^c(z)\right) \\ &\subseteq \bigcap_{x=yz}\left(\mathscr{f}_G{}^c(y) \cup \hbar_G{}^c(z)\right) \\ &= \left(\mathscr{f}_G \otimes_{i/st} \hbar_G\right)(x)\end{aligned}$$

is obtained, implying that $\mathscr{g}_G \otimes_{i/st} \hbar_G \,\tilde{\subseteq}\, \mathscr{f}_G \otimes_{i/st} \hbar_G$. Similarly, for all $x \in G$,

$$\begin{aligned}\left(\hbar_G \otimes_{i/st} \mathscr{g}_G\right)(x) &= \bigcap_{x=yz}\left(\hbar_G{}^c(y) \cup \mathscr{g}_G{}^c(z)\right) \\ &\subseteq \bigcap_{x=yz}\left(\hbar_G{}^c(y) \cup \mathscr{f}_G{}^c(z)\right) \\ &= \left(\hbar_G \otimes_{i/st} \mathscr{f}_G\right)(x)\end{aligned}$$

implying that $\hbar_G \otimes_{i/st} \mathscr{g}_G \,\tilde{\subseteq}\, \hbar_G \otimes_{i/st} \mathscr{f}_G$. □

Proposition 3.21. Let $\mathscr{f}_G$, $\mathscr{g}_G$, σ_G, and $\mathscr{k}_G$ be four $\mathcal{SS}$s. If $\mathscr{k}_G \,\tilde{\subseteq}\, \sigma_G$, and $\mathscr{f}_G \,\tilde{\subseteq}\, \mathscr{g}_G$, then $\sigma_G \otimes_{i/st} \mathscr{g}_G \,\tilde{\subseteq}\, \mathscr{k}_G \otimes_{i/st} \mathscr{f}_G$ and $\mathscr{g}_G \otimes_{i/st} \sigma_G \,\tilde{\subseteq}\, \mathscr{f}_G \otimes_{i/st} \mathscr{k}_G$.

PROOF. Let $\mathscr{f}_G$, $\mathscr{g}_G$, σ_G, and $\mathscr{k}_G$ be four $\mathcal{SS}$s such that $\mathscr{k}_G \,\tilde{\subseteq}\, \sigma_G$, and $\mathscr{f}_G \,\tilde{\subseteq}\, \mathscr{g}_G$. Then, for all $x \in G$, $\mathscr{k}_G(x) \subseteq \sigma_G(x)$ and $\mathscr{f}_G(x) \subseteq \mathscr{g}_G(x)$. Thus, $\sigma_G{}^c(x) \subseteq \mathscr{k}_G{}^c(x)$ and $\mathscr{g}_G{}^c(x) \subseteq \mathscr{f}_G{}^c(x)$, for all $x \in G$. Then,

$$\begin{aligned}\left(\sigma_G \otimes_{i/st} \mathscr{g}_G\right)(x) &= \bigcap_{x=yz}\left(\sigma_G{}^c(y) \cup \mathscr{g}_G{}^c(z)\right) \\ &\subseteq \bigcap_{x=yz}\left(\mathscr{k}_G{}^c(y) \cup \mathscr{f}_G{}^c(z)\right) \\ &= \left(\mathscr{k}_G \otimes_{i/st} \mathscr{f}_G\right)(x)\end{aligned}$$

for all $x \in G$, implying that $\sigma_G \otimes_{i/st} g_G \tilde{\subseteq} k_G \otimes_{i/st} f_G$. Similarly, for all $x \in G$,

$$\begin{aligned}(g_G \otimes_{i/st} \sigma_G)(x) &= \bigcap_{x=yz} \left(g_G{}^c(y) \cup \sigma_G{}^c(z)\right) \\ &\subseteq \bigcap_{x=yz} \left(f_G{}^c(y) \cup k_G{}^c(z)\right) \\ &= (f_G \otimes_{i/st} k_G)(x)\end{aligned}$$

is obtained, implying that $g_G \otimes_{i/st} \sigma_G \tilde{\subseteq} f_G \otimes_{i/st} k_G$.

4. CONCLUSION

This study introduces a novel binary operation on soft sets—the soft intersection-star product—defined over parameter domains with an intrinsic group-theoretic structure. A thorough algebraic analysis explores its structural behavior within layered hierarchies of soft subsethood and its compatibility with generalized soft equalities. The operation is positioned within the lattice of soft subset classifications through a rigorous comparative framework, offering deeper insights into its expressive power and algebraic coherence relative to existing soft products. Further investigation covers its interaction with null and absolute soft sets and other group-based binary operations, clarifying its integrative role within the broader algebraic topology of soft systems. Developed within a strict axiomatic framework grounded in abstract algebra, the study investigates the core properties—closure, associativity, commutativity, idempotency, and the presence or absence of identity, inverse, and absorbing elements. The results confirm the operation's structural consistency and theoretical robustness, establishing it as a foundational tool for advancing generalized soft group theory. In doing so, the framework opens avenues for further research into soft algebraic structures, generalized equalities, and applications in logic, abstract modeling, and decision-making under uncertainty.

Conflict of Interest

The authors declare no conflicts of interest.

Authors' Contributions

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September 2025, Vol:3, Issue:2

International Journal of New Findings in Engineering, Science and Technology

journal homepage: https://ijonfest.gedik.edu.tr/

Received:08.07.2025 Accepted:16.07.2025 Pablished:29.09.2025

Urea-Formaldehyde Resin Systems Modified with Partially Pyrolyzed and Delignified Lignin: A Review

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Abstract

Urea-formaldehyde UF resins are typical adhesives employed in the production of wood-derived products. Application of such fossil fuel-based resins that emit formaldehyde emissions endangers the environmental and human health conditions profoundly. Bio-based lignin polymer can be utilized as a replacement additive in UF resins because it has inherent adhesive and water repellent nature. When lignin is added into the structure of the resin, the C-N bonds are reduced through the creation of new bonds within regions containing methylene bonds. Raw lignin cannot be directly added to UF resins; it must undergo pretreatment due to its poor binding capacity and amorphous nature. Therefore, partial pyrolysis of lignin in the low temperature zone under inert atmosphere was suggested in this study. This reaction creates a longer chain structure by partial C-O bond fragmentation; thus lignin is altered. This method is likely to reduce the formaldehyde emissions, but the same chain structure will increase the water repellency and reduce the moisture content of lignin. Literature research reveals that lignin additives have great effects on resin viscosity, free formaldehyde content, adhesion quality and panel performance.

Keywords: Lignin; UF Resin; Depolimerization; Partial Pyrolysis; Adhesives.

1. INTRODUCTION

The negative effects of fossil fuels on sustainability, the environment, and human health have been increasingly recognized in scientific and industrial circles in recent years [1]; [2]. As a result, an increasing number of studies have focused on finding renewable, environmentally friendly, and safer alternatives to traditional raw materials [3]; [4]. In particular, the wood-based materials sector has increased its interest in bio-based resources due to their natural renewability and relatively low carbon footprint [1]; [5].

Ever since they were first introduced in 1884, urea-formaldehyde resins have been used extensively as adhesives in the wood sector [6]. Favorable properties of the resins—high reactivity, quick gelation, economy, nondiscoloration, and long-term durability make UF resins some of the most common formaldehyde-based adhesives in the world. Although used for ages, there has been growing controversy about their reported toxicological profiles, resultant implications, and recyclability-related issues. Huge efforts have been made in developing new formulations for UF resins that can reduce risks related to environmental sustainability and human health and support enhanced overall sustainability [7]; [8].

The high moisture resistance characteristic of urea-formaldehyde UF adhesives adversely impacts the performance and durability of wood products that rely on them, which makes optimization through formulation improvements essential [7].

https://doi.org/10.61150/ijonfest.2025030206

Towards this end, researchers have embarked on studies whose focus is reducing the formation of unwanted compounds, including toxic and non-recyclable high levels of formaldehyde, which are major human health hazards, while, at the same time, looking to enhance strength properties and improve the beneficial traits of adhesives [9]; [10]. Consequently, considerable focus has been on examining the use of bio-based lignocellulosic chemicals in UF resins. Lignin, the third most common lignocellulosic component, has attracted specific interest in these study efforts [10].

Due to the benefits of lignin, current research studies have sought to partially or entirely replace traditional raw material for adhesives such as phenol and melamine with lignin. However, the usage of lignin as an adhesive is regarded as more widespread and more extensive studies should be carried out in this area. Lignin's chemical composition is amorphous and complex. How pure lignin can be used and how it’s complicated structure can be retained has already been studied. In addition to these studies, it is also possible to reduce formaldehyde emissions by depolymerizing lignin into phenol units and using it as a monomer, and to increase its binding capacity with formaldehyde by converting it into a long chain [11]. However, it will also be expected that the water resistance of lignin will be improved due to the same chain structure [12]. Due to this reason, this study will attempt to review literature so that the role of lignin in UF resin can be discussed through the modification of the bond structure.

2. BASIC COMPONENTS OF PLANTS LIGNOCELLULOSIC STRUCTURES

Lignocellulosic structures consist of cellulose, hemicellulose, and lignin, the major plant cell wall and biomass components [13]. Cellulose is a glucose polymer consisting of long chains of glucose units linked to each other through β-1,4-glycosidic bonds. Hemicellulose is a heteropolymer consisting of the sugars xylose, mannose, galactose, and arabinose. Lignin is a phenylpropanoid polymer and an energy content enhancer compound for biomass [14]. These are the feedstock materials such as agricultural residues, forest residues, wood wastes, and energy crops that have immense potential for sustainable energy production along with the endless provision of bio-based chemicals and materials. A major benefit of lignocellulosic composition is that it does not compete for food resources and aligns with environmental sustainability as a carbon-neutral source; hence, such factors have placed lignocellulosic material top in the priority list within the bioeconomy [15].

Lignocellulosic biomass-based products not only have uses in the energy production but also in many others involving the composite materials, bioplastics, activated carbon preparations, adhesives, as well as resin processing [16]; [6]. Exploitation on the structural property auspitable in the aromatic compounds, specifically lignin, is predicted to prevail the next-generation material production development on the next-generation fiber reinforced biocomposites [17], among many other sustainable strategies. In addition, the studies on the structural change on the lignin-based products have also garnered significant interest, specifically on the consideration on the embracement on the advanced characterization techniques involving the scanning electron microscopy SEM, among others, with the aim to optimize the heat treatment conditions for the establishment on the quality on the resulting lignocellulosic biomass-based products [18]. During the previous decade, investment has been on the needs to reduce the reactors downsize, optimize the process for the defibrating, besides carrying the correct test on the products for the eventual exploitation on the lignocellulosic feedstock on the industrial scale [19]. Following the foregoing, the Plant Fundamental Constituent Ratios representing the proportional distribution between cellulose, the hemicellulose, as well as the lignin in the lignocellulosic biomass, are indicated in the following table.

Table 1. Plant Fundamental Constituent Ratios.

2	Component	3	Proportion on dry matter basis
4	Cellulose	5	20% - 50%
6	Hemicellulose	7	15% - 35%
8	Lignin	9	10% - 30%
10	Extractives	11	1% - 20%
12	Minerals	13	1% - 5%
14	Protein	15	5% - 15%
16	Fats	17	1% - 5%
18	Starch	19	5% - 30%

1.1 Lignin

The third most common component of lignocellulosic biomass is lignin. It is an amorphous polymer containing a phenylpropanoid unit [20]; [21]. The compound acts as a protective agent against microbial biomass degradation and increases the water resistance of plant cell walls. [22] & [23]. It is estimated that 225 million tonnes of industrial lignin are produced per year worldwide. [24]. Lignin is a by-product of biofuel production and is being used for the production of biomass energy [25]; [26].

The predominant content of plant cell walls is lignin. It is accompanied by cellulose and hemicellulose as the third most abundant wood-derived product biopolymer [27]. The biopolymer comprises phenylpropanoid units and has a complex and irregular structure [28]; [20]. Lignin has many notable characteristics such as high heat stability and strength due to its inherent polyphenolic structure [29]; [30]. The paper and pulp industry annually produces approximately 50 million tonnes of lignin [26]; [25].

This natural biopolymer occurring spontaneously in lignin holds significant potential for the reduction of the emission of formaldehyde [31]. With its complex aromatic structure containing units of phenylpropanoid, lignin possesses distinctive properties appropriate for both chemical as well as thermal conversions [28]. Because of this, it can simply be embedded in the matrices of polymers. In its resulting composite material, there is potential for the heat resistance to increase as well as for the gain in overall strength [30];[32]. Figure 1 below depicts the amorphous nature of the lignin, with an insistence on its disordered complex organization.

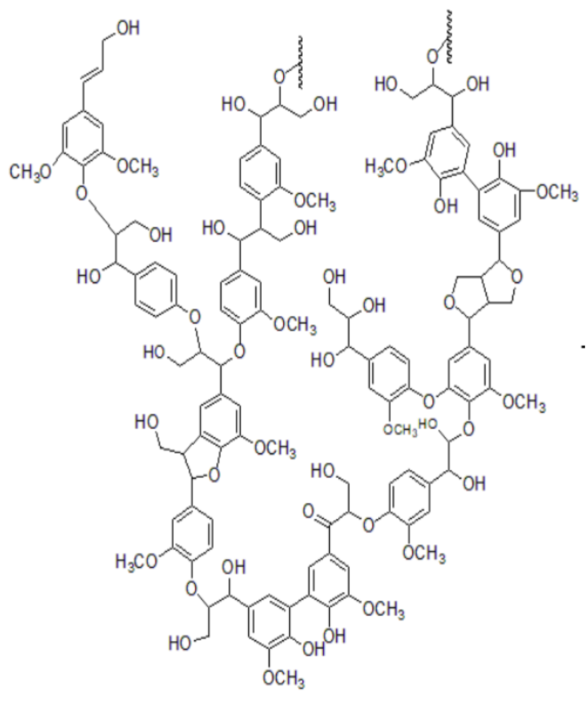

Figure 1. The amorphous structure of lignin.

3. DEPOLYMERIZATION PROCESSES

An essential step in the environmentally friendly synthesis of biofuels and biobased chemicals from plant biomass is the lignin depolymerization process [33]; [34]. In plant cell walls, native lignin is composed of phenylpropanoid units that combine to form an intricate polymer with mechanical strength and stiffness. However, its complex architecture poses limitations in biomass processing for biofuel generation [35]. Therefore, it becomes important to identify several methods that include thermochemical, catalyst, biological, and environmentally friendly solvent depolymerization methods, since depolymerization of the lignin through its breakdown into low molecular weight aromatics gives it greater value as a chemical feedstock [34]; [36].

3.1 Pyrolysis

Lignin pyrolysis is generally conducted in an oxygen-free environment at a temperature of 400 to 800 °C [37]. Phenolic monomers, tar, and gaseous products are formed when lignin is dissolved in pyrolysis [37]; [38]. Product composition differs with parameters like reactor type, temperature, heating rate, and residence time [39]; [37]. High-rate pyrolysis achieves maximum liquid bio-oil yield with high phenolic contents through high heating rates and brief reaction times [38]; [39]. Still, a drawback of this process is the intricate product distribution and polymeric tar generation [39]; [39]. Additionally, pyrolysis bio-oil is not usually directly usable as fuel; thus, it needs subsequent processes like hydrogenation and purification [40]; [39]. In addition, cross-linked polymers produced from side reactions during pyrolysis can decrease efficiency [37].

3.2 Partial Pyrolysis of Lignin

Partial pyrolysis of lignin takes place at comparatively low temperature zones, i.e., between 200 to 300 °C, and is not concerned with the total depolymerization of lignin to its basic phenylpropanoid units [34]; [41]. In this process, only the ether linkages present in the lignin structure are partially broken, while the carbon-carbon bonds are subjected to no breakage. Therefore, lignin remains a long-chain oligomer, which prevents its complete conversion into monomeric forms. At lower temperature limits, i.e., up to 250 °C, pyrolysis is a partial depolymerization process where lignin molecules are stable, resulting in breakage of only weaker bonds like the β-O-4 ether linkages [41]. Partial pyrolysis differs greatly from pyrolysis in that it is highly stable in maintaining the carbon structure of lignin within this temperature range [37]. Specifically, during the process, the lignin polymer's phenylpropanoid unit produces low-molecular-weight aromatic products, while other components mostly stay the same [37]; [42]. Oligomers with phenolic compounds and trace amounts of gas are the main products of partial pyrolysis. During pyrolysis, lignin is partially broken down by the breaking of ether bonds β-O-4, α-O-4, which releases lignin oligomers. In contrast, the lignin backbone's integrity is maintained for the synthesis of elongation products with phenolic structures due to the non-breakage of carbon-carbon C-C bonds [38]; [42].

Partial pyrolysis at the lower end of the temperature range successfully preserves the structural integrity of the lignin carbon matrix compared to more severe thermal treatments. This method, in turn, yields low-molecular-weight products rather than terminating in complete depolymerization of lignin, thus protecting the vital phenylpropanoid components. The resulting liquid products are typically described as low-emission phenolic materials and oligomers. In this regard, ether bond cleavage, especially of the β-O-4 type, plays a central role in the formation of oligomeric structures [38]. In contrast, the integrity of carbon-carbon bonds stabilizes the aromatic backbone, leading to lignin derivatives with structured chemical characteristics. Additionally, the low-temperature approach offers economic and environmental advantages by conserving energy and restricting the production of by-products. This low-temperature pyrolysis enables lignin to retain its carbon skeleton in relation to higher severity thermal treatment [37]. Within the temperature range produced via this technique, the yield of water-soluble product like phenolic and low molecular weight aromatic compounds is high, without breaking down the carbon skeleton critically [37]; [38].

Lignin oligomer extraction is also encouraged by combining the biochemical process with the catalytic boost during this pyrolysis procedure where the pyrolytic decomposition is managed [38]. Intramolecular forces including the van der Waal forces and the hydrogen bonding also keep the lignin construction units tightly held together at these temperatures. Figure 2 below illustrates the construction for the depolymerized lignin in part with the structural transformations during the procedure indicated.

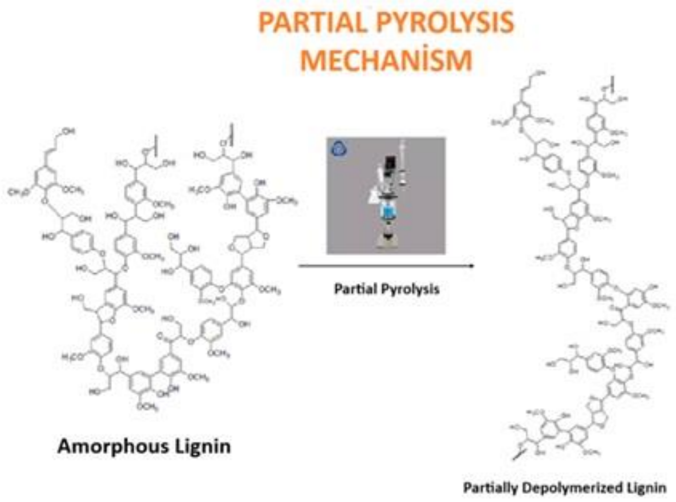

Figure 1. Formation of Partially Depolymerized Lignin

4. ADHESIVES

Wood adhesives were thoroughly discussed in the literature. The resin systems are typically categorized based on their chemical structure, and the most common class is formaldehyde F based systems. Adhesives in this class are urea UF, melamine MF, phenol PF and the MUF and PRF mixtures. But also highly reactive isocyanate-based adhesives are applied, e.g., polymeric diphenylmethane diisocyanate pMDI [43], emulsion polymer isocyanates EPI and polyurethane PUR systems [44]. Polyvinyl acetate PVAc and polyethylene-vinyl acetate EVA dispersions are common in the furniture and assembly industries. Biobased adhesives derived from tannin, protein or lignin are also significant options [45]. Natural polymers like tannin and lignin can be included in this category by reaction with formaldehyde [43].

Certain differences are made between structural binders e.g. for solid wood and wood composite board binders particleboard, MDF, OSB based on the application field. Categorize adhesives not only on the basis of the chemical basis but also on the basis of the chemical and mechanical response of the bond line into two main categories: in situ polymerized systems and pre-polymerized systems [44]. The first category includes rigid, highly cross-linked systems such as UF, MF, MUF, PF, PRF and pMDI.

The second group includes more flexible PVAc and PUR-based adhesives [44]. The differences between the two groups were stated to be very significant, especially for resisting moisture-induced stresses, which cause different types of failure .

4.1 Urea Formaldehyde Adhesives

Urea-formaldehyde UF resins are thermosetting adhesives that are extensively utilized in the production of wood-based composites and are known for their low price, rapid curing speed and superior bonding performance [46]; [47]. The resins form complex crosslinked three-dimensional networks via the condensation reaction of formaldehyde and urea to achieve superior bond strength [46]. Although UF adhesives are particularly favored in medium density fiberboard MDF, particleboard and plywood production; it is also of significant prominence in the construction and furniture industries because of the surface flatness benefit it offers [47]. Methylene bridges, which are the significant contributor to structure, are created through formaldehyde-urea reaction and enable quick curing even at low temperatures through acid catalysts [48]; [46]. The benefits of UF adhesives include low price, high bonding strength, and clear appearance after curing [49]. Because of these properties, UF adhesives are typically used in aesthetic surface applications, particularly in furniture production. Furthermore, the rapid curing rate speeds up the production processes and achieves economic efficiency through the saving of energy. But the most significant drawback of UF adhesives is that they are not resistant to water and moisture; therefore, they are not appropriate for outdoor use and their adhesive properties can weaken over time when exposed to humid environments. Formaldehyde, a hazardous and volatile chemical utilized in UF resins, is an important health and environmental hazard factor [50].

Specifically, long-term exposure has been linked to respiratory irritation, allergic reactions and possible carcinogenic effects. This prompted regulation of formaldehyde emissions with restrictions, and in this regard, studies on formaldehyde-free or low-emission adhesives as substitutes have intensified [51]; [50]. The emission of formaldehyde can be lowered by raising the urea/formaldehyde molar ratio, but at the expense of the bonding strength of the adhesive [52]. On the other hand, the emission of formaldehyde into the air can be avoided with the help of formaldehyde-absorbing additives. Low-emission UF adhesives have also been produced, and these adhesives have been designed to meet emission grades like E0 and E1. In addition, more robust and low-emission alternative resins, i.e., melamine formaldehyde MF and phenol formaldehyde PF adhesives, have also been created [53]. Although these alternatives are especially well-liked for exterior uses, bio-based adhesives i.e., soy-based adhesives also provide formaldehyde-free, eco-friendly alternatives [54]. The formaldehyde emissions can be lowered by raising the urea-formaldehyde U/F molar ratio but at the expense of the bond strength in urea-formaldehyde UF-bonded products [55]. The more realistic approach is to incorporate formaldehyde cleansers or absorbers e.g., tannins, lignosulfonates, or nano-fillers that bind chemically with free formaldehyde and lower its emission [56].

Meanwhile, new-generation low-emission UF resins are formulated to satisfy strict E0 and E1 levels of indoor air quality [57]. For outdoor or high-humidity applications, more durable resins like melamine-formaldehyde MF and phenol-formaldehyde PF show better moisture resistance at lower emissions [58]. Lastly, bio-based systems, specifically soy protein adhesives, have growing application as formaldehyde-free, environmentally friendly alternatives [59].

5. USE OF LIGNIN IN UF ADHESIVES

Lignin is a polyaromatic biomass by-product 50–75 million tons/year and the third most abundant natural polymer after cellulose and hemicellulose [56]; [60]. Due to the polyphenolic structure, it serves as an environmentally friendly alternative raw material for adhesives [60]. In resin uses, lignin has the potential to substitute urea or phenol partially or completely in thermosetting resins, thus saving petrochemical consumption of urea [56]. More significantly, lignin has many active hydroxyl and methoxyl groups which are capable of adsorbing free formaldehyde, thus acting as a formaldehyde emission reducer. For instance, adding modified lignin to UF resins has been demonstrated to greatly decrease formaldehyde emissions e.g., 74% decrease in a study and enhance indoor air quality [61]. Thus, lignin application is being explored with the objective of minimizing VOC and HCHO emissions from UF-bonded wood products. This strategy aids in attaining environmental objectives e.g., utilization of renewable waste materials and minimizes environmental and health problems [61]; [60].

Partial replacement of UF by lignin tends to decrease the quality of bonding and the strength of the panel onto which it is used, unless compensated for by formulation changes. Native lignin in UF resins reduces the bending strength MOR and internal bond IB values of particleboard and MDF [60]. For instance, bonded panels using neat lignin-based resins have had MOR values ranging from 8.1–11.0 N/mm² and IB values ranging from about 0.10–0.22 N/mm²; these are at the minimum necessary but lower than the case of UF being used individually reference MDF IB ~0.3–0.4 N/mm² [62]. Likewise, it has been noted that "panels manufactured with only UF resin have significantly better mechanical properties than panels bonded using lignin LS-UF adhesives". This is due to the lower cross-link density, as well as the larger molecular weight of lignin. Such is not the case, however, when additives or modification processes come into play. Inclusion of reactive crosslinkers or modification of lignin bonding mechanisms has a profound impact on performance. The addition of ~3% polymeric MDI pMDI to a 50:50 UF:Mg-lignosulfonate adhesive, for instance, increased IB by 366% from around 0.10 to 0.48 N/mm² and MOR by about 33% [60]. Additives UF + lignin + small pMDI can therefore restore and even surpass original strength. Moreover, nano-sized lignin additives can be utilized without strength loss. For instance, in a study, addition of 7% nanoparticles of dimethyl lignin to UF decreased HCHO but did not change/decrease the "physical and mechanical properties" of MDF [61]. In brief, the figures show that UF and pure lignin substitutions separately reduce MOR/IB but that such losses can be offset by the strategic application of partial substitutions like isocyanate additives or nano additives [60], [62].

Lignin addition effectively minimizes formaldehyde emission in UF panels [61]; [60]. In previous studies, the incorporation of lignin or lignosulfonate yielded far lower release than when UF was used by itself. For instance, MDF boards with 7% UF converter demethylated lignin nanoparticles released just 2.9 mg HCHO/100g formaldehyde. In boards made from UF resin alone in wood, there was a reduction by 74% from 11.2 mg/100g [61]. Wood panels with ammonium lignosulfonate and UF adhesive released low levels 0.7-1.0 mg/100g, as low as wood itself. That equates to a near-zero VOC [56]. To illustrate, adding Mg or Na lignosulphonate to UF was capable of decreasing formaldehyde by 91.1% and 56.9% respectively [60].

These values correspond to an E0 or super-E0 class emission ≤1.5 mg/100g, whereas the reference UF-bonded wood panel is an E1 ≤8 mg/100g Bekhta et al., 2021. These results confirm that lignin and lignin derivatives function as a scavenger of formaldehyde. The correct reactive position traps formaldehyde HCHO and minimizes the release. Quantitatively, the literature quotes 3-12 mg/100g for controls of lignin-modified UF wood panels [56]; [61]. This considerable reduction of formaldehyde release is also health- and environmentally friendly, rendering lignin-modified UF panels safe to be used indoors [56].

One of the most significant benefits of the application of modified lignin in UF resin is that the cost of raw materials is low. Lignin is an inexpensive and plentiful resource that comes from lignocellulosic material. It is used today as a fuel on a large scale and has been emphasized in the literature as being a "low-cost and widely used" additive [63]; [64]. However, the use of lignin often involves further processes demethylation, sulfonation, nanoparticle, pyrolysis, introducing some extra cost and process complexity in the production process [63]. In terms of processability, additives of lignin have great influence on resin properties. In a study, resins with sulfonated lignin content were found to be higher in pH, content of solids, viscosity and gel time but the formaldehyde release was reduced. Viscosity rose from 297.97 mPa-s to 4043.20 mPa-s and formaldehyde release reduced from 0.54% to 0.26% with an increase in the content of lignosulfonate from 0% to 2.5% [65]. This is because of crosslinking of lignin molecules in the adhesive and molecular weight increase. Consequently, lignin addition raises resin viscosity and strength and extends gel time and decreases formaldehyde release which can partly be compensated by pH adjustments. It has been found that lignosulfonate greatly improves the shelf life of UF resin. Lignosulfonate is said to enhance shelf life by enhancing electrostatic repulsion and lacks any chemical side reaction [64]. Chemical modification of lignin increases several parameters, namely resinoperability, which in turn affects its viscosity, pH value, and curing time and its long-term stability and formaldehyde emission. It is important to take into account viscosity-processing difficulties related thereto in using substantial levels of lignin. In short, empirical support exists for the inclusion of modified lignin in UF resins to provide numerous advantages in terms of environmental effect, human health, and sustainability. Additionally, urea-formaldehyde in conjunction with modified lignin can be used in a financially sound and aligned manner with the concept of resource conservation [63]; [64]. Free formaldehyde emission has greatly reduced and ensured functionality and wood-based mechanical properties. Medium Density Fiberboard MDF and plywood can be tailored and conform to EN E0/E1 requirements [61]; [64]. However, it should be considered that there will be increased viscosity due to the inclusion of lignin, longer curing time, and specific processing for lignin.

Research findings indicate that pre-pretreated lignin can be used as potential replacements for conventional urea-formaldehyde resin systems in wood-panel, medium-density fiberboard MDF, and domestic furniture applications [61]; [63]. This research falls into this category because they look towards replacements that are environment friendly and meet both ecologically and health-oriented requirements [61].

6. UF RESIN STUDIES WITH PARTIALLY PYROLYZED LIGNIN

Presence of phenolic hydroxyl OH functional groups in partially pyrolysed lignin is dominant in the alteration of urea-formaldehyde UF resin systems owing to participation of such functional groups in binding interactions with molecules of formaldehyde. Therefore, lignin is an active material that provides a urea-type interaction with molecules of formaldehyde. A comprehensive experimental investigation examined the effect of adding 4-8% partially pyrolysed ammonium lignosulphonate ALS to UF resin through differential scanning calorimetry DSC. Heat reaction was found to rise with an increase in lignin concentration at 8%. Further, the degree of polymerisation as well as crosslink density was found to rise with the addition of partially pyrolysed lignin. The reaction of polymerisation of formaldehyde with carbonyl or phenolic groups of the lignin structure leads to the decrease of free formaldehyde HCHO emissions [56] Therefore, the incorporation of partially pyrolysed lignin into the UF resin has the following effects:

i Partially pyrolysed lignin PPPL is a potential adsorbent for formaldehyde.

ii It assists in attaining greater network densities at low concentrations.

iii Without the presence of nitrifying ions, the accelerating effect of catalysis does not function. Beyond changing the curing kinetics, partially pyrolysed lignin addition to urea-formaldehyde adhesives brings an aromatic effect to the crosslinked structure [56].

The proportionate characteristics usually define the intensity of mechanical properties achieved from the application of UF resins with partially pyrolysed lignin. UF resin composite panels made fully from UF resin have mechanical properties that are marginally superior to those produced through the integration of UF resins and unmodified lignin. For example, it was reported in one study that the flexural strength MOR of a wood panel consisting of UF resin was about 4.88 MPa and its modulus of elasticity MOE was 573 MPa. When, however, a resin with 75% pyrolysis oil content 3:1 PyO:UF was used, the IB value reduced from 0.101 to 0.062, the MOR reduced to 2.30 MPa, and the MOE reduced to 189 MPa. The MOR of the board on 50% 1:1 based resin in the same study was around 0.64 MPa, a low value displaying a 67% decrease [66]. In other words, high lignin/oil content reduces the internal bond strength and reduces the internal bond homogeneity of the panel. Conversely, another study demonstrated that experiments with partially pyrolyzed lignosulfonate-based resins showed that the panels made with resins possessing 20% lignin achieved superior mechanical properties: MOR 15 MPa, MOE 3320 MPa, IB 0.48. These values show the partially pyrolyzed lignin meets the mechanical test standards. In conclusion, the inclusion of pyrolyzed lignin usually decreases mechanical properties for high addition ratios, etc., and although partially pyrolyzed lignin, given the appropriate addition ratios can provide enough strength. The numerical examples we have demonstrated state the following: UF without additives: MOR 4.9 MPa, IB 0.10; High-content pyrolyzed lignin 3:1, MOR 2.3 MPa, IB 0.062 approximate 50% reduction [66]; Partially pyrolyzed lignosulfonate 20%, MOR 15 MPa, IB ~0.48 [62]. The data demonstrate that their very well may be losses or improvements in sheet strength depending on lignin addition dosage.

Our research; looked in depth into the chemical, mechanical, and environmental performance of new-generation adhesives, which included UF resin systems that have been modified using partially pyrolyzed lignin. The literature shows that the partial pyrolysis of lignin at mild temperatures 150–300 °C produces low molecular weight, reactive lignin forms that still have phenolic structures. These lignin forms provide chemical bonding contributions and environmental benefits to UF resin systems. In the reaction of partially pyrolyzed lignin with formaldehyde, the aromatic –OH groups in the lignin structure can undergo condensation reactions with formaldehyde to capture free formaldehyde. The numerical data set forth in the studies demonstrate that, in panels, formaldehyde emissions can be reduced to 1.4–2.0 mg/100 g by including 4–8% partially pyrolyzed lignin, which corresponds to the E0 class for formaldehyde emissions. The reduction of formaldehyde is imperative because high indoor concentrations of formaldehyde and related emissions can reduce indoor air quality by making occupants ill.

In the case of mechanical performance, the study noted that for UF resins with the addition of partially pyrolyzed lignin, did not negatively influence mechanical properties IB, MOR, and MOE even when low amounts were added and may influence these properties in some situations positively. However, increasing the amount of lignin can lead to effects like increased viscosity of the resin, an increase in the cure time, and a reduction in wood panel strength. Therefore, a compromise is necessary between the performance and the lignin addition rate. Partially pyrolyzed lignin-based modification importantly has sustainability implications. Lignin is a waste product from the paper and bioethanol industries used as a low-value fuel; but it is possible to reprocess lignin through partial pyrolysis and make high-value-added products from it. The addition of partially pyrolyzed lignin may help reduce fossil raw material in resin systems, will lower the carbon footprint, and supports a renewable resource production model.

That said, the research in this area is somewhat underwhelming. There have been, especially, very few studies on the use of partially pyrolyzed lignin form in UF resins. There are many reasons for this including the heterogeneous nature of partially pyrolyzed products, the diverse sources of lignin, the inability to standardize pyrolysis conditions, and limited understanding of interaction mechanisms with resins which certainly justify further experimental and theoretical investigations in this area. In summary, partially pyrolyzed lignin has great potential to not only decrease formaldehyde emissions, but also to improve properties and enhance the percentage of bio-based content in UF resins. Yet, these systems will only continue to become viable alternatives if we develop additional literature data, scalable process development, and methods of testing and standardization. Furthermore, UF resin systems modified with partially pyrolyzed lignin represent a novel transition that could lead to an eco-friendly transition in the wood-based materials industry and help develop sustainable adhesive technology.

7. CONCLUSION

The current research examined comprehensively the chemical, mechanical, and environmental characteristics of novel adhesives from UF resin systems modified with partially pyrolyzed lignin. The literature data indicate that the low-temperature pyrolysis 150–300 °C of lignin yields low molecular weight, reactive derivatives of phenolic structure that are preserved. Chemical bonding contributions and environmental benefits are both present in lignin derivatives in UF resin systems.

Under the pyrolysis of lignin in the presence of formaldehyde, the aromatic –OH groups in the lignin molecule become condensed with formaldehyde, encapsulating free formaldehyde. According to the quantitative data presented in the investigations, formaldehyde emissions from the panels can be reduced to 1.4–2.0 mg/100 g with the addition of 4–8% partially pyrolyzed lignin, comparable to the E0 class. This is particularly beneficial for improving indoor air quality and reducing harmful emissions that are not good for the health of human beings. In mechanical performance, the addition of partially pyrolyzed lignin was found not to have a negative effect on the mechanical properties of UF resins such as internal bond strength IB, bending strength MOR, and elastic modulus MOE, even with low levels of additions, and in some cases may even increase these values. But to raise the addition rate can have the following implications such as increased viscosity of the resin, increased curing time, and reduced strength in the wood panel. Again, here there must be a trade-off between lignin addition rate and performance. Modification of the partially pyrolyzed lignin is also important on the sustainability side. Lignin is a byproduct in paper and bioethanol production and is used as a low-value fuel but can be recycled through partial pyrolysis and converted to high-value-added products. Through the addition of partially pyrolyzed lignin, use of fossil raw materials in resin systems is reduced, the carbon footprint is reduced, and a model for production based on renewable resources is promoted. But few studies exist in this field of literature. Particularly, few studies are available on the utilization of partially pyrolyzed lignin in UF resins. Structural heterogeneity in partially pyrolyzed products, diversity of lignin sources, lack of standardization in pyrolysis conditions, and incompleteness of knowledge in understanding interaction mechanisms with resins render experimental and theoretical studies in this field imperative.

In conclusion, partially pyrolyzed lignin has great potential to reduce the emission of formaldehyde, increase mechanical properties, and increase the bio-based content ratio in UF resins. For these systems to become a commercially acceptable alternative, additional literature data, scale-up process development, and standardization studies are needed. In this sense, UF resin systems formulated using partially pyrolyzed lignin seem to be a new area of research that can spark an environmental revolution in the wood-based materials industry and contribute towards the development of environmental friendly adhesive technology.

Acknowledgements

We would like to thank the individuals and institutions that contributed to the TÜBİTAK project No. 5230122 entitled "Urea Formaldehyde Resin Systems Modified with Lignin Degraded by Partial Pyrolysis" conducted by Istanbul Gedik University to provide the infrastructure for this study.

Funding

This research is supported by TÜBİTAK under project number 5230122, "Urea-Formaldehyde Resin Systems Modified with Lignin Depolymerized by Partial Pyrolysis."

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